U.S.NRC

United States Nuclear Regulatory Commission

Protecting People and the Environment

NUREG/CR-7197

Heat Release Rates of Electrical Enclosure Fires (HELEN-FIRE)

Final Report

Office of Nuclear Regulatory Research

AVAILABILITY OF REFERENCE MATERIALS IN NRC PUBLICATIONS

NRC Reference Material

As of November 1999, you may electronically access NUREG-series publications and other NRC records at NRC's Library at www.nrc.gov/reading-rm.html. Publicly released records include, to name a few, NUREG-series publications; *Federal Register* notices; applicant, licensee, and vendor documents and correspondence; NRC correspondence and internal memoranda; bulletins and information notices; inspection and investigative reports; licensee event reports; and Commission papers and their attachments.

NRC publications in the NUREG series, NRC regulations, and Title 10, "Energy," in the *Code of Federal Regulations* may also be purchased from one of these two sources.

1. **The Superintendent of Documents**
   U.S. Government Publishing Office
   Mail Stop IDCC
   Washington, DC 20402-0001
   Internet: bookstore.gpo.gov
   Telephone: (202) 512-1800
   Fax: (202) 512-2104

2. **The National Technical Information Service**
   5301 Shawnee Rd., Alexandria, VA 22312-0002
   www.ntis.gov
   1-800-553-6847 or, locally, (703) 605-6000

A single copy of each NRC draft report for comment is available free, to the extent of supply, upon written request as follows:

Address: **U.S. Nuclear Regulatory Commission**
Office of Administration
Publications Branch
Washington, DC 20555-0001
E-mail: distribution.resource@nrc.gov
Facsimile: (301) 415-2289

Some publications in the NUREG series that are posted at NRC's Web site address www.nrc.gov/reading-rm/doc-collections/nuregs are updated periodically and may differ from the last printed version. Although references to material found on a Web site bear the date the material was accessed, the material available on the date cited may subsequently be removed from the site.

Non-NRC Reference Material

Documents available from public and special technical libraries include all open literature items, such as books, journal articles, transactions, *Federal Register* notices, Federal and State legislation, and congressional reports. Such documents as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings may be purchased from their sponsoring organization.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at—

The NRC Technical Library
Two White Flint North
11545 Rockville Pike
Rockville, MD 20852-2738

These standards are available in the library for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from—

American National Standards Institute
11 West 42nd Street
New York, NY 10036-8002
www.ansi.org
(212) 642-4900

Legally binding regulatory requirements are stated only in laws; NRC regulations; licenses, including technical specifications; or orders, not in NUREG-series publications. The views expressed in contractorprepared publications in this series are not necessarily those of the NRC.

The NUREG series comprises (1) technical and administrative reports and books prepared by the staff (NUREG–XXXX) or agency contractors (NUREG/CR–XXXX), (2) proceedings of conferences (NUREG/CP–XXXX), (3) reports resulting from international agreements (NUREG/IA–XXXX), (4) brochures (NUREG/BR–XXXX), and (5) compilations of legal decisions and orders of the Commission and Atomic and Safety Licensing Boards and of Directors' decisions under Section 2.206 of NRC's regulations (NUREG–0750).

NUREG/CR-7197

Heat Release Rates of Electrical Enclosure Fires (HELEN-FIRE)

Final Report

Manuscript Completed: February 2015
Date Published: April 2016

Prepared by:
Kevin McGrattan
Scott Bareham

National Institute of Standards and Technology
Engineering Laboratory; Fire Research Division
Gaithersburg, MD 20899

David Stroup, NRC Project Manager

Prepared for:
Division of Risk Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

ABSTRACT

This report documents an experimental program to explore the heat release rate and burning behavior of electrical enclosures commonly found in nuclear power plants. Electrical enclosures are a potential source of fire in nuclear power plants because they contain both combustible materials and live electrical circuits. These fires have the potential to disrupt power, instrumentation, and control in the plant. Key parameters affecting fire in an enclosure include its size, openings, electrical voltage, and combustible load.

CONTENTS

ABSTRACT ..... **iii**
CONTENTS ..... **v**
LIST OF FIGURES ..... **vii**
LIST OF TABLES ..... **ix**
EXECUTIVE SUMMARY ..... **xiii**
ACKNOWLEDGMENTS ..... **xv**
ABBREVIATIONS ..... **xvii**
1 INTRODUCTION **1**
1.1 Background 1
1.2 Previous Studies 1
1.2.1 Sandia National Laboratories Experiments 1
1.2.2 VTT Experiments 1
1.2.3 IRSN Experiments 1
1.3 Current Practice 2
1.4 Objective 2
2 DESCRIPTION OF ENCLOSURES **3**
2.1 Survey of Electrical Enclosures 3
2.2 Enclosures used in the Experiments 9
2.2.1 Enclosure 1 10
2.2.2 Enclosure 2 12
2.2.3 Enclosure 3 14
2.2.4 Enclosures 4 and 5 16
2.2.5 Enclosure 6 18
2.2.6 Enclosure 7 20
2.2.7 Enclosure 8 22
3 CABLE PROPERTIES **25**
3.1 Properties of Cables used in Enclosure Fire Experiments 25
4 EXPERIMENTAL PROCEDURE **33**
4.1 Oxygen Consumption Calorimeter 33
4.2 Ignition Sources 36
4.2.1 Cartridge Heaters 36
4.2.2 Propane Line Burners 36
4.2.3 Liquid Fuel Pan Fires 38
4.2.4 Combustible Loading 38
5 FULL-SCALE MEASUREMENTS **41**
5.1 Description 41
5.2 Summary of Individual Experiments 54
5.3 General Observations 167
5.3.1 Ignition 167
5.3.2 Fire Spread 167
5.3.3 Ventilation 168
5.3.4 Peak Heat Release Rate 168

6 CONCLUSION AND FUTURE WORK 169
7 REFERENCES 171
APPENDIX A TEMPERATURE DATA A-1

LIST OF FIGURES

Figure 2-1. Photographs of enclosures typically found near the main control room 4
Figure 2-2. Photographs of enclosures typically found near the main control room 5
Figure 2-3. Photographs of the internal wiring of typical switchgear enclosures 6
Figure 2-4. Photographs of the internal wiring of medium voltage switchgear 7
Figure 2-5. Photographs of the internal wiring from typical motor control centers................... 8
Figure 2-6. Photographs of Enclosure 1 10
Figure 2-7. Sketch of Enclosure 1 11
Figure 2-8. Photographs of Enclosure 2 12
Figure 2-9. Sketch of Enclosure 2 13
Figure 2-10. Photographs of Enclosure 3 14
Figure 2-11. Sketch of Enclosure 3 15
Figure 2-12. Photographs of Enclosures 4 and 5 16
Figure 2-13. Sketch of Enclosures 4 and 5.. 17
Figure 2-14. Photographs of Enclosure 6 18
Figure 2-15. Sketch of Enclosure 6 19
Figure 2-16. Photographs of Enclosure 7 20
Figure 2-17. Sketch of Enclosure 7 21
Figure 2-18. Photographs of Enclosure 8 22
Figure 2-19. Sketch of Enclosure 8 23
Figure 3-1. Photograph of Cables 805-835 25
Figure 3-2. Photograph o Cables 836-842 26
Figure 3-3. Photograph of Cables 843-845 26
Figure 3-4. Photograph of a circuit card installed in Enclosure 3... 27
Figure 4-1. Schematic diagram of the small calorimeter.. 33
Figure 4-2. Schematic diagram of the small calorimeter underneath the large hood at the CBD test facility 34
Figure 4-3. Two 300 W cartridge heaters. One has an in-line circuit breaker......................... 36
Figure 4-4. Photograph of 30 cm (12 in) propane line burner.. 38

LIST OF TABLES

Table 3-1. Manufacturers’ descriptions of the cables ... 28
Table 3-2. Cable properties ... 30
Table 4-1. Propane burner heat release rate values ... 37
Table 5-1. Summary of enclosure conditions ... 42
Table 5-2. Summary of enclosure fire measurements ... 49
Table 5-3. Summary of Test 1 ... 55
Table 5-4. Summary of Test 2 ... 56
Table 5-5. Summary of Test 3 ... 57
Table 5-6. Summary of Test 4 ... 58
Table 5-7. Summary of Test 5 ... 59
Table 5-8. Summary of Test 6 ... 60
Table 5-9. Summary of Test 7 ... 61
Table 5-10. Summary of Test 8 ... 62
Table 5-11. Summary of Test 9 ... 63
Table 5-12. Summary of Test 10 ... 64
Table 5-13. Summary of Test 11 ... 65
Table 5-14. Summary of Test 12 ... 66
Table 5-15. Summary of Test 13 ... 67
Table 5-16. Summary of Test 14 ... 68
Table 5-17. Summary of Test 15 ... 69
Table 5-18. Summary of Test 16 ... 70
Table 5-19. Summary of Test 17 ... 71
Table 5-20. Summary of Test 18 ... 72
Table 5-21. Summary of Test 19 ... 73
Table 5-22. Summary of Test 20 ... 74
Table 5-23. Summary of Test 21 ... 75
Table 5-24. Summary of Test 22 ... 76
Table 5-25. Summary of Test 23 ... 77
Table 5-26. Summary of Test 24 ... 78
Table 5-27. Summary of Test 25 ... 79
Table 5-28. Summary of Test 26 ... 80
Table 5-29. Summary of Test 27 ... 81
Table 5-30. Summary of Test 28 ... 82
Table 5-31. Summary of Test 29 ... 83
Table 5-32. Summary of Test 30 ... 84
Table 5-33. Summary of Test 31 ... 85
Table 5-34. Summary of Test 32 ... 86
Table 5-35. Summary of Test 33 ... 87
Table 5-36. Summary of Test 34 ... 88
Table 5-37. Summary of Test 35 ... 89
Table 5-38. Summary of Test 36 ... 90
Table 5-39. Summary of Test 37 ... 91
Table 5-40. Summary of Test 38 ... 92
Table 5-41. Summary of Test 39 ... 93
Table 5-42. Summary of Test 40 ... 94
Table 5-43. Summary of Test 41 ... 95
Table 5-44. Summary of Test 42 ... 96
Table 5-45. Summary of Test 43 ... 97

Table 5-46. Summary of Test 44 98
Table 5-47. Summary of Test 45 99
Table 5-48. Summary of Test 46 100
Table 5-49. Summary of Test 47 101
Table 5-50. Summary of Test 48 102
Table 5-51. Summary of Test 49 103
Table 5-52. Summary of Test 50 104
Table 5-53. Summary of Test 51 105
Table 5-54. Summary of Test 52 106
Table 5-55. Summary of Test 53 107
Table 5-56. Summary of Test 54 108
Table 5-57. Summary of Test 55 109
Table 5-58. Summary of Test 56 110
Table 5-59. Summary of Test 57 111
Table 5-60. Summary of Test 58 112
Table 5-61. Summary of Test 59 113
Table 5-62. Summary of Test 60 114
Table 5-63. Summary of Test 61 115
Table 5-64. Summary of Test 62 116
Table 5-65. Summary of Test 63 117
Table 5-66. Summary of Test 64 118
Table 5-67. Summary of Test 65 119
Table 5-68. Summary of Test 66 120
Table 5-69. Summary of Test 67 121
Table 5-70. Summary of Test 68 122
Table 5-71. Summary of Test 69 123
Table 5-72. Summary of Test 70 124
Table 5-73. Summary of Test 71 125
Table 5-74. Summary of Test 72 126
Table 5-75. Summary of Test 73 127
Table 5-76. Summary of Test 74 128
Table 5-77. Summary of Test 75 129
Table 5-78. Summary of Test 76 130
Table 5-79. Summary of Test 77 131
Table 5-80. Summary of Test 78 132
Table 5-81. Summary of Test 79 133
Table 5-82. Summary of Test 80 134
Table 5-83. Summary of Test 81 135
Table 5-84. Summary of Test 82 136
Table 5-85. Summary of Test 83 137
Table 5-86. Summary of Test 84 138
Table 5-87. Summary of Test 85 139
Table 5-88. Summary of Test 86 140
Table 5-89. Summary of Test 87 141
Table 5-90. Summary of Test 88 142
Table 5-91. Summary of Test 89 143
Table 5-92. Summary of Test 90 144
Table 5-93. Summary of Test 91 145
Table 5-94. Summary of Test 92 146
Table 5-95. Summary of Test 93 147
Table 5-96. Summary of Test 94 148

Table 5-97. Summary of Test 95 149
Table 5-98. Summary of Test 96 150
Table 5-99. Summary of Test 97 151
Table 5-100. Summary of Test 98 152
Table 5-101. Summary of Test 99 153
Table 5-102. Summary of Test 100 154
Table 5-103. Summary of Test 101 155
Table 5-104. Summary of Test 102 156
Table 5-105. Summary of Test 103 157
Table 5-106. Summary of Test 104 158
Table 5-107. Summary of Test 105 159
Table 5-108. Summary of Test 106 160
Table 5-109 Summary of Test 107 161
Table 5-110. Summary of Test 108 162
Table 5-111. Summary of Test 109 163
Table 5-112. Summary of Test 110 164
Table 5-113. Summary of Test 111 165
Table 5-114. Summary of Test 112 166

EXECUTIVE SUMMARY

Electrical enclosures are a potential source of fire in nuclear power plants because they contain both combustible materials and live electrical circuits. These fires have the potential to disrupt power, instrumentation, and control in the plant. Fire growth in an electrical enclosure can be influenced by its size, openings, electrical voltage, and combustible load.

To better quantify the heat release rate and burning behavior of electrical enclosures, 112 full-scale experiments were conducted at the Chesapeake Bay Detachment of the Naval Research Laboratory. Eight electrical enclosures were acquired from Bellefonte Nuclear Generating Station, a plant owned by the Tennessee Valley Authority located in Hollywood, Alabama. The enclosures were installed in the early 1980s, but the plant was never operated. The enclosures were originally low voltage control cabinets, but in the experiments they were reconfigured with various amounts and types of electrical cable to represent other kinds of enclosures that would be found in a typical plant.

The key experimental parameters are as follows:

1. Enclosure geometry. Six of the enclosures were vertically oriented with various size doors and base area. Two of the enclosures were sections of the main control room "horseshoe" control panel.

2. Ventilation, mainly via opening or closing the enclosure doors. Some of the enclosures had a false bottom which could be removed. One enclosure had vertical conduits through its top.

3. Ignition strength, *i.e.*, the amount of energy necessary to start the fire. A small propane burner and various size pans of acetone were used.

4. Combustible load, *i.e.*, the amount and type of electrical cables or other materials in the enclosure that can burn. Cables typically fall into two categories: thermoplastic and thermoset. The former typically burn more readily than the latter.

An oxygen consumption calorimeter was built on site to measure the heat release rate (HRR) of the fire as a function of time. Of particular interest is the peak HRR, the time to peak, and the total energy released. Thermocouples were positioned at various heights within the enclosures to monitor internal temperatures.

Of the 112 experiments, the peak HRR, over that of the ignitor itself, varied from 0 kW to 576 kW. The mean was 43 kW; the median was 19 kW. Eleven fires peaked at greater than 100 kW.

ACKNOWLEDGMENTS

The work described in this report was supported by the Office of Nuclear Regulatory Research (RES) of the US Nuclear Regulatory Commission (USNRC). This program was directed by David Stroup. Gabriel Taylor and Nicholas Melly provided additional information on the cable composition and typical installation practice.

The large-scale experiments described in this report were conducted at the Chesapeake Bay Detachment of the Naval Research Laboratory. The facility is directed by John Farley and logistical support was provided by Clarence Whitehurst. Data acquisition support was provided by staff members of Hughes Associates, Inc., Joshua Dinaburg and Andrew Wolf.

Technical support for the experiments was provided by NIST Fire Research Division staff members Michael Selepak and Mariusz Zarzecki. Roy McLane and Jay McElroy supervised the construction and dismantling of the small calorimeter. Edward Hnetkovsky and Scott Bareham designed the calorimeter, with support from Matthew Bundy, Doris Rinehart, Laurean DeLauter, and Anthony Chakalis of the NIST Large Fire Research Facility.

Finally, a draft of this report was Noticed in the Federal Register for public comment on May 1, 2015 (80 FR 24981) by the NRC. The authors thank the Office of Nuclear Reactor Regulation and those members of the public, specifically Victoria K. Anderson, Nuclear Energy Institute; and James Barstow and Richard Gropp, Exelon Generation; who provided comments during the public comment period.

Disclaimer

ABBREVIATIONS

ASTM	American Society for Testing and Materials
AWG	American Wire Gauge
CAROLFIRE	Cable Response to Live Fire
CBD	Chesapeake Bay Detachment
CDRS	Conductors
CHRISTIFIRE	Cable Heat Release, Ignition, and Spread in Tray Installations
CPE	Chlorinated Polyethylene
CSPE	Chloro-Sulfonated Polyethylene
DEG C	Degrees Celsius
DIR BUR	Direct Burial
EPR	Ethylene-Propylene Rubber
EPRI	Electric Power Research Institute
FR	Flame Retardant
HRR	Heat Release Rate
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
NEC	National Electric Code
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
NRL	Naval Research Laboratory
NRR	NRC Office of Nuclear Reactor Regulation
OIL RES	Oil Resistant
PE	Polyethylene
PMMA	Polymethyl Methacrylate
PRA	Probabilistic Risk Assessment
PVC	Poly-vinyl Chloride
Q	Qualified
RES	NRC Office of Nuclear Regulatory Research
SIS	Synthetic Insulated Switchboard
SNL	Sandia National Laboratories
SP	Swedish National Testing and Research Institute
SR	Silicone Rubber
SUN RES	Sun Resistant
TC	Thermocouple or Tray Cable
TC-ER	Tray Cable - Exposed Run
TC/NCC	Tray Cable/Nickel Coated Copper
Tefzel®	DuPont ETFE (Ethylene-Tetrafluoroethylene) Resin
TFN	Thermoplastic Fixture wire Nylon jacketed
TP	Thermoplastic
TPE	Thermoplastic Elastomer
TS	Thermoset
UL	Underwriters Laboratories
UQ	Unqualified
VNTC	Vinyl Nylon Tray Cable

XHHW	Cross-linked High Heat Water resistant
VTT	Valtion Teknillinen Tutkimuskeskus (Technical Research Centre, Finland)
XLPE, XLP or XPE	Cross-Linked Polyethylene

1 INTRODUCTION

1.1 Background

Electrical enclosures are a potential source of fire in nuclear power plants (NPPs) because they contain both combustible materials and live electrical circuits. These fires have the potential to disrupt power, instrumentation, and control in the plant. Parameters that affect fire growth in an electrical enclosure include its size, openings, electrical voltage, and combustible load.

1.2 Previous Studies

Heat release rate (HRR) measurements for electrical enclosure fires have been conducted at Sandia National Laboratories (Chavez, 1987; Chavez and Nowlen, 1988), VTT Technical Research Centre of Finland (Mangs *et al*., 2003), and the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) in France (Plumecocq *et al*., 2011; Coutin *et al*., 2012). In these studies, various configurations of electrical enclosure sizes, combustible loads and ventilation conditions were tested to determine the HRRs and thermal conditions in and around the enclosures.

1.2.1 Sandia National Laboratories Experiments

Sandia conducted 22 full-scale fire experiments in the mid-1980s, with an emphasis on control room and switchgear room configurations. The test report (Chavez, 1987) concludes that fires in either benchboard or vertical enclosures containing qualified[1] or unqualified cable can be ignited, but that fires burning unqualified cable spread more rapidly and to a greater extent than fires with qualified cable. The report also concludes that these fires are not severe enough to ignite combustibles in adjacent enclosures or outside the enclosure of origin.

1.2.2 VTT Experiments

VTT conducted 22 fire experiments that are reported in three separate reports: Mangs and Keski-Rahkonen (1994; 1996), Mangs (2004), and a paper summarizing the findings (Mangs *et al*., 2003). The enclosures contained a variety of electronic components, including relays, connectors, bundled wiring, circuit boards, and (mostly) PE/PVC cable. The purpose of the experiments was to determine maximum HRRs, minimum igniter strengths, and the effect of opening area on the burning rate. A small propane line burner, typically 10 cm in length and varying between 0.5 kW and 7.5 kW was used to ignite the fires.

1.2.3 IRSN Experiments

Plumecocq *et al*. (2011) and Coutin *et al*. (2012) conducted experiments and performed analysis with the goal of developing a simplified model of fire behavior within an electrical enclosure. This model is based on the assumption that the ventilation within the enclosure is limited and that the HRR can be inferred from the limited oxygen supply. Experiments were performed using gas burners and PMMA (polymethyl methacrylate, a common plastic). A few experiments were performed with actual electrical components and cabling.

[1] “Qualified” typically means that the cable has passed the IEEE-383 flame spread test.

1.3 Current Practice

In 2005, the US Nuclear Regulatory Commission (NRC) and the Electric Power Research Institute (EPRI) jointly published NUREG/CR-6850/EPRI TR-101989, *EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities*. This report contains methods and data for conducting fire probabilistic risk assessments (PRAs) in commercial NPP applications. Appendix G of NUREG/CR-6850 expresses the peak HRR for five different categories of electrical enclosures in the form of gamma distributions. The enclosures are categorized by their combustible load (one vs multiple cable bundles), flammability of materials (qualified vs unqualified cable), and ventilation (door open vs door closed). The distributions were developed by a panel of experts who considered actual fire events in NPPs and other industrial facilities, and the experimental data cited above.

Since the publication of NUREG/CR-6850, it has been noted that there is a considerable gap between the database of actual fire events and the experimental data. The reason for this gap is that the experiments cited in Section 1.2 were *not* intended to mimic the distribution of actual fire events. The VTT and IRSN experiments were aimed at validating empirical models that predict the peak HRR as a function of ventilation and enclosure geometry. The Sandia experiments were designed to answer specific questions like whether it is possible to propagate a fire on qualified cables with a particular kind of igniter, or whether it is possible to spread a fire from one side of an enclosure to another. In all of these studies, the aim was to determine the largest possible fire as opposed to the typical fire. The latter question is more difficult to answer because it would be extremely difficult to mimic realistic electrical malfunctions in operating electrical enclosures in such a way as to generate a statistically significant sample of test results. The nearest substitute would be to invoke the database of actual fire events in NPPs (Wachowiak and Lindeman, 2013), but in these cases, human intervention prevented the relatively small fires from spreading. It would be impossible to recreate the fires in the events database and allow them to progress with no suppression.

1.4 Objective

The objective of the current study is to measure the HRRs of fires in electrical enclosures containing a wide variety of cable types, geometries, ventilation configurations, and ignition sources. The enclosures used in the experiments have been acquired from an NPP built in the late 1970s but never operated. As received, these enclosures contain wiring typical of those built after the Browns Ferry fire of 1975. In addition, these enclosures were refurbished after an initial set of experiments so that they resembled other types of enclosures found in other plants. The procedure for refurbishing is described in the next chapter.

2 DESCRIPTION OF ENCLOSURES

This chapter contains a survey of electrical enclosures commonly found in nuclear power plants (NPPs).

2.1 Survey of Electrical Enclosures

On the following pages are different types of electrical enclosures that were photographed during plant visits to several operating and decommissioned NPPs. These and other photographs were used as guidance in developing the wiring configurations that were simulated in the experiments. This should not be considered a comprehensive survey of all enclosures in all plants, but rather a collection of typical combustible loads and ventilation configurations.

Figure 2-1 and Figure 2-2 display photographs of enclosures in and around the main control room. These enclosures typically contain tight bundles of relatively small diameter insulated wiring and a large number of connection points. Racks of circuit boards are also common.

Figure 2-3 and Figure 2-4 displays photographs of switchgear enclosures. In general, these types of enclosures contain less wiring than the enclosures in the control room. These enclosures are also relatively large with large amounts of open volume inside.

Figure 2-5 displays photographs of motor control centers (MCCs). These enclosures contain relatively small compartments containing a variety of wiring and equipment. It is difficult to characterize these compartments in general terms other than to say that each “bucket” is relatively self-contained and isolated from its neighbors.

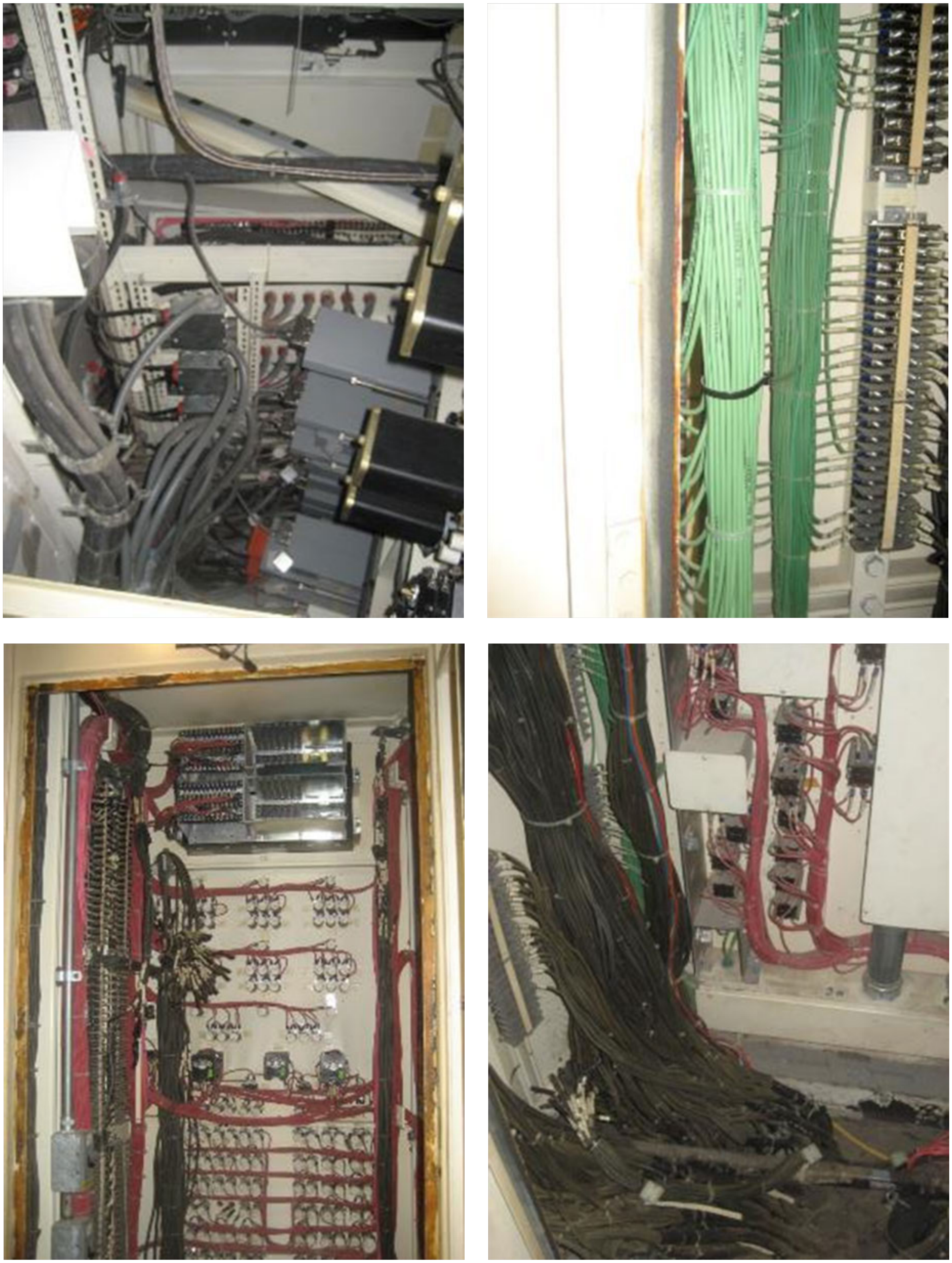


Figure 2-1. Photographs of enclosures typically found near the main control room.

Figure 2-2. Photographs of enclosures typically found near the main control room.

Figure 2-3. Photographs of the internal wiring of typical switchgear enclosures.

Figure 2-4. Photographs of the internal wiring of medium voltage switchgear.

Figure 2-5. Photographs of the internal wiring from typical motor control centers.

2.2 Enclosures used in the Experiments

The electrical enclosures used in the experiments were acquired from Bellefonte Nuclear Generating Station, a plant owned by the Tennessee Valley Authority located in Hollywood, Alabama. The enclosures were installed in the early 1980s, but the plant was never operated. The enclosures appear to have been manufactured in the late 1970s. All were constructed of steel with a thickness of approximately 3 mm (1/8 in).

All of the enclosures were low voltage control cabinets, but they were reconfigured to take on typical characteristics of other types of electrical enclosures found throughout a plant. In the initial set of experiments, the enclosures were tested as is; that is, in the condition that they were received from the plant. After these initial experiments, cables of different amounts and configurations were added to the enclosures such as to mimic photographs collected from a variety of existing and decommissioned U.S. plants. In some cases, the amount and configuration of the cables did not resemble any of the photographs in the collection.

As previously stated, electrical cables used in commercial NPPs can be grouped into one of two categories; thermoplastic (TP) or thermoset (TS). TS cables are typically harder to ignite than TP cables, but can reach peak HRRs similar to TP cables once ignited. Some electrical cables will have a TS jacket to improve its flammability properties while the individual conductors within the cable will have TP insulation. For some of the experiments conducted during this test series, some amount of cable jacket was removed to expose the individual insulated conductors. While the conductors may or may not have remained twisted, all the associated packing material was removed from around the individual conductors. This was done to increase the amounts and types of potential fuels, i.e., electrical cables, available for use in the experiments. The stripping of the cable jacket was not intended to provide any significant information relative to the installation practice in operating plants.

2.2.1 Enclosure 1

Enclosure 1 was classified as a “protection system auxiliary cabinet.” When removed from Bellefonte NPP, there were a relatively large number of multi-conductor cables connected to a panel dividing the front of the enclosure from the back. There were 432 connection points, divided among 6 levels. The floor opening was covered by a steel plate. As installed, the cables would be routed through the floor or access openings on one side.

Figure 2-6. Photographs of Enclosure 1.

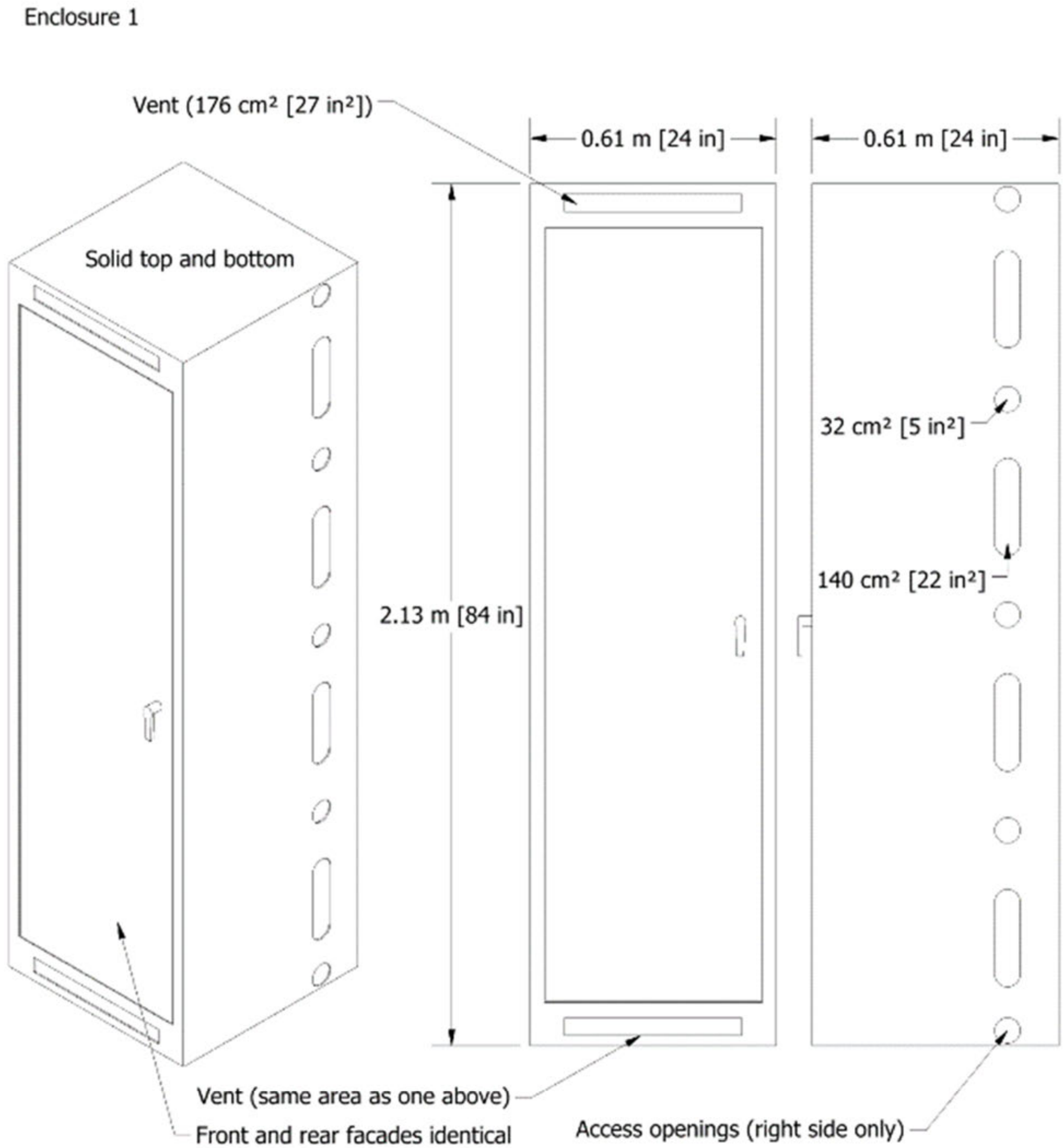


Figure 2-7. Sketch of Enclosure 1.

2.2.2 Enclosure 2

Enclosure 2 was very similar to Enclosure 1 on the exterior. The interior of Enclosure 2 was dedicated primarily to racks for circuit cards. There were a number of bundles containing relatively small wires running both vertically and horizontally. Plastic conduits (labelled "Panduit") was used to route the wire to the switches.

Figure 2-8. Photographs of Enclosure 2.

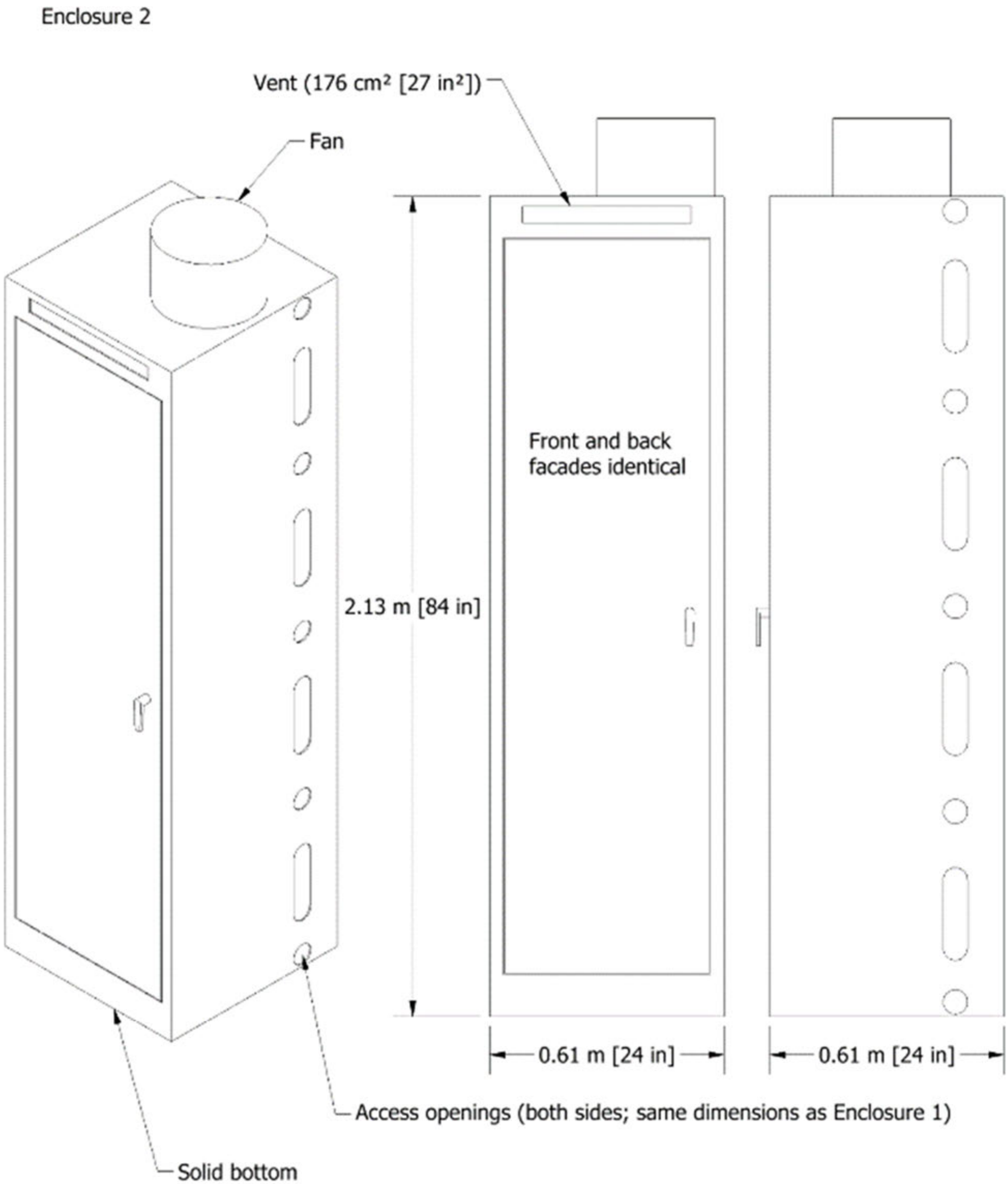


Figure 2-9. Sketch of Enclosure 2.

2.2.3 Enclosure 3

Enclosure 3 was labelled a "solid state control system." It was divided into three sections. The front section contained a rack for holding circuit cards, as seen through the polymethyl methacrylate (PMMA) or Plexi-glass® window in Figure 2-10. The middle section (upper right photo) contained a large amount of relay wire. The rear section contained little combustible material. There was a relatively large access opening on the left side of the enclosure. There was also a relatively large opening in the floor.

Figure 2-10. Photographs of Enclosure 3.

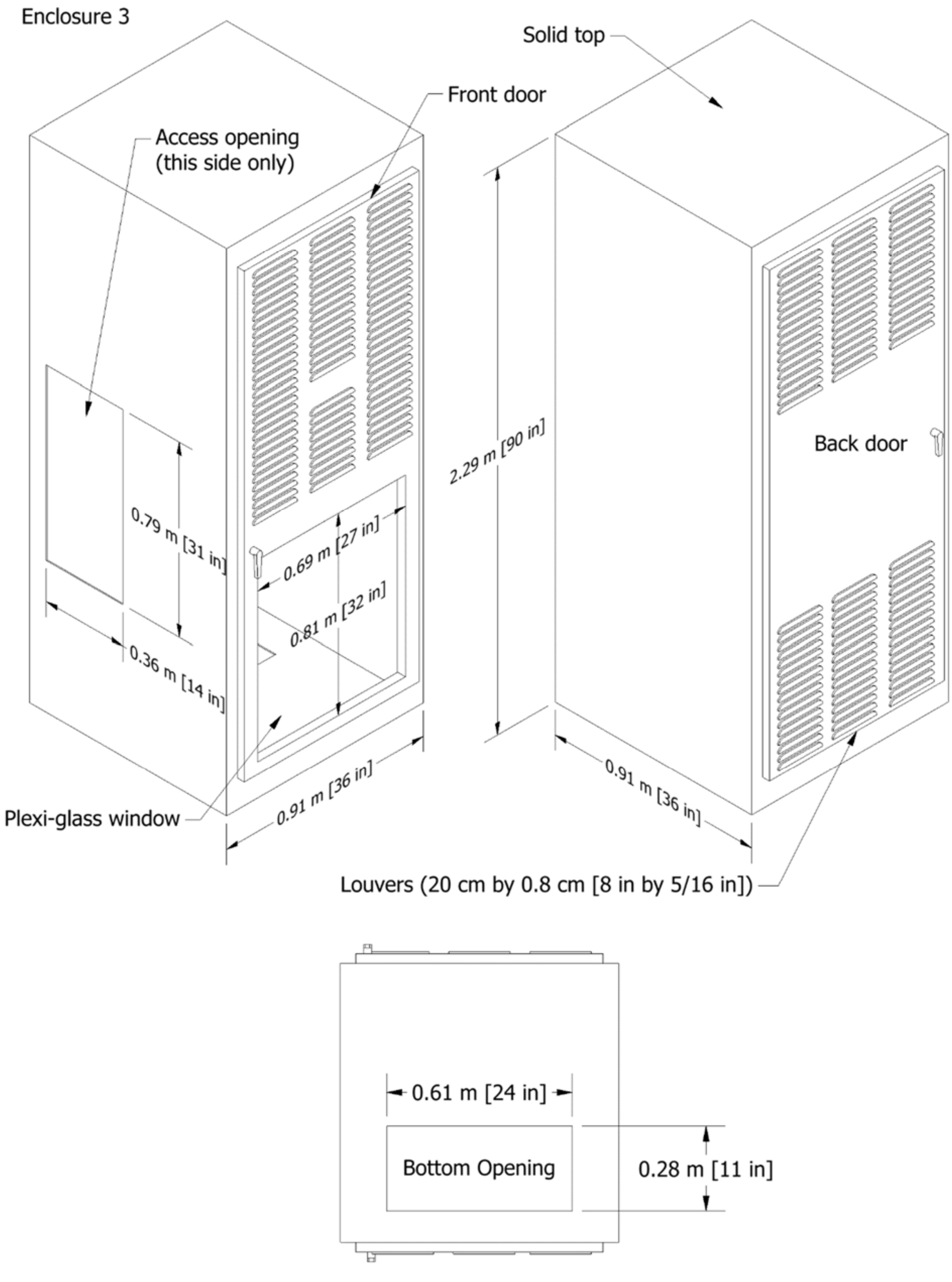


Figure 2-11. Sketch of Enclosure 3.

2.2.4 Enclosures 4 and 5

Enclosures 4 and 5 were bolted together and served as part of the “reactor protection system.” Both enclosures had similar exterior and interior features, including metal racks for circuit cards. Most of the circuit cards were removed prior to delivery, and the enclosure was reconfigured to mimic other types of enclosures. There was a small amount of miscellaneous wire left in the enclosure, but not enough to constitute a significant combustible load. The fans on the tops of the enclosures were functional, but it was decided not to operate them during testing because each would drive smoke downward and out the bottom, and this smoke would not be captured by the exhaust hood. An exploratory test was conducted to verify this effect, but it is not documented in this report.

Figure 2-12. Photographs of Enclosures 4 and 5.

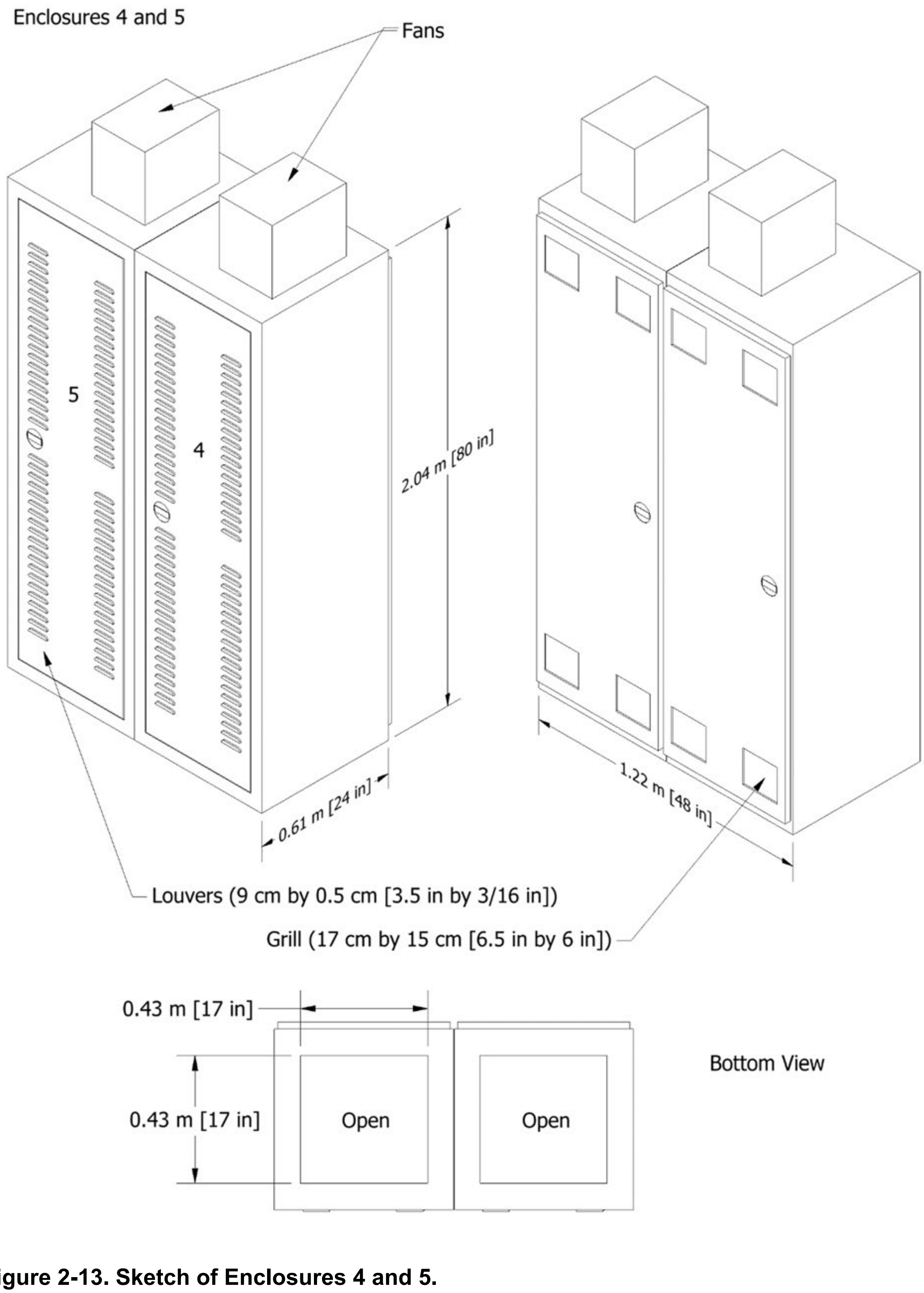


Figure 2-13. Sketch of Enclosures 4 and 5.

2.2.5 Enclosure 6

Enclosure 6 was a section of the main control room “horseshoe.” Its two side panels were beveled at angles of 22.5° to achieve a 45° turn near the apex of the horseshoe. The enclosure was well-ventilated via louvers on its front, rear, and top. Additionally, its floor was largely open.

Figure 2-14. Photographs of Enclosure 6.

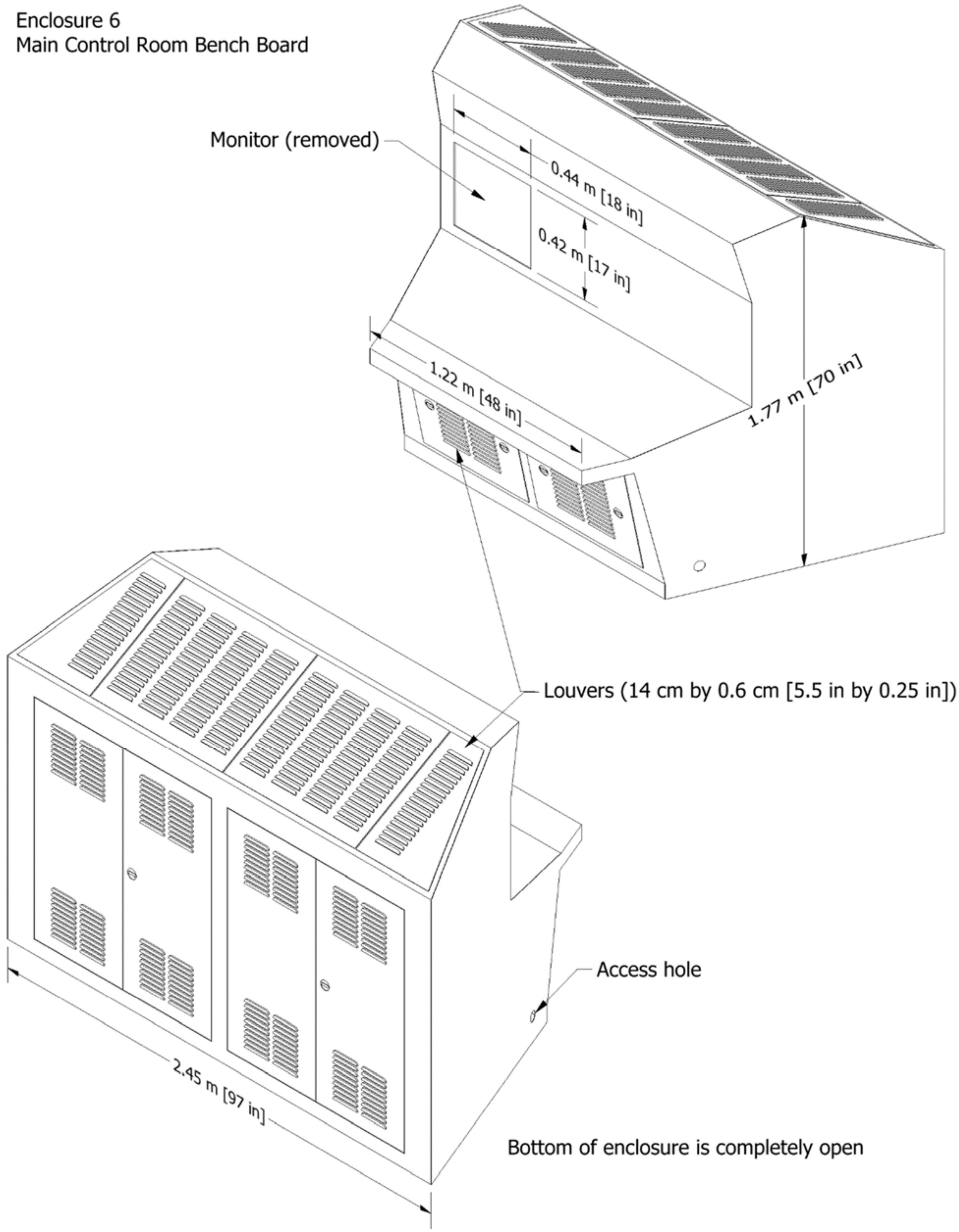


Figure 2-15. Sketch of Enclosure 6.

2.2.6 Enclosure 7

Enclosure 7 was a straight section of the main control room “horseshoe”. Its interior was similar to that of Enclosure 6. Much of it was compartmentalized, and, as delivered, there was not a significant amount of combustible materials.

Figure 2-16. Photographs of Enclosure 7.

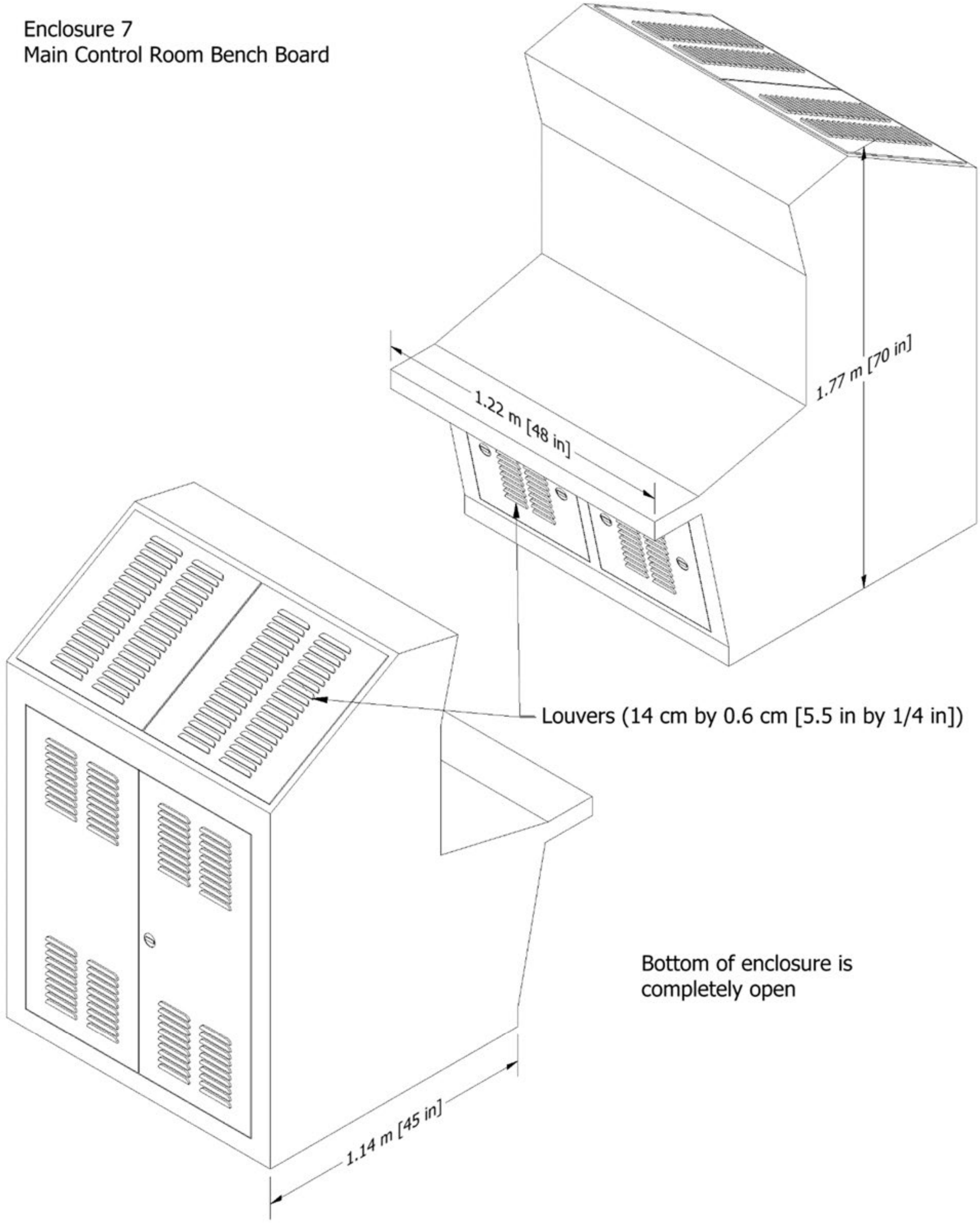


Figure 2-17. Sketch of Enclosure 7.

2.2.7 Enclosure 8

Enclosure 8 was labelled a “SEAMS Multiplexer”. SEAMS means “Support Equipment Acquisition Management System.” The notable feature of this enclosure were the conduits used for routing cable out the top and, presumably, into cable trays overhead. To mimic this configuration, a 1.2 m (4 ft) section of cable tray was mounted 45 cm (18 in) above the enclosure to collect the exiting cables.

Figure 2-18. Photographs of Enclosure 8.

Enclosure 8

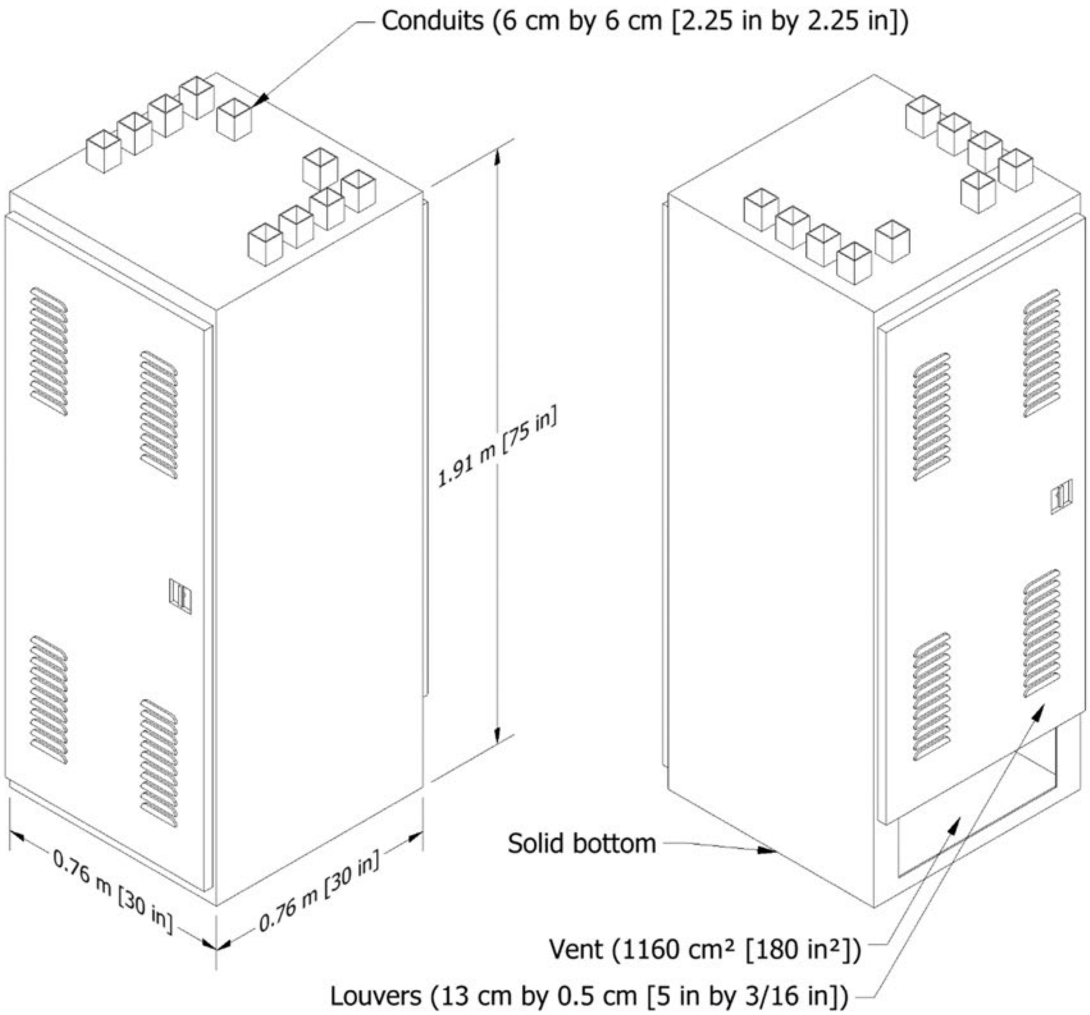


Figure 2-19. Sketch of Enclosure 8.

3 CABLE PROPERTIES

3.1 Properties of Cables used in Enclosure Fire Experiments

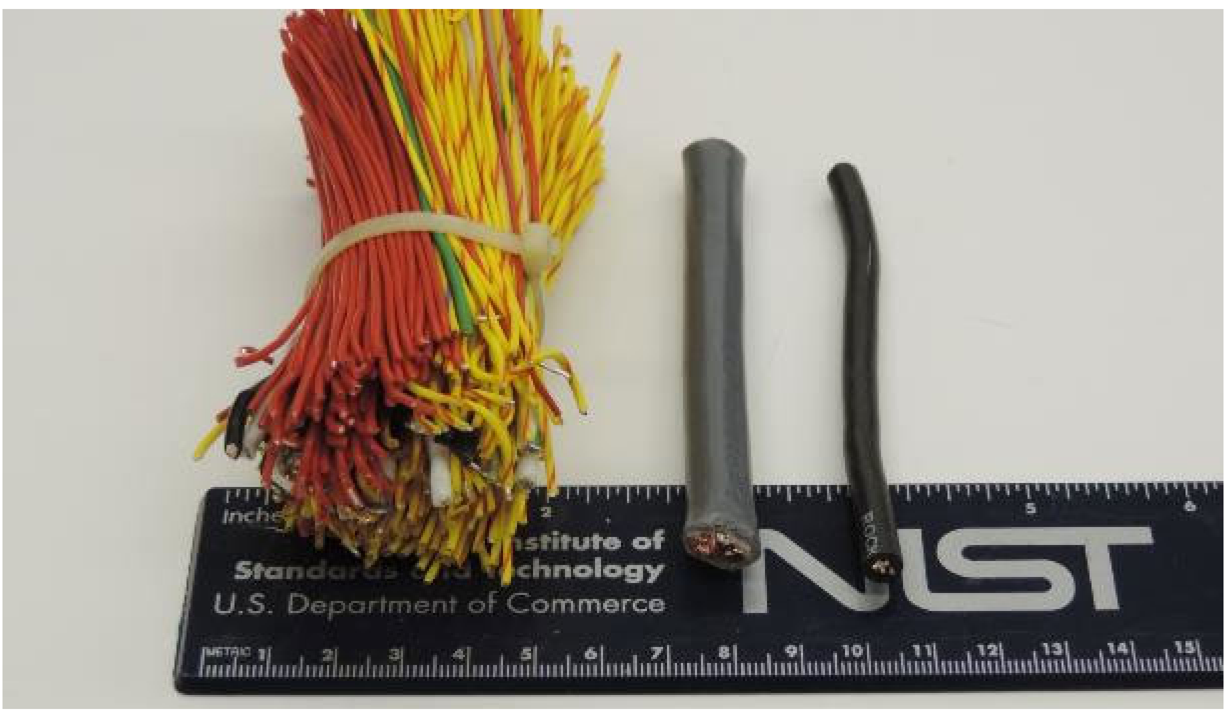
The tables on the following pages contain a general description of the cables that were used to mock up different enclosure configurations. Note that the “Cable No.” is merely an identifier and has no relevance beyond this project. Photographs of the cables are shown in Figure 3-1 through Figure 3-3. The cable markings are listed in Table 3-1. The cable properties are listed in Table 3-2. The property data was obtained by dissecting 20 cm (8 in) cable segments into their constituent parts – jacket, filler, insulators, and conductors. Note that the “Class” of cables, either TS for thermoset or TP for thermoplastic, refers to the broad classification of the two main types of cables used in plants.

805 807 809 813 814 817 818 830 831 832 833 834 835

Figure 3-1. Photograph of Cables 805-835.

836 837 838 839 840 841 842

Figure 3-2. Photograph of Cables 836-842.



843 844 845

Figure 3-3. Photograph of Cables 843-845.

Figure 3-4. Photograph of a circuit card installed in Enclosure 3.

Table 3-1. Manufacturers' descriptions of the cables.

Cable No.	SOURCE	MANUFACTURER*	DATE	CABLE MARKINGS
805	CAROLFIRE #12	CABLE USA	UNKNOWN	NO MARKINGS
807	CAROLFIRE #15	GENERAL CABLE	2006	GENERAL CABLE® BICC® BRAND SUBSTATION CONTROL CABLE 7/C #12AWG 600V 30 MAY 2006
809	CAROLFIRE #9	FIRST CAPITOL		NO MARKINGS
813	CAROLFIRE #13	ROCKBESTOS	2006	12/C 18 AWG COPPER ROCKBESTOS-SURPRENANT(G) 600V 90 DEG C WET OR DRY FIREWALL(R) III SUN RES DIR BUR OIL RES II NEC TYPE TC (UL) FRXLPE CSPE I57-0120 2006 6C-399
814	CAROLFIRE #6	GENERAL CABLE	2006	GENERAL CABLE® BICC® BRAND (WC) VNTC 12C 18AWG (UL) TYPE TC-ER TFN CDRS SUN RES DIR BUR 600V 09 MAR 2006
817	CAROLFIRE #7	ROCKBESTOS	2006	2/C 16 AWG COPPER ROCKBESTOS-SURPRENANT (G) 600V 90 DEG C WET OR DRY FIREWALL(R) III SUN RES DIR BUR OIL RES II NEC TYPE TC (UL) FRXLPE SHIELDED CSPE I46-0021 2006 6C-191
818	BROOKHAVEN	ROCKBESTOS	1981	ROCKBESTOS® RSS-6-104 1981
830	SANDIA	UNKNOWN		8 AWG 3/C XLP/CPE 600V 90C TC TYPE SNRS DE6 6WC-03
831	PURCHASED	UNKNOWN	UNKNOWN	14 AWG (UL) XHHW-2 OR SIS VW-1 600V E7088 CSA SIS 600V FTI FT2 LL25850
832	BROOKHAVEN # 32	BOSTON INSULATED WIRE AND CABLE CORP.	1980	BOSTON INSULATED WIRE AND CABLE CORP BOSTON, MASS. 1980
833	BROOKHAVEN #308 AND SANDIA # 6	OKONITE	UNKNOWN	NO MARKINGS
834	1/C 12 AWG XLPE REMOVED FROM 37/C XLPE/CSPE	ROCKBESTOS - SURPRENANT	UNKNOWN	NO MARKINGS
835	BROOKHAVEN #39	ROCKBESTOS - SURPRENANT	UNKNOWN	NO MARKINGS
836	INSTALLED IN CB 1	TVA	UNKNOWN	BIW, TVA # 77K5-820991 MARK WVA # 16 AWG, 2/C 600V
837	INSTALLED IN CB 1	TVA	UNKNOWN	BIW, TVA # 77K5-820991 MARK WWZ-2 # 16 AWG, 2P 600V

Cable No.	SOURCE	MANUFACTURER*	DATE	CABLE MARKINGS
838	INSTALLED IN CB 1	TVA	UNKNOWN	BIW, TVA # 77K5-820991 MARK WWZ-3 # 16 AWG, 3P 600V
839	INSTALLED IN CB 1	TVA	UNKNOWN	BIW, TVA # 77K5-820991 MARK WWZ-4 # 16 AWG, 4P 600V
840	INSTALLED IN CB 1	TVA	UNKNOWN	BIW, TVA # 77K5-820991 MARK WWZ-5 # 16 AWG, 5P 600V
841	RECEIVED FROM NRL	HOUSTON WIRE & CABLE COMPANY	UNKNOWN	HOUFLEX 16-3 SE00 WA 105°C (-40°C) WATER RESISTANT E54864 DRC 105 P-241-3 MSHA CSA LL39753 16-3ST 105C FT2
842	INSTALLED IN CB-6	UNKNOWN	UNKNOWN	NO MARKINGS
843	INSTALLED IN CB-2	UNKNOWN	UNKNOWN	NO MARKINGS
844	PURCHASED	CAROL BRAND OF GENERAL CABLE	UNKNOWN	14/3 BUS DROP CABLE 600V 554567-8 (UL)
845	BROOKHAVEN # 29	ROCKBESTOS	1976	ROCKBESTOS® FIREWALL® EP 10 AWG 600V (UL) TYPE RHH ROCKBESTOS 1976

*Certain commercial equipment, instruments, or materials are identified in this report to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

Table 3-2. Cable properties.

Cable No.	Insulation Material	Jacket Material	Class.	Conductors	Diameter (mm)	Jacket Thickness (mm)	Insulator Thickness (mm)	Mass per Length (kg/m)	Copper Mass Fraction	Jacket Mass Fraction	Insulation Mass Fraction	Filler Mass Fraction
805	Tefzel®		TP	7	10.2	0.76	0.45	0.29	0.74	0.08	0.15	0.02
807	PE	PVC	TP	7	14.0	1.54	0.27	0.37	0.59	0.24	0.15	0.01
809	SR	Aramid Braid	TS	7	14.5	1.21	1.10	0.35	0.62	0.08	0.31	0.01
813	XLPE	CSPE	TS	12	12.7	1.46	1.18	0.25	0.37	0.33	0.29	0.01
814	PVC	PVC	TP	12	11.3	1.15	0.54	0.19	0.56	0.03	0.40	0.00
817	XLPE	CSPE	TS	2	7.8	1.64	0.92	0.11	0.24	0.58	0.15	0.00
818	PE	PVC	TP	1	6.3	1.35	1.41	0.06	0.38	0.40	0.07	0.15
830	XLP	CPE	TS	3	17.1	3.06	1.74	0.44	0.52	0.33	0.13	0.02
831	SIS	TS	TS	1	3.6	0.00	1.25	0.03	0.65	0.00	0.35	0.00
832	Unknown	Unknown	Unknow n	1	6.8	0.98	2.34	0.08	0.41	0.37	0.21	0.01
833	Unknown	Unknown	Unknow n	1	4.7	N/A	1.74	0.05	0.63	0.00	0.37	0.00
834	XLPE	No Jacket	TS	1	4.0	N/A	1.98	0.04	0.73	0.00	0.27	0.00
835	SR	Aramid Braid	TS	1	3.64	0.44	1.47	0.02	0.46	0.13	0.41	0.00
836	XLPE	CSPE	TS	2	8.6	2.60	1.48	0.11	0.31	0.46	0.13	0.10
837	XLPE	CSPE	TS	4	16.9	2.86	1.48	0.38	0.19	0.53	0.07	0.20
838	XLPE	CSPE	TS	6	18.4	2.86	1.48	0.46	0.24	0.55	0.09	0.12
839	XLPE	CSPE	TS	8	19.8	2.86	1.48	0.55	0.29	0.53	0.11	0.07
840	XLPE	CSPE	TS	10	23.4	3.65	1.48	0.77	0.24	0.63	0.08	0.05

Cable No.	Insulation Material	Jacket Material	Class.	Conductors	Diameter (mm)	Jacket Thickness (mm)	Insulator Thickness (mm)	Mass per Length (kg/m)	Copper Mass Fraction	Jacket Mass Fraction	Insulation Mass Fraction	Filler Mass Fraction
841	TPE	TPE	TP	3	13.5	2.08	1.19	0.12	0.29	0.50	0.15	0.06
842	Unknown	Unknown	Unknown	40	1.2	N/A	N/A	0.08	--	--	--	--
843	Unknown	Unknown	Unknown	352	36.1	N/A	N/A	2.86	--	--	--	--
844	PVC	PVC	TP	3	10.2	01.80	0.76	0.17	0.47	0.33	0.18	0.03
845	EP	TS	TS	1	5.9	0	2.10	0.08	0.60	0.40	0.00	0.00

4 EXPERIMENTAL PROCEDURE

4.1 Oxygen Consumption Calorimeter

The measurements of the heat release rate (HRR) of the enclosure fires were performed at the Chesapeake Bay Detachment of the Naval Research Laboratory[2]. This facility has a large-scale calorimeter that is nominally 6.1 m by 6.1 m (20 ft by 20 ft), designed to measure the HRR of fires ranging from approximately 100 kW to 10 MW. However, its instruments are not sensitive enough to measure accurately the HRR of the small fires that were expected in many of the enclosure experiments. For this reason, a smaller calorimeter (see Figure 4-1) was built to fit underneath the large hood (see Figure 4-2). The smaller hood was 2.4 m by 2.4 m (8 ft by 8 ft), and 2.4 m (8 ft) off the floor. Its 46 cm (18 in) duct was instrumented with a Rosemount Annubar® to measure the volume flow, four thermocouples to measure the gas temperature, and a gas extraction tube to measure the oxygen concentration of the exhaust gases. The instruments were located approximately 4 m (13 ft) from the vertical centerline of the hood.

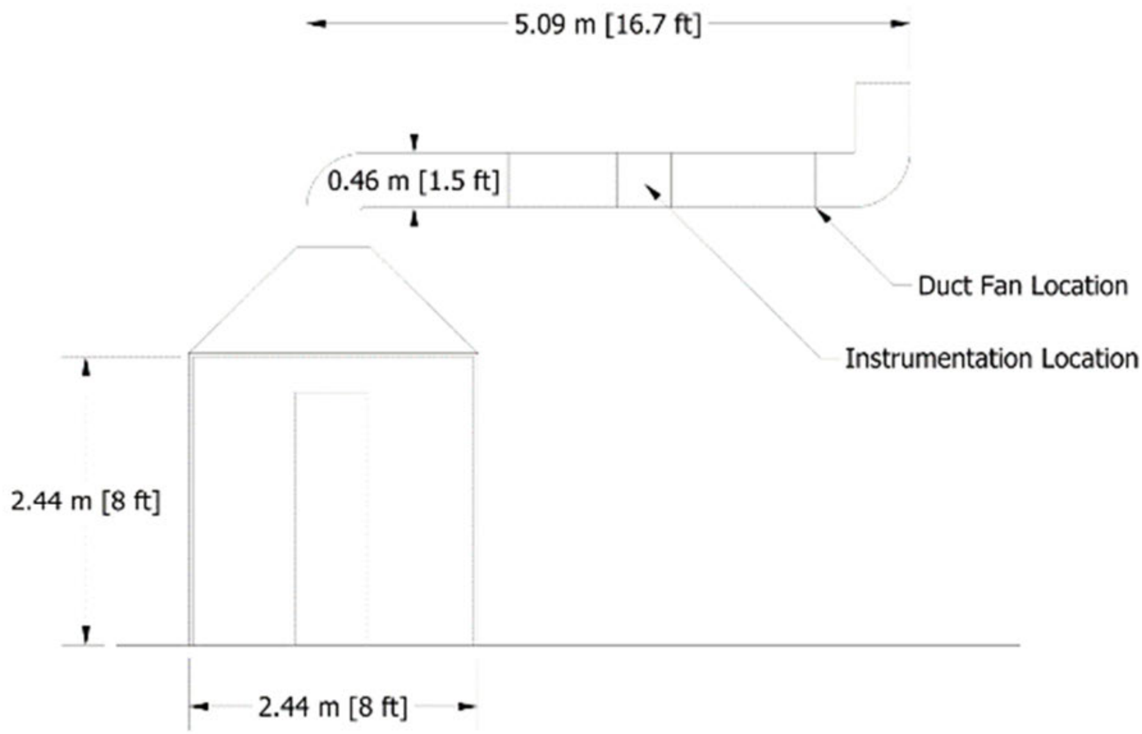


Figure 4-1. Schematic diagram of the small calorimeter.

[2] The experiments were conducted at the Naval Research Laboratory because the Large Fire Facility of NIST was undergoing renovation at the time the program was conducted.

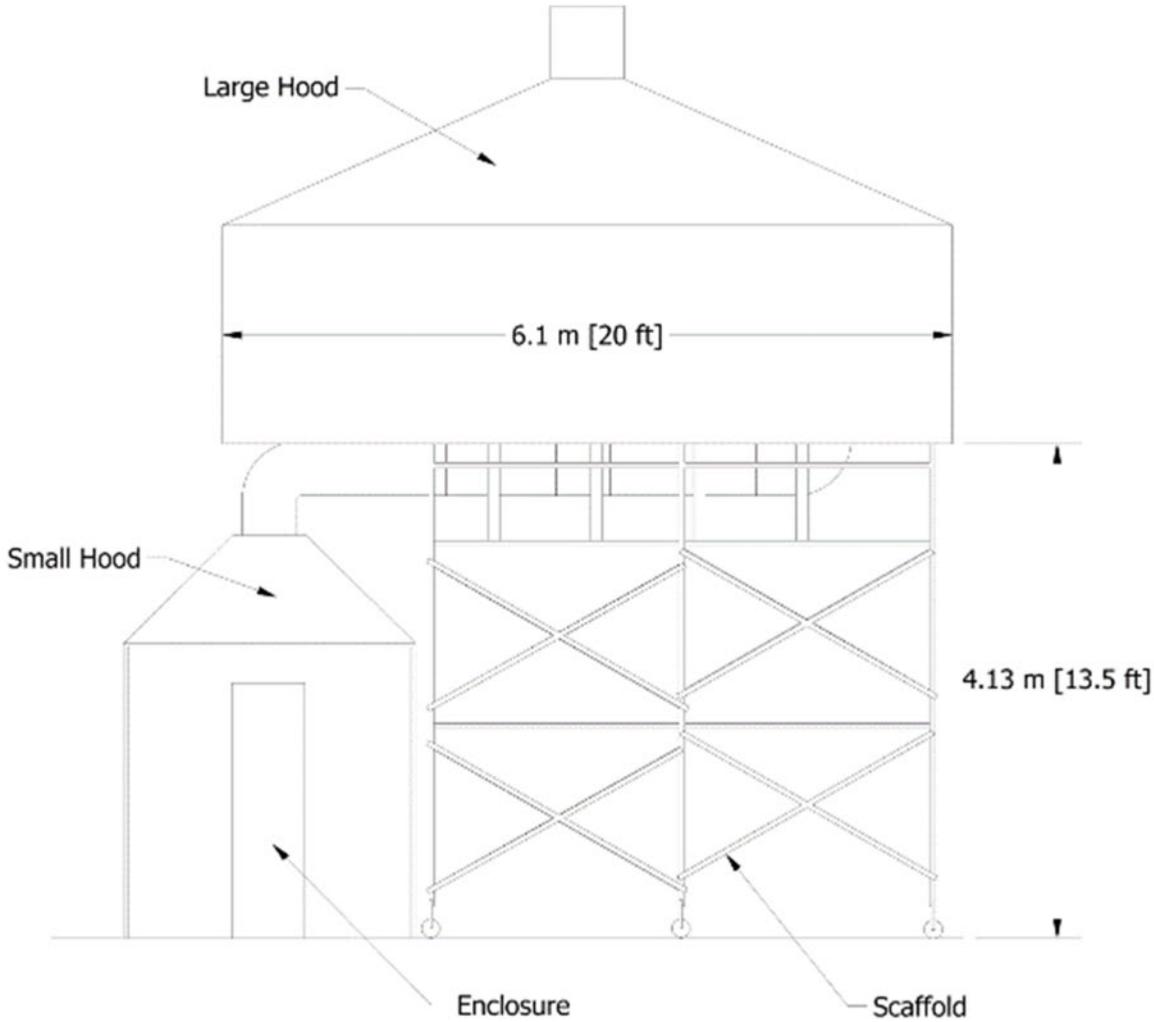


Figure 4-2. Schematic diagram of the small calorimeter underneath the large hood at the CBD test facility.

The HRR of the fire is given by the following formula under the assumption that both oxygen and carbon dioxide are measured in the exhaust duct (*SFPE Handbook*, 2008, chapter Calorimetry):

$$\dot{Q} = E \frac{\varphi}{1 + \varphi(\alpha - 1)} \dot{m}_{\mathrm{e}} \frac{M_{\mathrm{O_2}}}{M_{\mathrm{a}}} \left(1 - X^{\mathrm{a}}_{\mathrm{H_2O}} - X^{\mathrm{a}}_{\mathrm{CO_2}}\right) X^{\mathrm{a}}_{\mathrm{O_2}} \qquad \text{Equation 4-1}$$

with:

$$\varphi = \frac{X^{\mathrm{a}}_{\mathrm{O_2}}\left(1 - X^{\mathrm{e}}_{\mathrm{CO_2}}\right) - X^{\mathrm{e}}_{\mathrm{O_2}}\left(1 - X^{\mathrm{a}}_{\mathrm{CO_2}}\right)}{\left(1 - X^{\mathrm{e}}_{\mathrm{O_2}} - X^{\mathrm{e}}_{\mathrm{CO_2}}\right) X^{\mathrm{a}}_{\mathrm{O_2}}} \qquad \text{Equation 4-2}$$

where

where	$\dot{Q}$	Heat release rate (kW)
	E	Heat release per unit mass of oxygen consumed (13100 kJ/kg)
	φ	Oxygen depletion factor
	α	Volumetric expansion factor (1.105)

$\dot{m}_e$	Mass flow rate in the exhaust duct (kg/s)
M_{O_2}	Molecular mass of oxygen (32 g/mol)
M_a	Molecular mass of the ambient air (29 g/mol)
$X_{H_2O}^a$	Volume fraction of water vapor in the ambient air
$X_{CO_2}^a$	Volume fraction of carbon dioxide in the ambient air
$X_{O_2}^a$	Volume fraction of oxygen in the ambient air
$X_{CO_2}^e$	Volume fraction of carbon dioxide in the exhaust duct
$X_{O_2}^e$	Volume fraction of oxygen in the exhaust duct

The mass flow rate of the exhaust gases, $\dot{m}_e$, is the product of the density, ρ, and the volume flow rate, $\dot{V}$. The density was determined from the four thermocouple measurements via the ideal gas law:

$$\rho = \frac{p\,\overline{W}}{R\,\overline{T}} \qquad \text{Equation 4-3}$$

where p is the pressure (assumed to be 101325 Pa), $\overline{W}$ is the average molecular weight of the gases (assumed to be that of air, 29 g/mol), R is the universal gas constant (8.3145 J/(mol·K)), and $\overline{T}$ is the average of the four thermocouple measurements. The volume flow rate is calculated:

$$\dot{V} = C A_d \sqrt{\frac{2\,\Delta p}{\rho}} \qquad \text{Equation 4-4}$$

where A_d is the cross sectional area of the duct, and Δp is the pressure difference across the Annubar®. The flow coefficient, C, was set to 0.75 rather than the recommended value of 0.61. This decision was based on initial calibration fires using propane as the fuel. Because the duct of the smaller hood was required to fit under the larger hood, the flow was not sufficiently straightened and developed to the extent recommended by the manufacturer of the Annubar®.

The uncertainty in the HRR measurement is primarily due to the value of the heat of combustion based on oxygen consumption, E, the mass flow rate in the duct, $\dot{m}_e$, and the oxygen depletion, $X_{O_2}^a - X_{O_2}^e$. Janssens (*SFPE Handbook*, 2008, chapter Calorimetry) states that E equals 13100 kJ/kg with a relative standard uncertainty of 5 %. The uncertainties of the mass flow rate and oxygen concentration measurements were not evaluated independently because the flow coefficient, C, was selected based on calibration fires rather than an isothermal flow test.

As a way of estimating the combined uncertainty of the mass flow rate and oxygen depletion measurements, the acetone pan fires that were used to preheat the electrical enclosures provided a second set of calibration burns. Five experiments were performed in which 1 L of acetone was burned in a small pan. As discussed further in Section 4.2.3, this fire ought to produce approximately 22.7 MJ of energy. The mean energy release for the five test burns was 23.5 MJ, with a standard deviation of 1.7 MJ. From this exercise, it is estimated that the aleatoric uncertainty of the HRR measurement is approximately 7 % when the fuel stoichiometry is known. However, for general combustibles this estimate of the uncertainty must then be combined via quadrature with the uncertainty in the value of E, the heat of combustion based on oxygen consumption. The combined relative standard deviation in the HRR is thus estimated to be approximately 9 % (Taylor and Kuyatt, 1994).

4.2 Ignition Sources

Three types of ignition sources were used in the experiments: cartridge heaters, line burners, and pans of liquid fuel. A cartridge heater is a surrogate for an over-heated electrical component or cable. The line burner is a surrogate for a small fire that could result from an over-heated wire or component. The pan fire is a surrogate for a relatively large fire whose origin is difficult to specify exactly, but most likely due to an event such as a high energy arc fault or similar malfunction resulting in the ignition of a relatively large amount of combustible material.

4.2.1 Cartridge Heaters

A cartridge heater is a cylindrical rod approximately 15 cm (6 in) in length and 1 cm (0.4 in) in diameter (Figure 4-3) that can be inserted lengthwise within a bundle of electrical wires or cables. Bench-scale experiments were conducted prior to the full-scale experiments to determine the exact dimensions and power requirements for reliable, reproducible ignition. A bundle of cables, each 15 mm in diameter, was ignited with a 300 W heater and spark igniter. However, the heaters were used only for a single full-scale experiment because they were prone to shorting following ignition and the spark igniter drew too much power from the existing electrical circuit in the laboratory. Consequently, the cartridge heaters were abandoned for the remainder of the program.

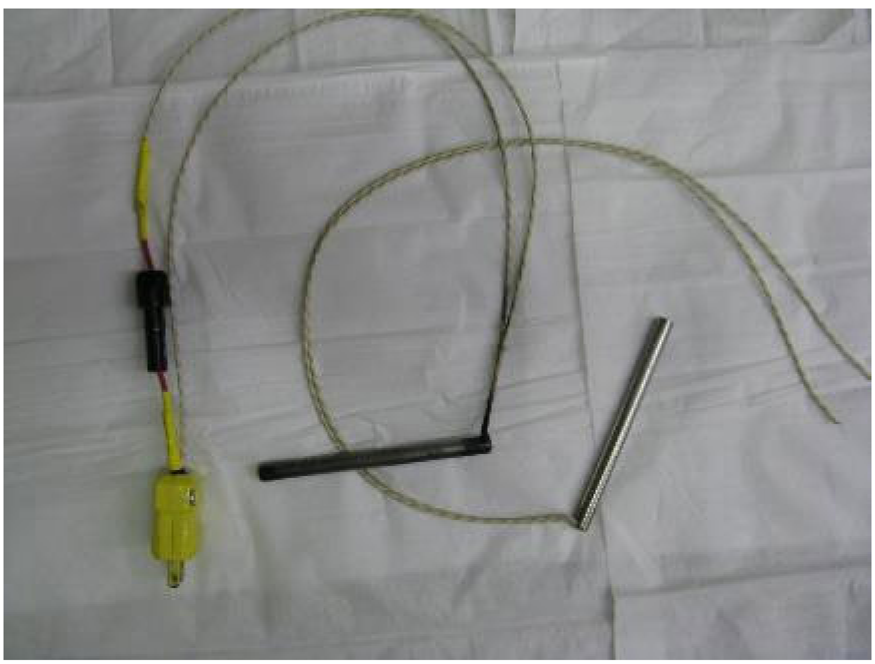


Figure 4-3. Two 300 W cartridge heaters. One has an in-line circuit breaker.

4.2.2 Propane Line Burners

Two propane “line burners” were used as the principal ignition sources. The smaller of the two was constructed from 0.95 cm (3/8 in) copper tubing and was 5 cm (2 in) long. The larger was constructed of the same type of copper tubing and was 30 cm (12 in) long (see Figure 4-4). The smaller burner produced flames with HRRs in the range of 0.5 kW to 2 kW. The larger burner produced flames in the range of 4 kW to 10 kW. The propane flowing to the burners was controlled by several different flow meters. Table 4-1 summarizes the settings of the flow meters and the expected HRR for each. Each flow meter was calibrated for air (29.0 g/mol) at 24 °C (297 K, 70 °F). The average temperature over the five months of testing was approximately 10 °C (283 K, 50 °F). To correct for the difference in temperature and molecular weight of propane (44.1 g/mol), the reading from the flow meter, $\dot{V}_{\mathrm{air}}$, was multiplied by a correction factor of 0.8:

$$\dot{V}_{\mathrm{p}} = \dot{V}_{\mathrm{air}} \sqrt{\frac{W_{\mathrm{a}}\, T_{\mathrm{p}}}{W_{\mathrm{p}}\, T_{\mathrm{a}}}} = \dot{V}_{\mathrm{air}} \sqrt{\frac{29.0\ \mathrm{g/mol} \times 283\ \mathrm{K}}{44.1\ \mathrm{g/mol} \times 297\ \mathrm{K}}} \cong 0.8\, \dot{V}_{\mathrm{air}} \qquad \text{Equation 4-5}$$

where $\dot{V}_{\mathrm{p}}$ is the volumetric flow rate of propane corrected for molecular weight and temperature. The heat of combustion of propane is taken as 46,300 kJ/kg (*SFPE Handbook*, 2008, Appendix C). The HRR of the burner is given by the expression:

$$\dot{Q} = \dot{V}_{\mathrm{p}}\, \rho_{\mathrm{p}}\, \Delta H_{\mathrm{p}} \qquad \text{Equation 4-6}$$

where $\dot{Q}$ is the HRR (kW), $\dot{V}_{\mathrm{p}}$ is the volumetric flow rate (L/s), ρ_{p} is the density of propane at the ambient temperature (kg/L), and ΔH_{p} is the heat of combustion of propane (kJ/kg).

Table 4-1. Propane burner heat release rate values.

Flowmeter Manufacturer	Units	Range	Value	Burner Size (cm)	HRR (kW)
Cole-Parmer	L/min, Air	0.2-1.0	0.4 ± 0.05	5	0.47 ± 0.06
Cole-Parmer	L/min, Air	0.2-1.0	0.6 ± 0.05	5	0.70 ± 0.06
Dwyer Instruments	ft^3/h, Air	0.3-3.0	1.5 ± 0.15	5	0.83 ± 0.08
Dwyer Instruments	ft^3/h, Air	0.3-3.0	3.0 ± 0.15	5	1.6 ± 0.08
Dwyer Instruments	ft^3/h, Air	4-40	10 ± 2	30	5.5 ± 1.1

The uncertainty in the HRR of the propane burners is primarily due to the uncertainty in the flow meter, which is given as 5 % of the calibrated range.

Figure 4-4. Photograph of 30 cm (12 in) propane line burner.

4.2.3 Liquid Fuel Pan Fires

The pan fires served two purposes. In some cases, they served only to pre-heat the enclosure to temperatures comparable to those expected in an actual NPP. In other cases, they served to ignite the combustibles directly. Two liquid fuels were used – ethanol and acetone. A variety of pan sizes were used; most typically a 15 cm by 23 cm (6 in by 9 in) steel baking pan. It was approximately 10 cm (4 in) deep. Most often, 1 L of acetone was used as the fuel. This fire burned for approximately 20 min at a rate of 20 kW, but the duration and rate depended on the ambient temperature and pan size. Acetone has a density of 0.792 kg/L and a heat of combustion of 28,600 kJ/kg (*SFPE Handbook*, 2008, Appendix C). Thus, 1 L releases approximately 22,650 kJ of energy. This fire also served as a convenient means to calibrate the oxygen consumption calorimeter.

4.2.4 Combustible Loading

Typical electrical enclosures will contain a variety of combustible materials including electrical cables, circuit cards, electrical components, and combustible insulation. This test series utilized a variety of electrical cables with various flammability properties in different configurations to represent the combustible loading. To intentionally vary the flammability properties of the cables or conductors, some cables were stripped of their outer jacket and filler material to expose the individual conductors. During the first and some subsequent experiments, the combustible loading in the enclosures also included circuit cards and other combustible components that were in the enclosures when they were originally manufactured.

The combustible loading in the original enclosures was not determined. For subsequent tests, the combustible load was determined based on the amount of cable that was placed inside the enclosure. Depending on the cable configuration, the total length of cable was translated into a combustible mass using the mass per unit length (kg/m) and the mass fraction values in Table 3-2. The mass fraction of copper was removed from all cable load calculations and the jacket mass fraction was removed for cases were the cables were stripped. In cases where limited or no significant burning took place during one test, a subsequent test was often conducted in the same enclosure with the existing combustible load. The remaining combustible load for the subsequent test was estimated based on review of the test data and video records.

Finally, the electrical cables used for this test series were stored in an unheated trailer prior to use in a particular test. While some tests utilized acetone or other methods to raise the interior temperature of the enclosure, the cables were typically at temperatures around 0 ºC (32 ºF) at the start of a test. The impact of the difference between typical operating temperatures and the test conditions on electrical cable flame spread has not been evaluated.

5 FULL-SCALE MEASUREMENTS

This chapter presents the results of 112 full-scale electrical enclosure fire experiments.

5.1 Description

The experiments were conducted from late October of 2013 through early March of 2014, in the large fire calorimeter of the Naval Research Laboratory Chesapeake Bay Detachment (CBD). The facility was not heated, and temperatures ranged from approximately 0 °C (32 °F) to 20 °C (68 °F). Typically, electrical enclosures are operated at 32 °C (90 °F), but in the experiments, the enclosures were not powered. For some a experiments, a pan of ethanol or acetone was placed at the base of the enclosure away from the combustibles to raise the interior enclosure temperature. These same pans of alcohol were sometimes used to ignite the combustibles directly. In the description of each experiment, therefore, there is a distinction made between "Ignition Source" and "Preheating Source." Table 5-1 shows the conditions for each test. A summary of measurements obtained during each test is presented in Table 5-2. The temperatures measured 0.15 m (6 in) below the top of the test enclosure during each test are shown in Appendix A.

The order of experiments was determined largely for practical reasons. All of the vertical enclosures (1, 2, 3, 4, 5 and 8) were outfitted with heavy-duty caster wheels to enable their easy movement to and from under the calorimeter hood. Typically, as one enclosure was being tested, other enclosures could be refurbished with new cables or wiring. Sometimes additional experiments would be conducted on a given enclosure if the fires did not spread beyond the igniter.

The propane line burner was typically positioned within a bundle of cable as if it were just another cable. Wire was used to hold the burner firmly in place. The exact placement of the burner varied from test to test, and there was no particular emphasis on a "standard" ignition system. Rather, the burner position and heat release rate (HRR) were varied as would be expected in actual fire events. The cables and wiring were not installed in a particularly systematic way either. Typically, bundles of cables would be hung using wires on either the left or right side of the enclosure, as had been observed in enclosures found on the plant visits. Sometimes the cables and/or individual conductors would be tightly bundled using plastic wire or "zip ties," and at other times they would be left to hang in no particular arrangement. It was observed that "loose" or non-bundled cables or wires led to higher HRRs, even though bundling was necessary to accumulate enough combustible mass in the vicinity of the igniter to facilitate fire spread. The total combustible mass ("Comb. Mass") refers to the mass of cable jacketing and insulation material derived from the measured length of cable multiplied by the mass of non-metallic materials per unit length found in Table 3-2.

Table 5-1. Summary of enclosure conditions

Test		Date	Test Start (min)	Condition Change	National Weather Temp. (Low) (°C)	National Weather Temp. (High) (°C)
1		October 30, 2013	0		6	21
2		October 31, 2013	0		2	16
3		October 31, 2013	0		2	16
4		October 31, 2013	0		2	16
5		October 31, 2013	0		2	16
6		October 31, 2013	0		2	16
7		October 31, 2013	0		2	16
8		November 1, 2013	0		2	16
9		November 1, 2013	0		2	16
10		November 4, 2013	0		1	16
11		November 4, 2013	0		1	16
12	A	November 4, 2013	0		1	16
12	B	November 4, 2013	40	Door opened briefly	1	16
12	C	November 4, 2013	80	Door opened and left open	1	16
13		November 5, 2013	0		6	19
14	A	November 5, 2013	0		6	19
14	B	November 5, 2013	20	Door opened and propane blowtorch used	6	19
15	A	November 5, 2013	0		6	19
15	B	November 5, 2013	37	Door closed	6	19
16		November 5, 2013	0		6	19

Table 5-1. Summary of enclosure conditions (continued)

Test		Date	Test Start (min)	Condition Change	National Weather Temp. (Low) (°C)	National Weather Temp. (High) (°C)
17		November 5, 2013	0		6	19
18		November 5, 2013	0		6	19
19		November 6, 2013	0		11	20
20		November 6, 2013	0		11	20
21		November 6, 2013	0		11	20
22		November 6, 2013	0		11	20
23		November 6, 2013	0		11	20
24		November 6, 2013	0		11	20
25		November 7, 2013	0		8	20
26		November 7, 2013	0		8	20
27	A	November 7, 2013	0		8	20
27	B	November 7, 2013	40	Door opened and cables moved with crowbar	8	20
28	A	November 7, 2013	0		8	20
28	B	November 7, 2013	19	Door opened briefly and cables moved with crowbar	8	20
28	C	November 7, 2013	40	Door opened briefly and cables moved with crowbar	8	20
29		December 11, 2013	0		0	9
30		December 11, 2013	0		0	9
31		December 12, 2013	0		0	7
32	A	December 12, 2013	0		0	7
32	B	December 12, 2013	16	Door opened and left open	0	7
33		December 12, 2013	0		0	7

Table 5-1. Summary of enclosure conditions (continued)

Test		Date	Test Start (min)	Condition Change	National Weather Temp. (Low) (°C)	National Weather Temp. (High) (°C)
34		December 12, 2013	0		0	7
35		December 13, 2013	0		-4	7
36	A	December 13, 2013	0		-4	7
36	B	December 13, 2013	12	Door opened and left open	-4	7
37		December 13, 2013	0		-4	7
38		December 13, 2013	0		-4	7
39		December 16, 2013	0		1	13
40		December 16, 2013	0		1	13
41	A	December 16, 2013	0		1	13
41	B	December 16, 2013	11	Front panel burned through creating an open door configuration	1	13
42		December 16, 2013	0		1	13
43		December 16, 2013	0		1	13
44		December 17, 2013	0		1	10
45		December 17, 2013	0		1	10
46		December 17, 2013	0		1	10
47		December 18, 2013	0		-1	13
48		December 18, 2013	0		-1	13
49		December 18, 2013	0		-1	13
50		December 19, 2013	0		-1	4
51		December 19, 2013	0		-1	4
52		December 19, 2013	0		-1	4

Table 5-1. Summary of enclosure conditions (continued)

Test		Date	Test Start (min)	Condition Change	National Weather Temp. (Low) (°C)	National Weather Temp. (High) (°C)
53	A	December 19, 2013	0		-1	4
53	B	December 19, 2013	0	Blow torch used to ignite cables	-1	4
54		December 19, 2013	0		-1	4
55		December 19, 2013	0		-1	4
56		February 4, 2014	0		-6	2
57		February 4, 2014	0		-6	2
58		February 4, 2014	0		-6	2
59	A	February 4, 2014	0		-6	2
59	B	February 4, 2014	20	Cable bundle loosened with a crowbar	-6	2
60		February 4, 2014	0		-6	2
61		February 6, 2014	0		-12	4
62		February 6, 2014	0		-12	4
63		February 6, 2014	0		-12	4
64		February 7, 2014	0		-12	2
65		February 7, 2014	0		-12	2
66	A	February 10, 2014	0		-2	4
66	B	February 10, 2014	23		-2	4
67	A	February 10, 2014	0		-2	4
67	B	February 10, 2014	13		-2	4
68		February 10, 2014	0		-2	4
69		February 10, 2014	0		-2	4

Table 5-1. Summary of enclosure conditions (continued)

Test		Date	Test Start (min)	Condition Change	National Weather Temp. (Low) (°C)	National Weather Temp. (High) (°C)
70		February 10, 2014	0		-2	4
71		February 10, 2014	0		-2	4
73		February 11, 2014	0		-3	3
74		February 11, 2014	0		-3	3
75		February 19, 2014	0		-16	1
76		February 19, 2014	0		-16	1
77	A	February 19, 2014	0		-16	1
77	B	February 19, 2014	16.5	Door was opened and left open	-16	1
78	A	February 19, 2014	0		-16	1
78	B	February 19, 2014	12.5	Door was opened and left open	-16	1
79	A	February 19, 2014	0		-16	1
79	B	February 19, 2014	14		-16	1
80	A	February 20, 2014	0		-18	-7
80	B	February 20, 2014	18	Door was opened and left open	-18	-7
81		February 20, 2014	0		-18	-7
82	A	February 20, 2014	0		-18	-7
82	B	February 20, 2014	22	Door was opened and left open	-18	-7
83		February 20, 2014	0		-18	-7
84		February 24, 2014	0		-13	2
85		February 24, 2014	0		-13	2
86	A	February 24, 2014	0		-13	2

Table 5-1. Summary of enclosure conditions (continued)

Test		Date	Test Start (min)	Condition Change	National Weather Temp. (Low) (°C)	National Weather Temp. (High) (°C)
86	B	February 24, 2014	27.5	Door opened and cables moved with crowbar	-13	2
87		February 24, 2014	0		-13	2
88		February 24, 2014	0		-13	2
89		February 24, 2014	0		-13	2
90		February 25, 2014	0		-13	-3
91		February 25, 2014	0		-13	-3
92		February 25, 2014	0		-13	-3
93		February 25, 2014	0		-13	-3
94		February 25, 2014	0		-13	-3
95		February 25, 2014	0		-13	-3
96		February 26, 2014	0		-11	6
97	A	February 26, 2014	0		-11	6
97	B	February 26, 2014	16.5	Door opened briefly and cables moved with crowbar	-11	6
98		February 26, 2014	0		-11	6
99		February 26, 2014	0		-11	6
100		February 26, 2014	0		-11	6
101		February 27, 2014	0		-11	6
102		February 27, 2014	0		-11	6
103		February 27, 2014	0		-4	3
104		February 28, 2014	0		-9	1
105		February 28, 2014	0		-9	1

Table 5-1. Summary of enclosure conditions (continued)

Test		Date	Test Start (min)	Condition Change	National Weather Temp. (Low) (°C)	National Weather Temp. (High) (°C)
106	A	February 28, 2014	0		-9	1
106	B	February 28, 2014	9		-9	1
107		March 4, 2014	0		2	6
108		March 4, 2014	0		2	6
109		March 4, 2014	0		2	6
110	A	March 4, 2014	0		2	6
110	B	March 4, 2014	13.5	Door was opened and left open	2	6
111	A	March 4, 2014	0		2	6
111	B	March 4, 2014	20	Door was opened and left open	2	6
112		March 4, 2014	0		2	6

Table 5-2. Summary of enclosure fire measurements

Test		Encl.	Ignition HRR (kW)	Preheat HRR (kW)	Ambient Temp. (°C)	Comb. Mass (kg) Note 4	Cable Class.	Door Position	Peak HRR (kW) Note 2	Total Energy Release (MJ)
1		1	0.3	0	17.3	Note 1	Q	Open	2	2
2		2	0.5	0	17.3	Note 1	Q	Open	2	1
3		2	0.5	0	20.1	Note 1	Q	Open	2	2
4		4	0.7	0	20.3	Note 1	Q	Open	2	1
5		4	0.7	0	19.4	Note 1	Q	Open	1	1
6		4	0.7	0	18	Note 1	Q	Open	2	1
7		5	0.7	0	17.5	Note 1	Q	Open	9	6
8		3	0.7	0	19.7	Note 1	Q	Open	0	1
9		3	0.7	0	19.8	Note 1	Q	Open	1	1
10		3	0.7	0	5.8	Note 1	Q	Open	1	1
11		1	0.7	0	6.5	Note 1	Q	Open	1	1
12	A	1	0.7	0	8.2	Note 1	Q	Closed	3	120
	B	1	0.7	0	Note 3	Note 1	Q	Closed	39	
	C	1	0.7	0	Note 3	Note 1	Q	Open	52	
13		8	0.7	0	9.6	Note 1	Q	Closed	2	4
14	A	8	0.7	0	14	Note 1	Q	Closed	2.2	2
	B	9	0.7	0	Note 3	Note 1	Q	Open	4	
15	A	5	0.7	0	12	3.23	Q	Open	3	7
	B	5	0.7	0	Note 3	3.23	Q	Closed	0	
16		5	0.7	0	12.4	1.89	Q	Open	2	2
17		4	0.7	0	12.1	2.70	Q	Open	0	0
18		4	0.7	0	12.1	1.76	Q	Open	3	3
19		5	0.7	0	19.5	3.23	Q	Closed	3	7
20		5	0.7	0	31.5	1.89	Q	Closed	5	9
21		4	0.7	0	24.2	1.89	Q	Closed	4	3
22		4	0.7	0	23	1.76	Q	Closed	4	4
23		5	0.7	0	24.2	1.56	UQ	Open	18	12
24		5	0.7	0	26.3	0.73	Q	Closed	4	4

Table 5-2. Summary of enclosure fire measurements (continued)

Test		Encl.	Ignition HRR (kW)	Preheat HRR (kW)	Ambient Temp. (°C)	Comb. Mass (kg) Note 4	Cable Class.	Door Position	Peak HRR (kW) Note 2	Total Energy Release (MJ)
25		1	0.7	0	39.1	3.11	Q	Closed	4	5
26		1	0.7	0	40.6	3.03[4]	Q	Closed	1	0
27	A	1	0.7	14	18.3	2.99[4]	Q	Closed	1.7	9
	B	1	0.7	14	Note 3	2.99[4]	Q	Closed	7	
28	A	1	0.7	16	30.6	2.87[4]	Q	Closed	4.7	17
	B	1	0.7	16	Note 3	2.87[4]	Q	Closed	11.3	
	C	1	0.7	16	Note 3	2.87[4]	Q	Closed	10	
29		1	18	0	4.5	2.64[4]	Q	Closed	82	76
30		1	18	0	6.1	1.32[4]	Q	Closed	72	59
31		4	5.5	22	0.4	0.73	Q	Closed	28	45
32	A	4	5.5	25	38.8	0.73	Q	Closed	5.6	35
	B	4	5.5	25	Note 3	0.73	Q	Open	11	
33		5	25	0	11.5	1.46	Q	Closed	50	40
34		5	35	0	34.2	1.22[4]	Q	Closed	35	46
35		8	27	0	2.8	11.37	Q	Open	146	153
36	A	2	4	0	5.1	2.71	Q	Closed	2.5	4
	B	2	4	0	Note 3	2.71	Q	Open	4	
37		2	54	0	18.4	5.41	Q	Closed	35	27
38		2	20	0	33.1	4.74[4]	Q	Closed	169	95
39		8	25	0	2.5	5.68	Q	Closed	60	65
40		3	12	0	3.5	Note 1	Q	Closed	2	19
41	A	3	20	0	5.2	5.00	Q	Closed	122	141
	B	3	20	0	Note 3	5.00	Q	Open	232	
42		4	5.5	0	1.6	2.88	Q	Closed	34	35
43		4	16	0	21.1	2.88	Q	Closed	18	21
44		5	5.5	0	3.6	2.88	Q	Closed	31	32
45		5	5.5	22	24.4	2.88	Q	Closed	5	34
46		4	19	0	4.2	5.41	Q	Closed	45	68
47		4	19	0	4.4	2.71	Q	Closed	40	49
48		4	19	0	21	5.41	Q	Open	87	89

Table 5-2. Summary of enclosure fire measurements (continued)

Test		Encl.	Ignition HRR (kW)	Preheat HRR (kW)	Ambient Temp. (°C)	Comb. Mass (kg) Note 4	Cable Class.	Door Position	Peak HRR (kW) Note 2	Total Energy Release (MJ)
49		4	19	0	23.9	5.41	Q	Closed	50	76
50		4	22	0	4.5	2.65	Q	Closed	1	21
51		4	30	0	31.3	1.33	Q	Open	31	34
52		4	5.5	0	18.3	2.17	UQ	Open	122	61
53	A	4	5.5	0	17.7	2.17	UQ	Closed	57	60
	B	4	5.5	0	Note 3	0.54[4]	UQ	Open	85	
54		4	2.2	0	41.7	3.12	UQ	Open	94	41
55		4	10	0	38	3.12	UQ	Closed	21	26
56		5	0.8	22	1.1	1.68	UQ	Closed	8	16
57		5	0.8	24	12.6	1.68	UQ	Closed	5	26
58		5	0.8	21	2.4	2.33	UQ	Closed	26	36
59	A	5	0.8	0	45.4	2.33	UQ	Open	5.3	14
	B	5	0.8	0	Note 3	2.33	UQ	Open	22	
60		1	0.8	19	1.2	7.39	UQ	Closed	88	96
61		1	0.8	19	1.1	11.84	Q	Closed	5	29
62		1	1.6	19	4.1	11.84	Q	Closed	3	33
63		1	5.5	19	3.5	11.84	Q	Closed	92	156
64		8	0.8	11	1.5	6.05	Q	Closed	6	13
65		8	0.8	11	5.7	6.05	Q	Closed	7	15
66	A	4	5.5	24	-2.1	3.36	UQ	Closed	26	57
	B	4	5.5	24	Note 3	3.36	UQ	Open	26	
67	A	4	5.5	0	13.1	3.36	UQ	Closed	26	21
	B	4	5.5	0	Note 3	3.36	UQ	Open	29	
68		1	0.8	0	0.9	4.74	UQ	Closed	216	121
69		8	1.6	13	0.8	3.53	UQ	Closed	10	22
70		1	1.6	0	1.6	3.11	Q	Closed	2	1
71		1	5.5	0	2.6	3.11	Q	Closed	138	99
73		4	1.6	22	1	2.88	Q	Closed	4	26
74		5	1.6	20	23.4	2.56	Q	Closed	5	28
75		5	5.5	26	9.4	2.88	Q	Closed	15	57

Table 5-2. Summary of enclosure fire measurements (continued)

Test		Encl.	Ignition HRR (kW)	Preheat HRR (kW)	Ambient Temp. (°C)	Comb. Mass (kg) Note 4	Cable Class.	Door Position	Peak HRR (kW) Note 2	Total Energy Release (MJ)
76		5	22	0	38.2	2.88	Q	Closed	9	25
77	A	5	5.5	24	29.7	2.56	Q	Closed	10	53
	B	5	5.5	24	Note 3	2.56	Q	Open	18	
78	A	5	5.5	0	18.6	2.56	Q	Closed	30	27
	B	5	5.5	0	Note 3	2.56	Q	Open	54	
79	A	4	5.5	0	14.6	6.12	Q	Closed	40	63
	B	4	5.5	0	Note 3	6.12	Q	Open	65	
80	A	4	5.5	19	6.3	2.77	Q	Closed	20	92
	B	4	5.5	19	Note 3	2.77	Q	Open	100	
81		5	30	0	12.5	2.88	Q	Closed	24	48
82	A	1	1.6	19	10	7.39	UQ	Closed	1	112
	B	1	1.6	19	Note 3	7.39	UQ	Open	63	
83		1	0.8	0	16.5	4.74	UQ	Open	577	152
84		7	0.8	20	6.5	3.27	Q	Open	37	51
85		7	0.8	0	45.4	1.96	Q	Closed	2	2
86	A	7	5	0	26.4	1.96	Q	Open	0	15
	B	7	5	0	Note 3	1.96	Q	Open	24	
87		7	0.8	21	11.4	3.27	Q	Closed	29	35
88		7	0.8	0	26.9	1.15	UQ	Closed	147	18
89		7	0.8	0	45	1.15	UQ	Closed	25	10
90		7	0.8	16	2	3.41	Q	Closed	12	33
91		7	1.6	20	23.6	2.07	Q	Closed	3	26
92		7	5.5	20	24.8	2.07	Q	Closed	15	37
93		7	5.5	0	5.2	3.25	UQ	Closed	59	27
94		7	5.5	0	54	4.78	Q	Closed	37	23
95		7	5.5	0	29.2	5.37	UQ	Closed	30	27
96		6	5.5	21	1	5.37	UQ	Closed	33	47
97	A	6	5.5	0	53.1	4.87	UQ	Closed	9	120
	B	6	5.5	0	Note 3	4.87	UQ	Closed	89	
98		6	20	0	21.7	7.67	Q	Closed	121	126

Table 5-2. Summary of enclosure fire measurements (continued)

Test		Encl.	Ignition HRR (kW)	Preheat HRR (kW)	Ambient Temp. (°C)	Comb. Mass (kg) Note 4	Cable Class.	Door Position	Peak HRR (kW) Note 2	Total Energy Release (MJ)
99		6	5.5	0	26.5	2.30	UQ	Open	3	7
100		6	5.5	0	16.4	6.24	Q	Closed	34	42
101		6	20	0	1.2	6.24	Q	Closed	66	70
102		6	23	0	68.5	3.56	Q	Open	10	17
103		6	5.5	0	19.6	1.15	UQ	Closed	42	50
104		1	0.8	24	-5.2	4.74	UQ	Open	250	141
105		1	5.5	0	-3.3	6.10	UQ	Closed	80	25
106	A	1	5.5	0	69.8	3.05[4]	UQ	Closed	17	25
	B	1	5.5	0	Note 3	3.05[4]	UQ	Open	38	
107		1	5.5	19	-4.9	5.53	Q	Open	55	51
108		1	5.5	0	48	1.38[4]	Q	Closed	32	15
109		8	5.5	19	-4.7	5.98	Q	Closed	64	61
110	A	4	5.5	24	0.5	3.36	UQ	Closed	7	32
	B	4	5.5	24	Note 3	3.36	UQ	Open	11	
111	A	5	5.5	20	2.8	3.12	Q	Closed	49	120
	B	5	5.5	20	Note 3	3.12	Q	Open	268	
112		4	5.5	0	113.9	1.68	UQ	Open	22	12

Notes:

1. Experiments 1-10, 13, and 14 were performed in the enclosures as delivered from Bellefonte NPP. The mass of the combustibles was not measured because these materials could not be extracted from the enclosure without disrupting the original construction.

2. The Peak HRR is the total HRR minus the Ignition HRR and the Preheat HRR.

3. Ambient enclosure temperatures were not relevant during the mid test conditions.

4. Estimated based on initial loading and review of test videos and pictures.

5.2 Summary of Individual Experiments

The following 112 pages contain a brief description of each experiment, including the important test parameters, a plot of the HRR, and some illustrative photographs. The HRR plots include the peak recorded temperature in the enclosure. The HRR of the ignition or preheating source, shown in red on the plots, is estimated either from a gas flow measurement of the propane igniters, or from oxygen consumption calorimetry of the pan of liquid fuel. The temperature history within the enclosure 0.15 m (6 in) below the top is shown in Appendix A for each experiment.

Four to six shielded thermocouples (TC) were installed at various locations in each enclosure. The uppermost TC was typically 15 cm (6 in) from the top, depending on the interior contents. This uppermost TC usually recorded the peak temperature of the gases accumulating near the enclosure ceiling and provided a single value indicating the overall thermal environment within the enclosure. The TCs were not placed in direct proximity of the fire itself. Such a measurement would record a flame temperature but would not indicate the extent to which the entire enclosure was heated.

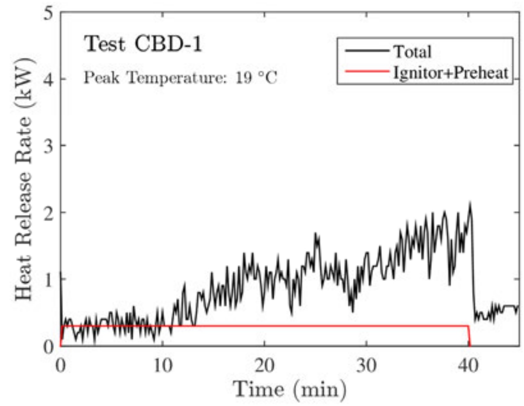
For certain tests, there may be a letter designation written with the number (e.g., 12 (A,B,C)). In all tests where this designation is present, the beginning of the test is “A” and the times at which the next test “B” or “C” starts is written in the Notes part of the description. These letters refer to the designations that are used to characterize a change in fire conditions, i.e., ventilation while a test was ongoing. These designations are also noted in the RACHELLE-FIRE report listing of these tests.

Table 5-3. Summary of Test 1

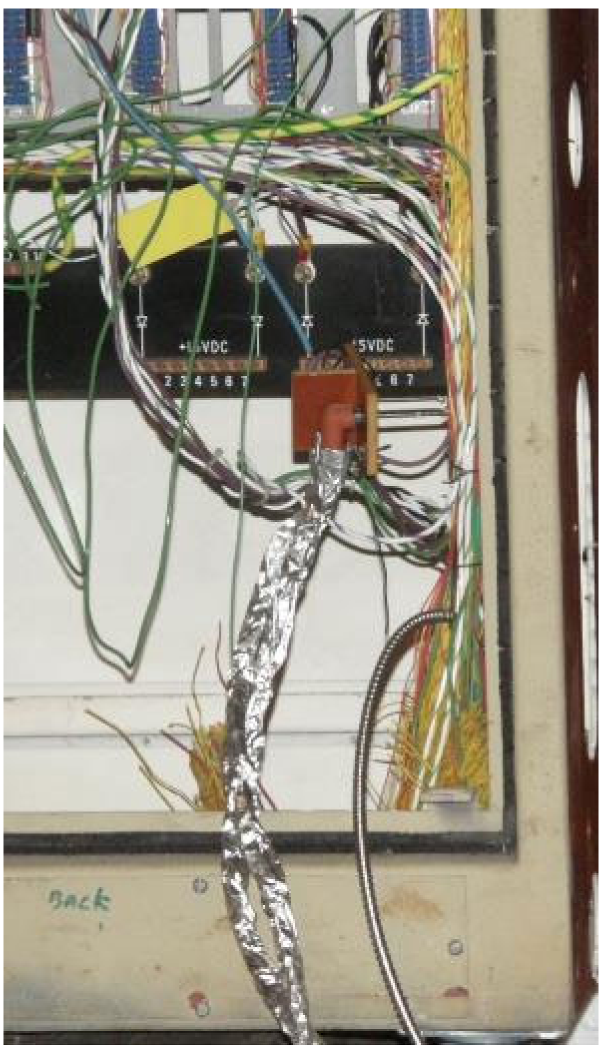
<table>
<tr>
<td>

Test: 1
Enclosure: 1
Fuel Load: 7/C control cables
Ignition Source: 300 W cartridge heater
Ventilation: Door open
Notes: The fire did not spread beyond its point of origin (right side of photos below). The heater was turned off at 40 min.

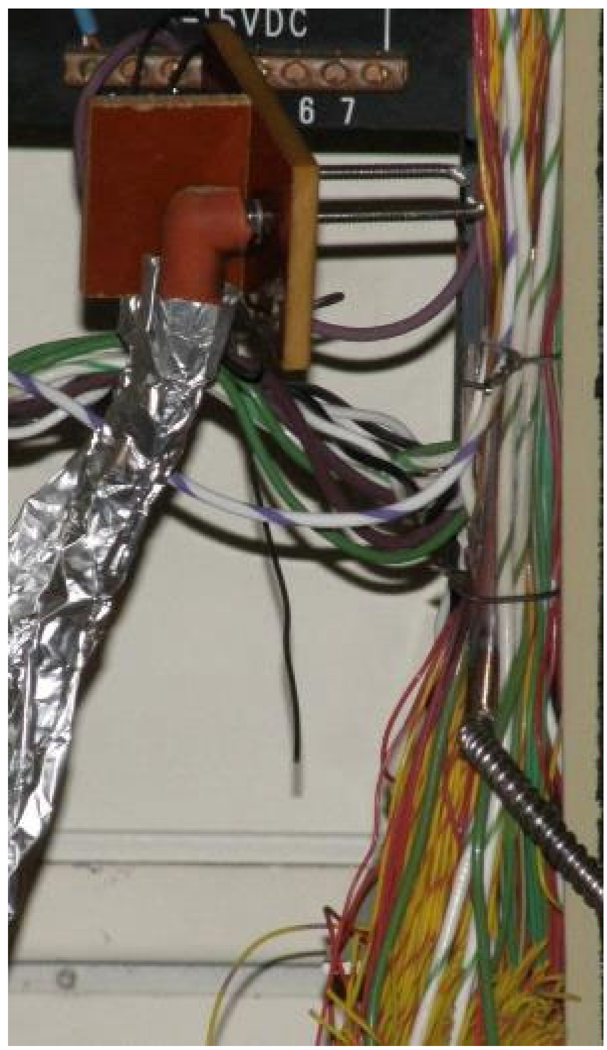
</td>
<td>



</td>
</tr>
<tr>
<td>



</td>
<td>



</td>
</tr>
</table>

Table 5-4. Summary of Test 2

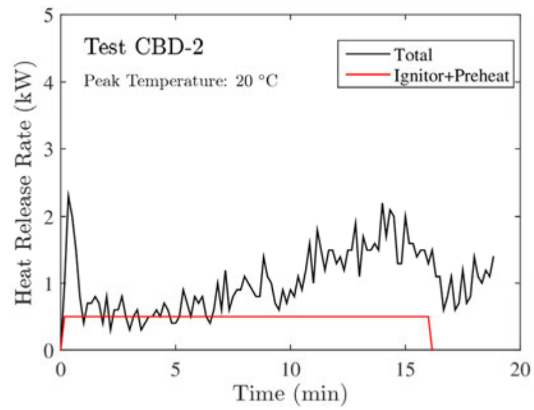
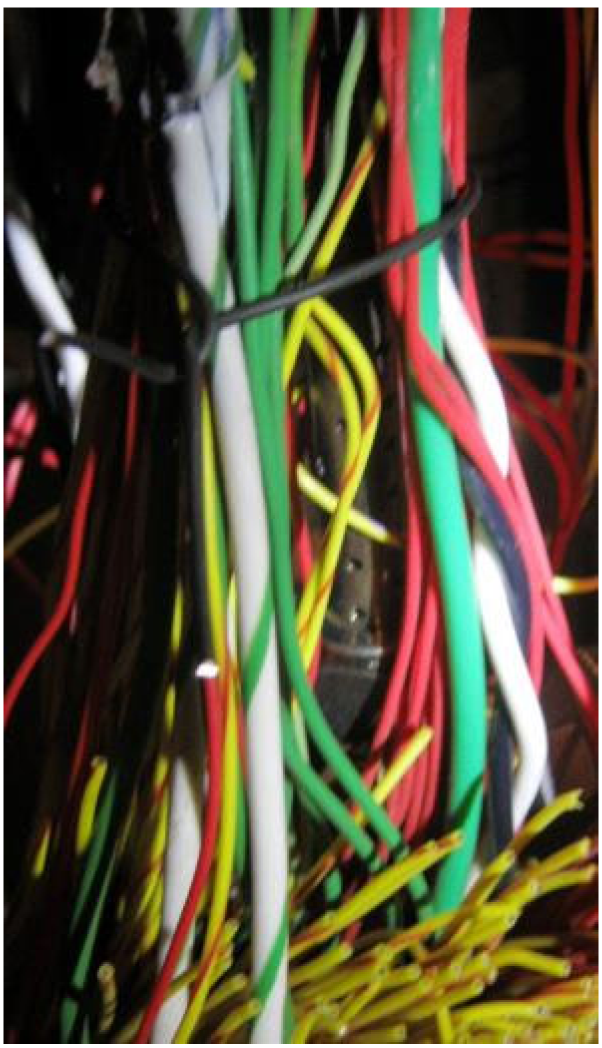
Test: 2 **Enclosure:** 2 **Fuel Load:** Vertical bundle of SIS wire **Ignition Source:** 0.5 kW propane burner **Ventilation:** Door open **Notes:** The fire did not spread beyond its point of origin. The burner was turned off after approximately 16 min.	
	

Table 5-5. Summary of Test 3

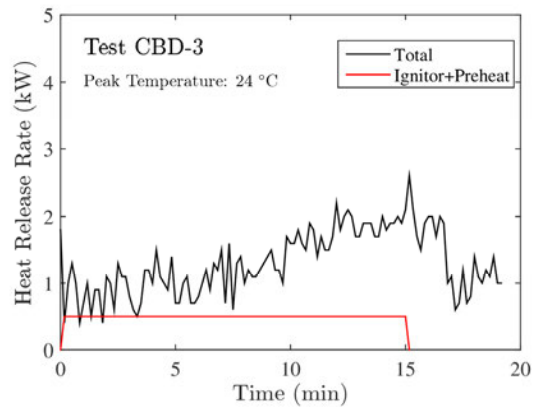
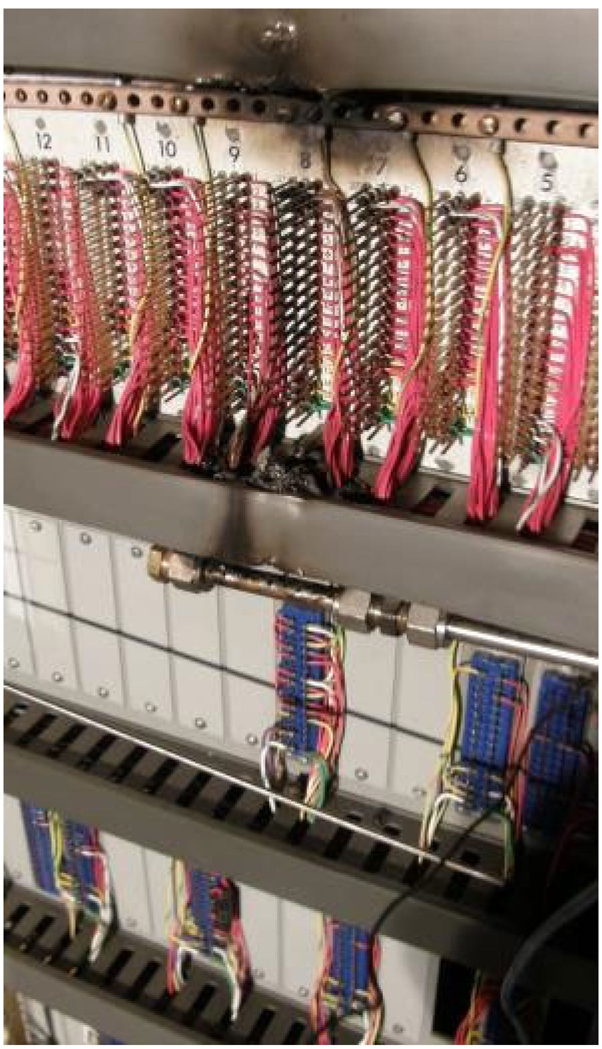
Test: 3 **Enclosure:** 2 **Fuel Load:** Horizontal bundle of SIS wire enclosed by plastic conduit **Ignition Source:** 0.5 kW propane burner **Ventilation:** Door open **Notes:** The fire did not spread beyond its point of origin. The plastic harness charred and deformed, but did not appear to add to the heat release rate. The burner was turned off after approximately 15 min.	
	

Table 5-6. Summary of Test 4

<table>
<tr><td>

Test: 4

Enclosure: 4

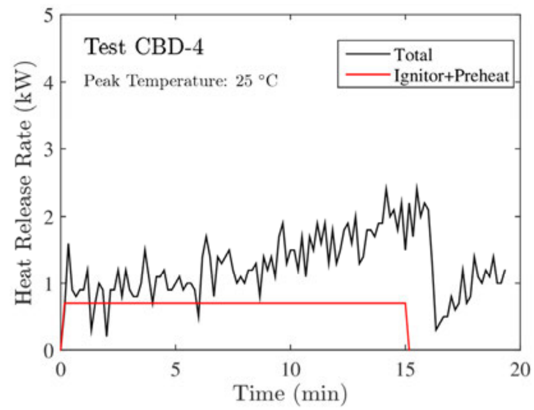
Fuel Load: Vertical bundle of SIS wire enclosed by plastic conduit

Ignition Source: 0.7 kW propane burner

Ventilation: Door open

Notes: The fire did not spread beyond point of origin. The burner was turned off at approximately 15 min.

</td><td>



</td></tr>
<tr><td>

</td><td>

</td></tr>
</table>

Table 5-7. Summary of Test 5

Test: 5

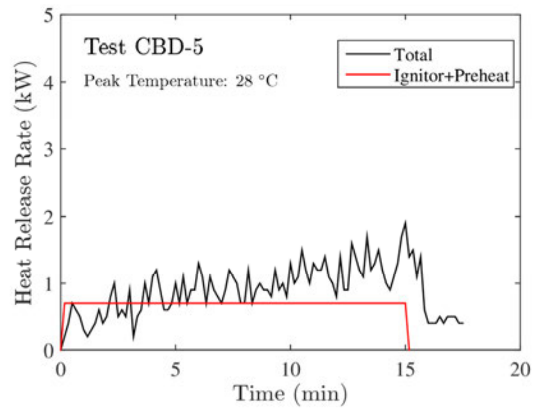
Enclosure: 4

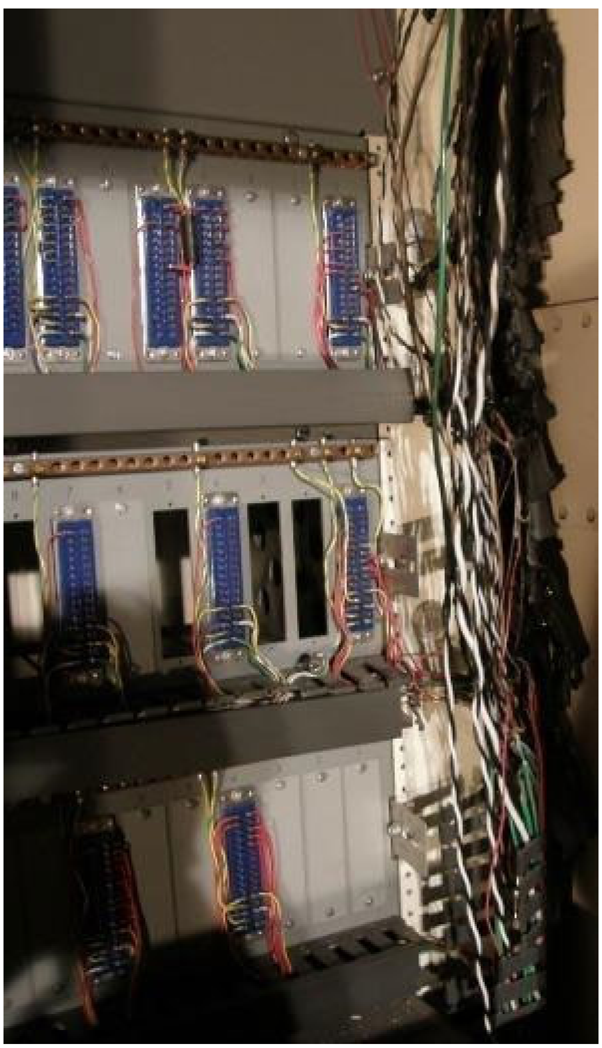
Fuel Load: Horizontal bundle of SIS wire inside a plastic conduit

Ignition Source: 0.7 kW propane burner

Ventilation: Door open

Notes: The fire did not spread beyond point of origin. The burner was turned off at approximately 15 min.





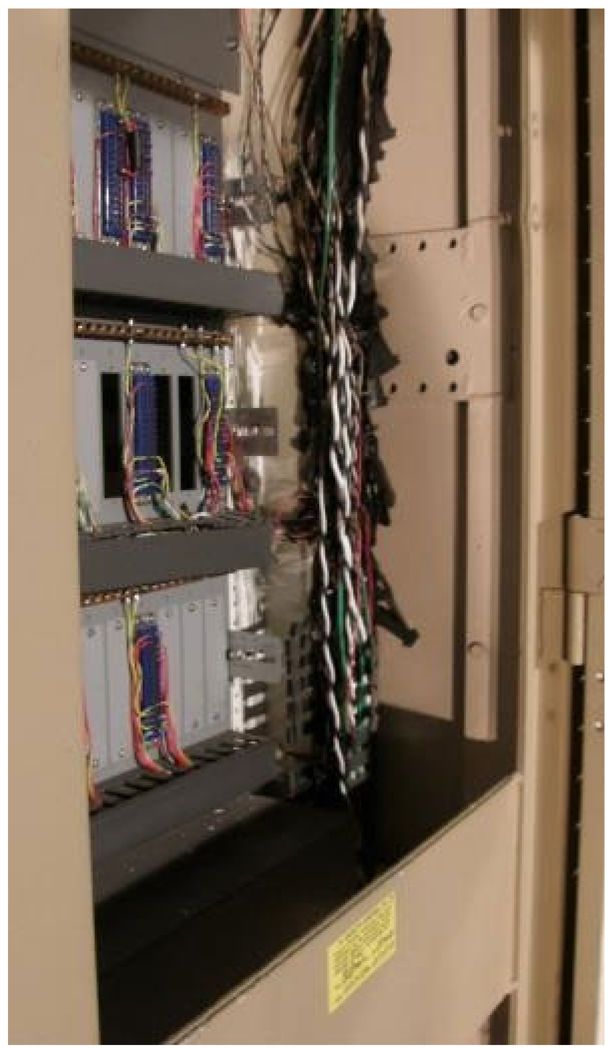


Table 5-8. Summary of Test 6

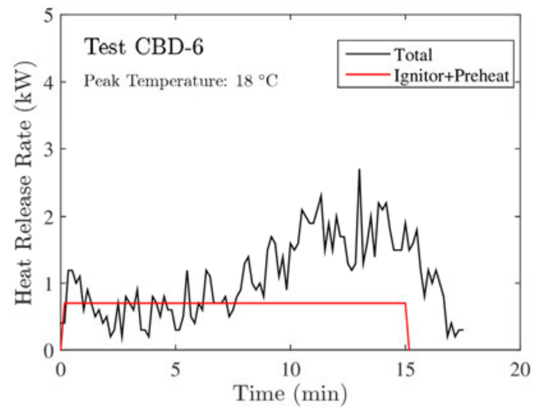
Test: 6 **Enclosure:** 4 **Fuel Load:** Vertical bundle of SIS wire enclosed by plastic conduit **Ignition Source:** 0.7 kW propane burner **Ventilation:** Door open **Notes:** The fire did not spread beyond point of origin. The plastic melted near the burner but did not appear to add much to the HRR. The burner was turned off at approximately 15 min.	
	

Table 5-9. Summary of Test 7

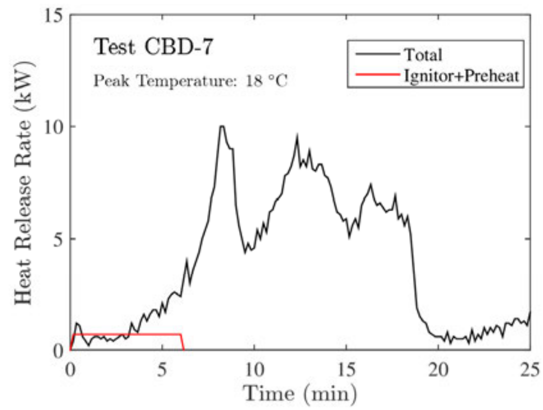
Test: 7 **Enclosure:** 5 **Fuel Load:** Vertical bundle of SIS wire encased in plastic jacket **Ignition Source:** 0.7 kW propane burner **Ventilation:** Door open **Notes:** The fire spread on the plastic jacket used to harness the wires. Some of the jacketing material and loose plastic material fell to the floor where it continued to burn. The propane burner was turned off at 6 min.	
	No picture available

Table 5-10. Summary of Test 8

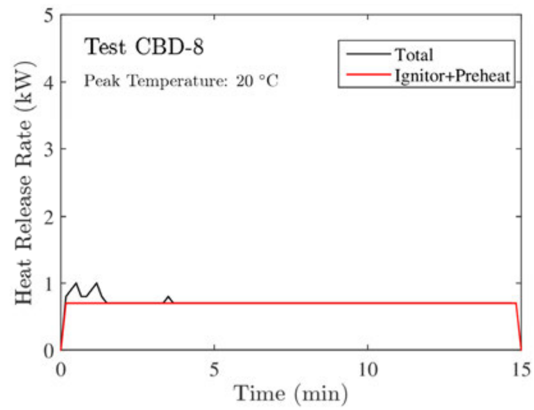
Test: 8 **Enclosure:** 3 **Fuel Load:** Circuit boards **Ignition Source:** 0.7 kW propane burner **Ventilation:** Door open **Notes:** The fire was ignited between two circuit boards at the bottom of a four tier array. Each card was approximately 20 cm by 30 cm. The fire did not spread upwards, and only scorched the boards. The burner was turned off at 15 min.	
	

Table 5-11. Summary of Test 9

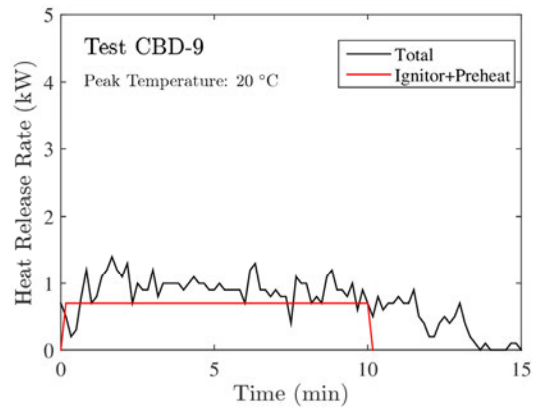
Test: 9 **Enclosure:** 3 **Fuel Load:** Assorted bundles of relay wire **Ignition Source:** 0.7 kW propane burner **Ventilation:** Door open **Notes:** The fire did not spread beyond its point of origin (blue bundles in left photo). There was only minor scorching of the coating on the wires. The propane burner was turned off at 10 min.	
	

Table 5-12. Summary of Test 10

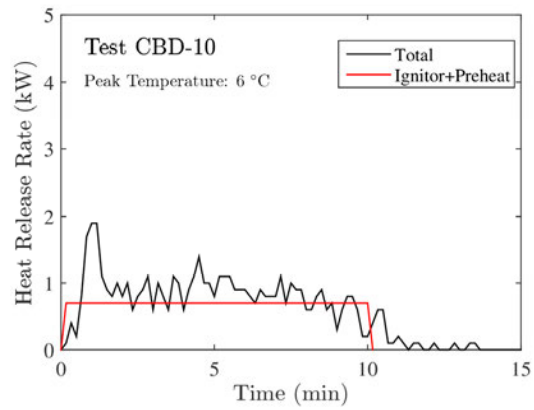
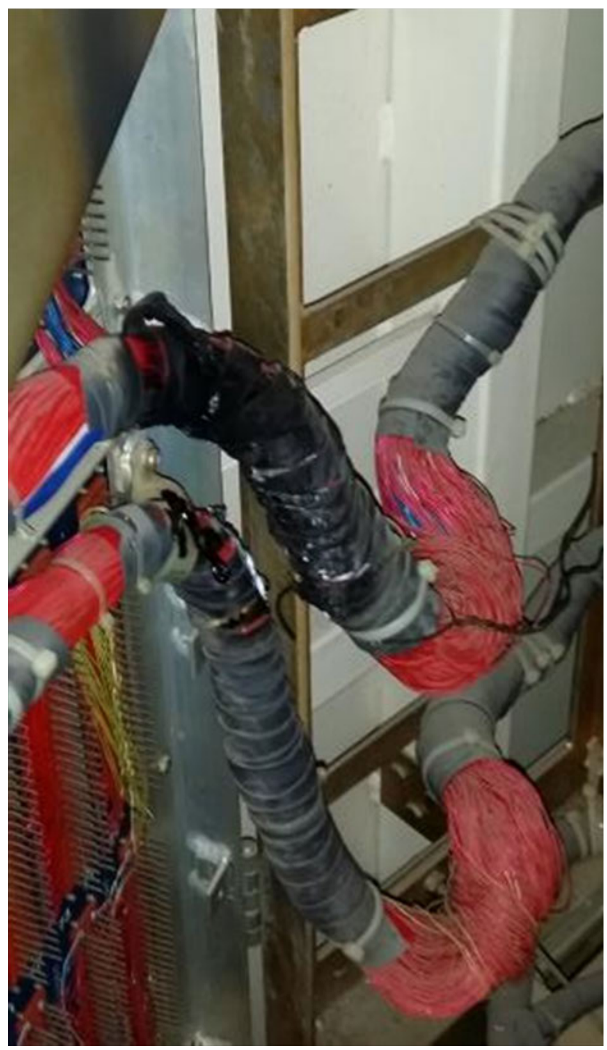
Test: 10 **Enclosure:** 3 **Fuel Load:** Vertical bundle of relay wire bound by a rubber harness **Ignition Source:** 0.7 kW propane burner **Ventilation:** Door open **Notes:** The rubber harness material burned, but there was no measureable heat release or significant spread. The burner was turned off at 10 min.	
	

Table 5-13. Summary of Test 11

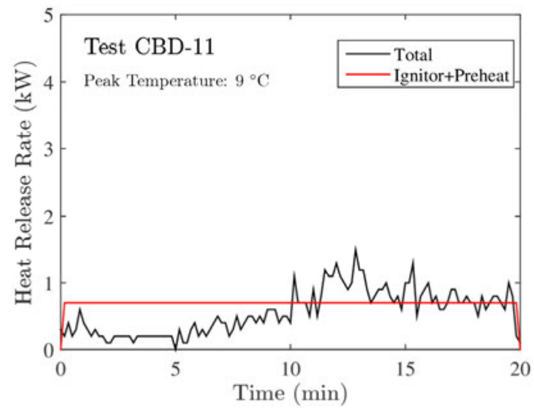
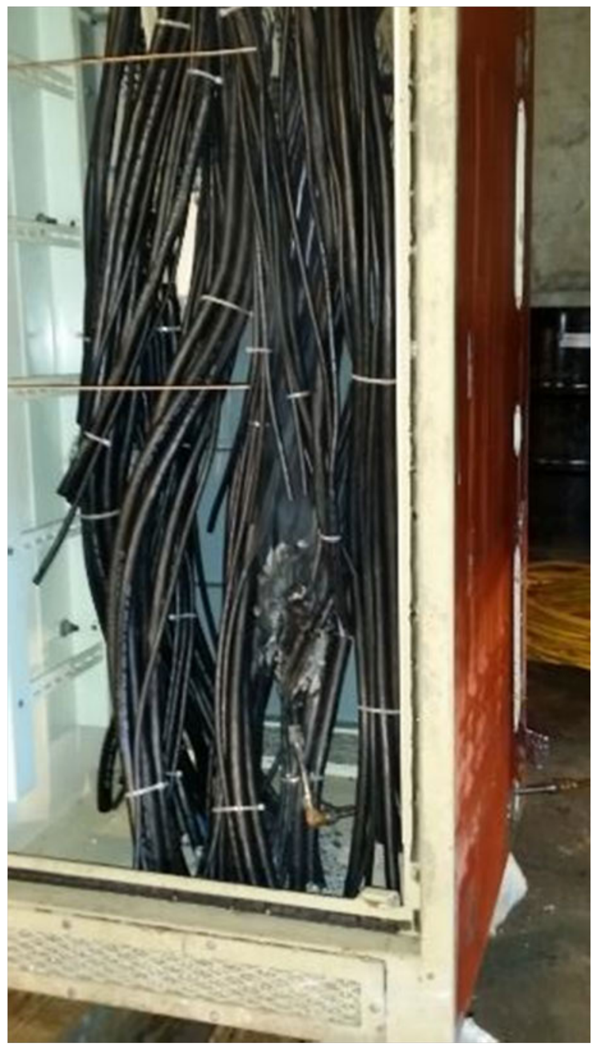
Test: 11 **Enclosure:** 1 **Fuel Load:** Loose collection of control cables that were originally installed in the enclosure **Ignition Source:** 0.7 kW propane burner **Ventilation:** Door open **Notes:** The fire burned some of the cable jackets in the immediate vicinity of the propane burner, shown at the bottom right of the enclosure in the photo on the right. The burner was turned off at approximately 20 min.	
	

Table 5-14. Summary of Test 12

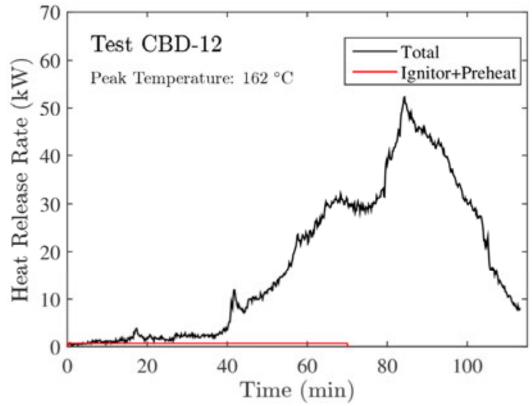
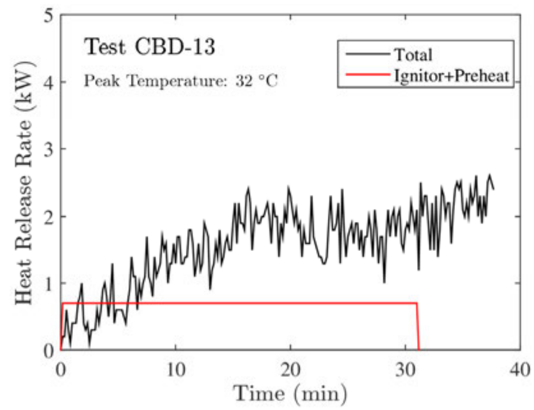
<table>
<tr>
<td>Test: 12 (A,B,C)
Enclosure: 1
Fuel Load: Same unburned cables from Test 11
Ignition Source: 0.7 kW propane burner
Ventilation: Door closed, open at end of test
Notes: The door of the enclosure was initially closed, but it was opened at approximately 40 min (B) to check on progress. The fire flared up due, presumably, to the introduction of fresh air. The door was closed at about 41 min. The door was opened at 80 min (C) and left open. The cables burned or smoldered for about an hour. All that remained was glowing char.</td>
<td>
</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</table>

Table 5-15. Summary of Test 13

<table>
<tr>
<td>

Test: 13
Enclosure: 8
Fuel Load: Control cables originating at interior connection panel and directed through conduits at the top of the enclosure into a cable tray
Ignition Source: 0.7 kW propane burner
Ventilation: Door closed, opened briefly
Notes: The door was opened at 23 min for approximately a minute and then closed again. The burner was turned off at approximately 31 min. The fire did not spread beyond its point of origin.

</td>
<td>



</td>
</tr>
<tr>
<td>

</td>
<td>

</td>
</tr>
</table>

Table 5-16. Summary of Test 14

Test: 14 (A,B)

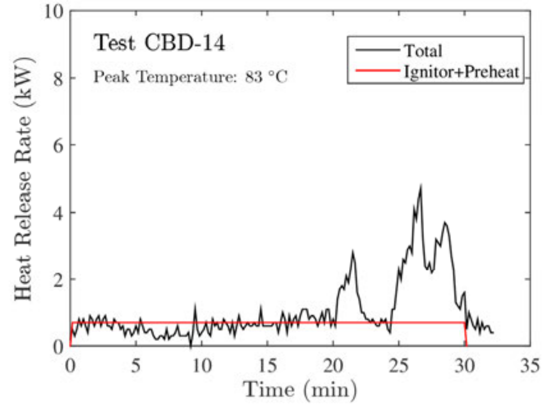
Enclosure: 8

Fuel Load: Same as Test 13

Ignition Source: 0.7 kW propane burner

Ventilation: Door closed, opened briefly

Notes: This experiment was similar to Test 13, but the cables were bundled closer together around the igniter. There was no measureable increase in the HRR for approximately 20 min, at which time the door was opened (B) and a propane blow torch was used to try to spread the fire. The test was ended at approximately 30 min.



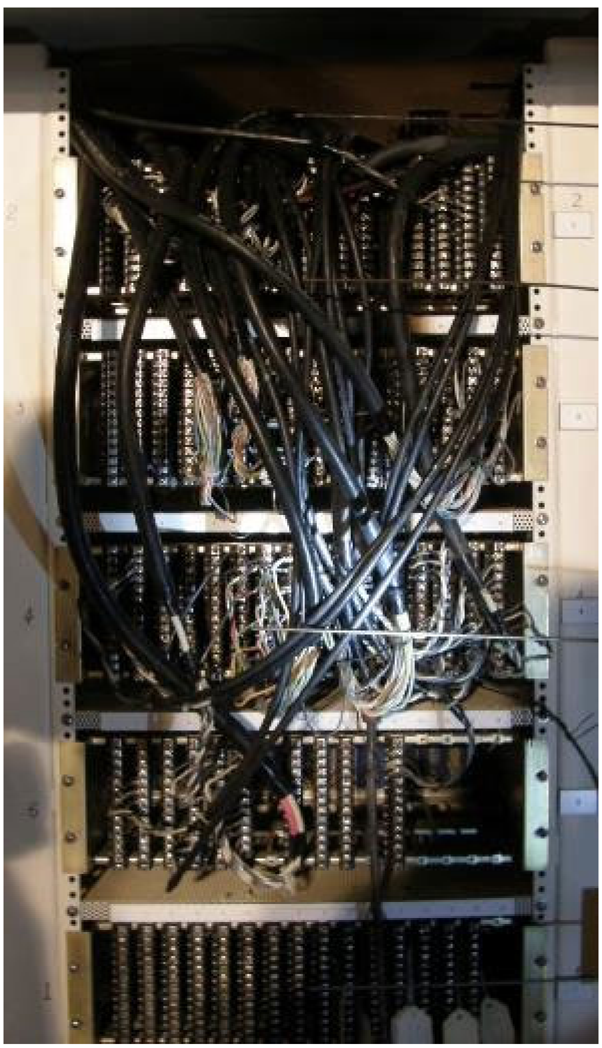


Table 5-17. Summary of Test 15

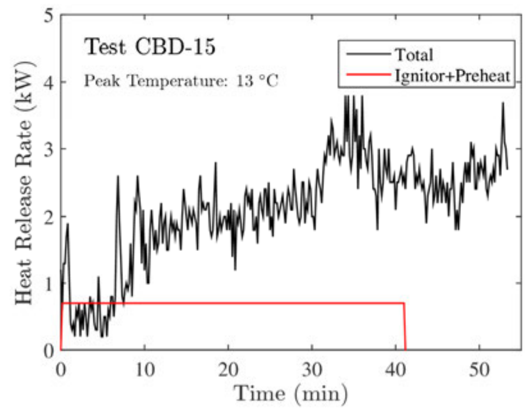
Test: 15 (A,B) **Enclosure:** 5 **Fuel Load:** 22 cables (#817), 1.8 m (6 ft) long, routed up left side of enclosure **Ignition Source:** 0.7 kW propane burner **Ventilation:** Door open, then closed **Notes:** The fire did not spread or grow appreciably in 30 min. At approximately 35 min (B), the door was closed to determine if this might better trap the heat and enhance burning. The burner was turned off at approximately 41 min.	
	

Table 5-18. Summary of Test 16

<table>
<tr>
<td>

Test: 16

Enclosure: 5

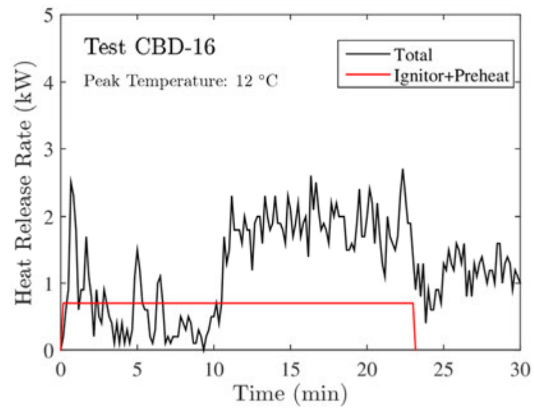
Fuel Load: 7 cables (#807), 1.8 m (6 ft) long, routed up right side of enclosure

Ignition Source: 0.7 kW propane burner

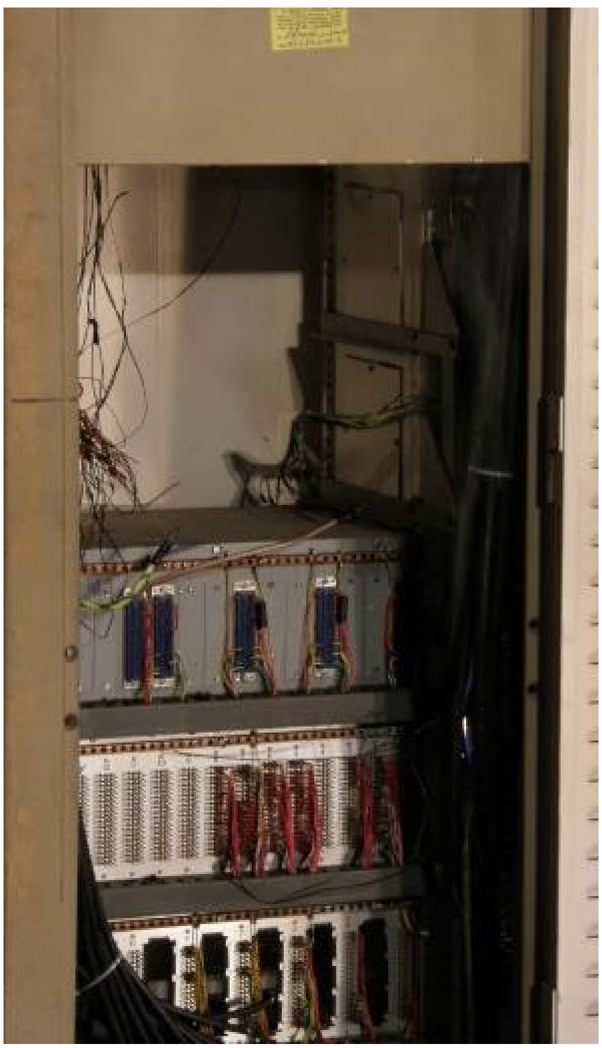
Ventilation: Door open

Notes: The holes of the propane burner became clogged, and the burner was cleaned at approximately 10 min. The fire did not spread beyond its point of origin. The burner was turned off at 23 min.

</td>
<td>



</td>
</tr>
<tr>
<td>



</td>
<td>

</td>
</tr>
</table>

Table 5-19. Summary of Test 17

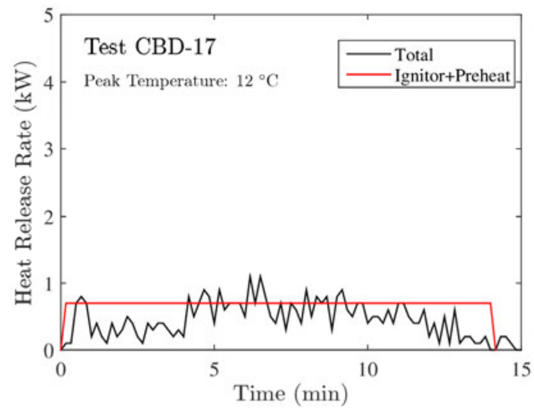
Test: 17 **Enclosure:** 4 **Fuel Load:** 7 cables (#830), 1.8 m (6 ft) long, routed up left side of enclosure **Ignition Source:** 0.7 kW propane burner **Ventilation:** Door open **Notes:** The fire did not spread beyond its point of origin. The burner was turned off at 14 min.	
	

Table 5-20. Summary of Test 18

Test: 18

Enclosure: 4

Fuel Load: 30 cables (#845), 1.8 m (6 ft) long, routed up right side of enclosure

Ignition Source: 0.7 kW propane burner

Ventilation: Door open

Notes: The fire spread upwards approximately 60 cm (2 ft) above the propane burner. The burner was turned off at 20 min.

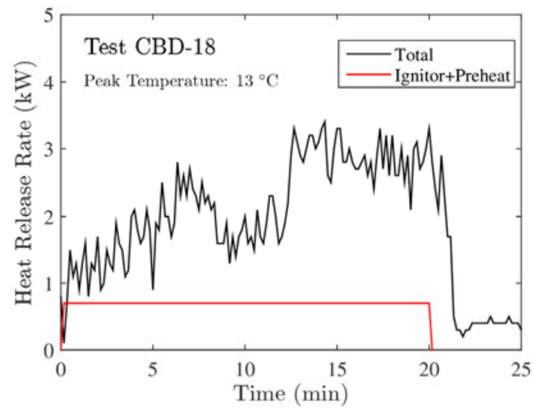


Table 5-21. Summary of Test 19

Test: 19

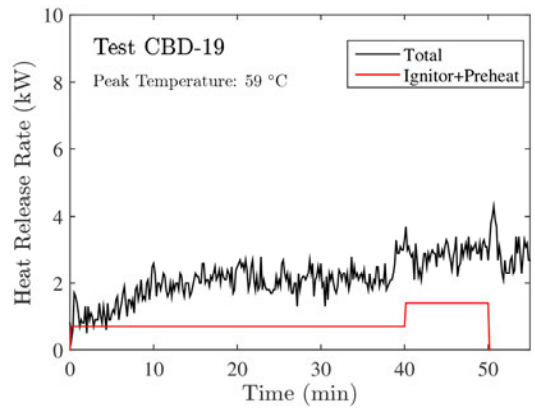
Enclosure: 5

Fuel Load: 22 cables (#817), 1.8 m (6 ft) long, routed up left side of enclosure

Ignition Source: 0.7 kW propane burner

Ventilation: Door closed

Notes: The fire did not spread beyond its point of origin. The door was opened at 24 min and at 40 min, for approximately 1 min each time. At 40 min, the propane burner was increased to 1.7 kW, but the fire still did not spread.



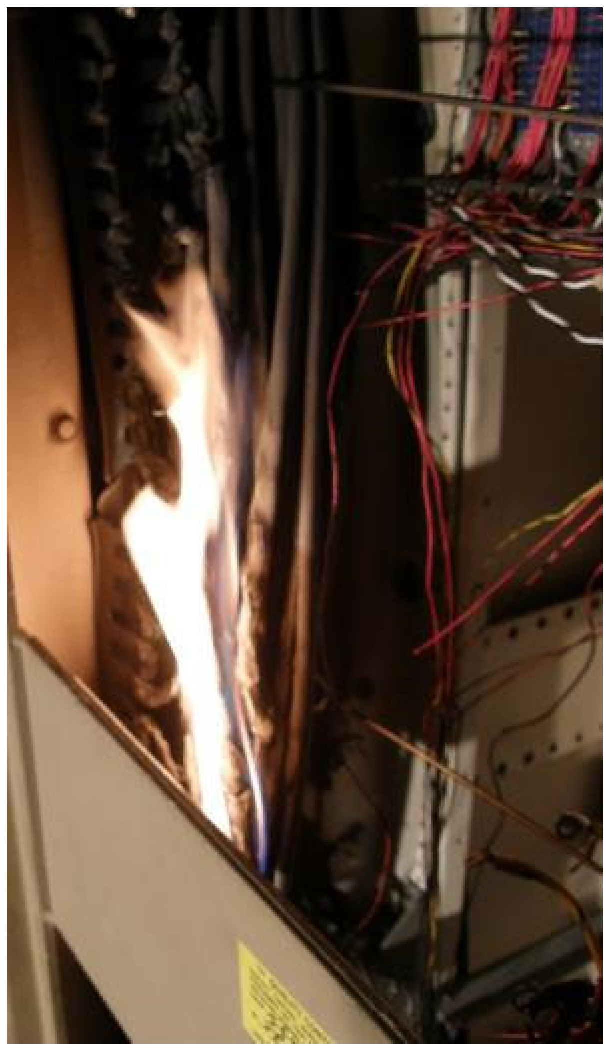


Table 5-22. Summary of Test 20

Test: 20

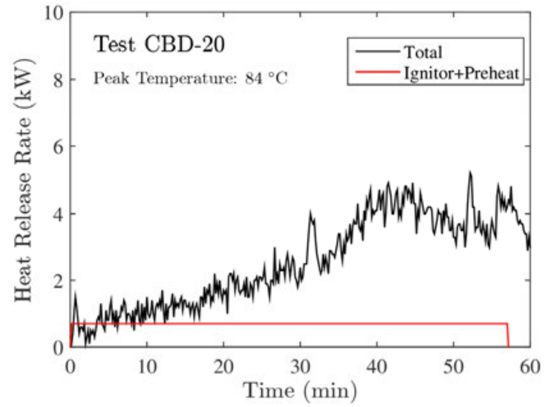
Enclosure: 5

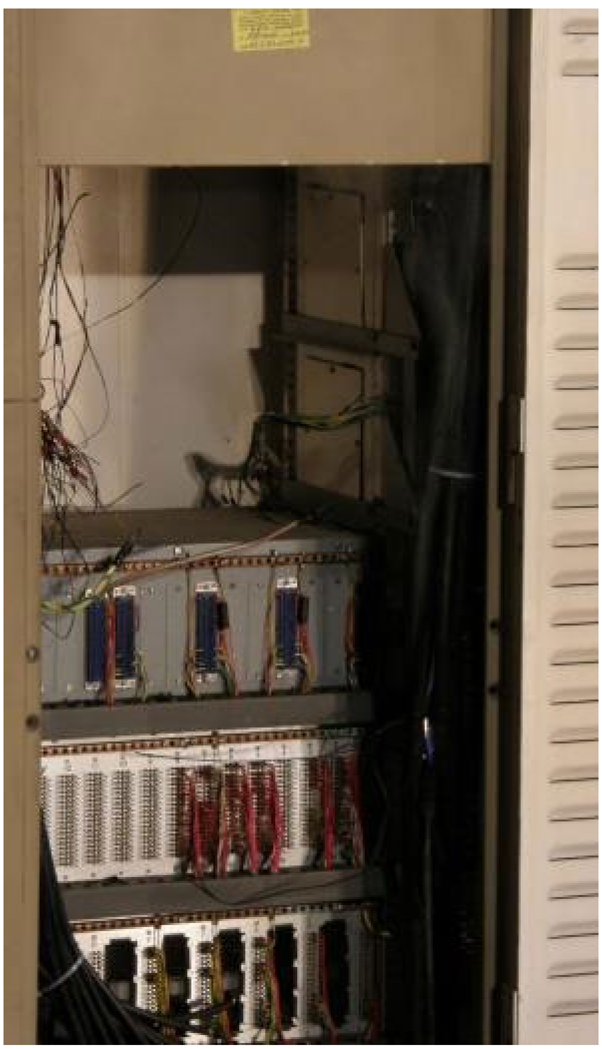
Fuel Load: 7 cables (#807), 1.8 m (6 ft) long, routed up right side of enclosure

Ignition Source: 0.7 kW propane burner

Ventilation: Door closed, opened briefly

Notes: The burner was placed above the damaged cables left over from Test 16, approximately at mid-height. The flames extended about 60 cm (2 ft) above the burner. The door was opened at 30 min and at 50 min to check progress, for approximately 1 min each time. The fire did not spread beyond 60 cm (2 ft). The burner was turned off just short of an hour.





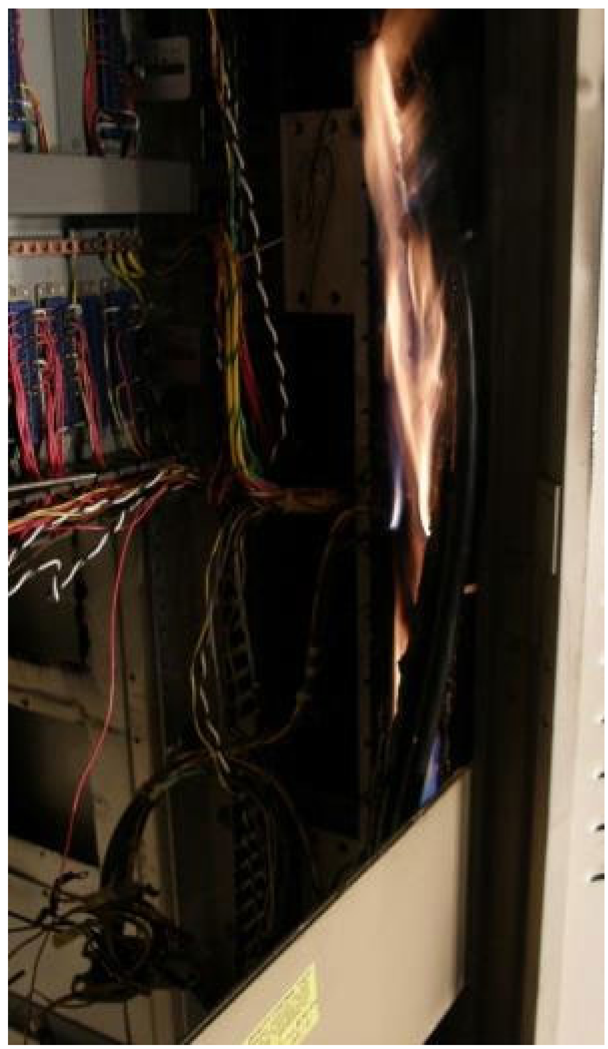


Table 5-23. Summary of Test 21

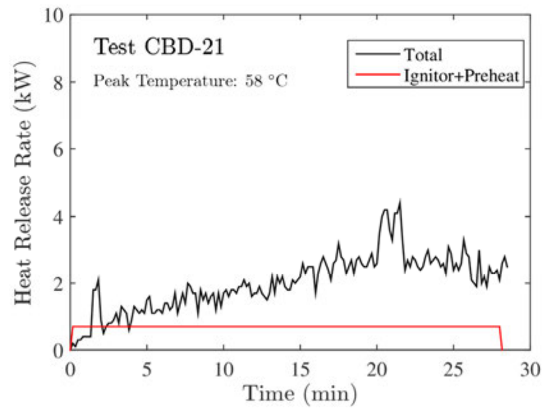
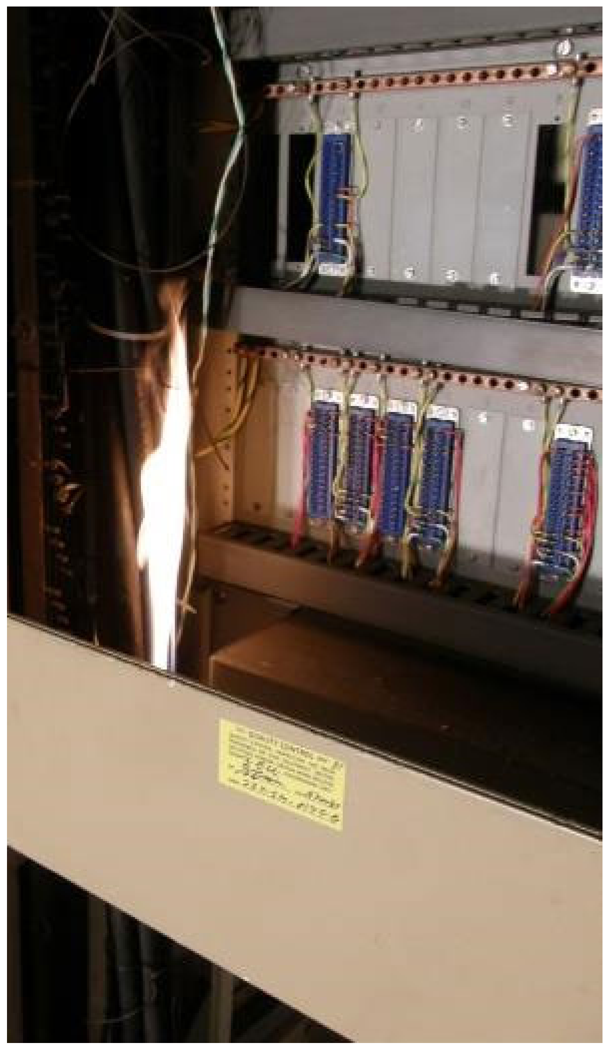
Test: 21 **Enclosure:** 4 **Fuel Load:** 7 cables (#807), 1.8 m (6 ft) long, routed up left side of enclosure **Ignition Source:** 0.7 kW propane burner **Ventilation:** Door closed **Notes:** The fire did not spread beyond its point of origin.	
	

Table 5-24. Summary of Test 22

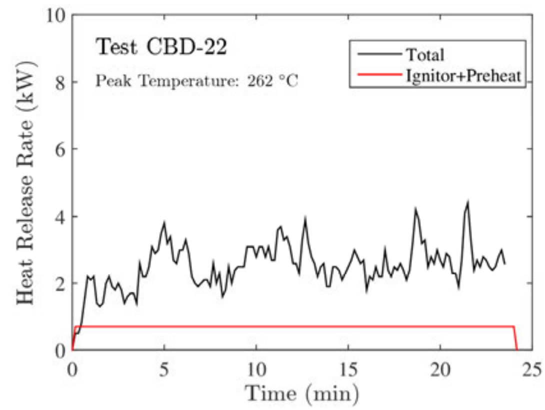
Test: 22 **Enclosure:** 4 **Fuel Load:** 30 cables (#845), 1.8 m (6 ft) long, routed up right side of enclosure **Ignition Source:** 0.7 kW propane burner **Ventilation:** Door closed **Notes:** The fire did not spread beyond the point of origin.	
	

Table 5-25. Summary of Test 23

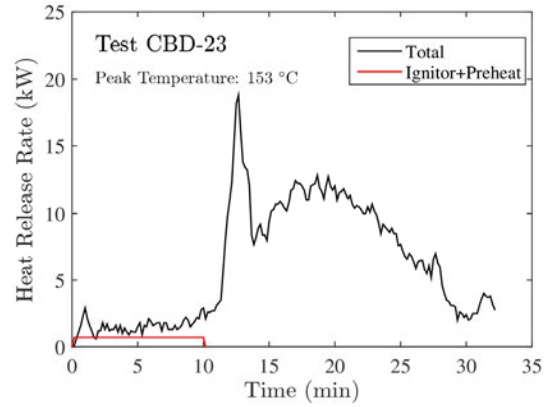
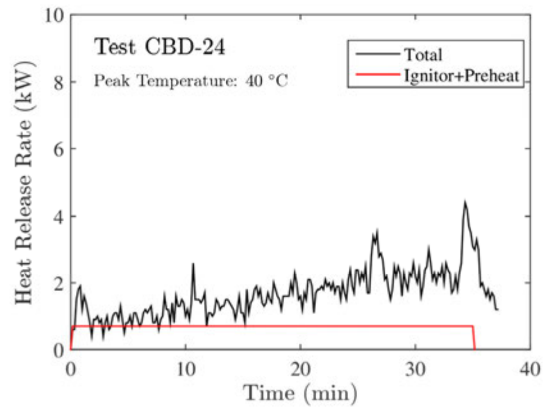
Test: 23 **Enclosure:** 5 **Fuel Load:** 10 cables (#841), 1.8 m (6 ft) long, routed up left side of enclosure **Ignition Source:** 0.7 kW propane burner **Ventilation:** Door open **Notes:** The cable was cut from old power cords that were being discarded. The fire spread rapidly upwards after approximately 10 min, at which point the bundle fell from its restraining harness and onto the floor of the enclosure where it burned for approximately 20 min.	
	

Table 5-26. Summary of Test 24

<table>
<tr>
<td>
Test: 24
Enclosure: 5
Fuel Load: 1.8 m (6 ft) vertical bundle of 37 insulated conductors (#834) routed up right side of enclosure
Ignition Source: 0.7 kW propane burner
Ventilation: Door closed
Notes: The fire did not spread beyond its point of origin. The burner was turned off at 35 min.
</td>
<td>


</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</table>

Table 5-27. Summary of Test 25

<table>
<tr>
<td>

Test: 25

Enclosure: 1

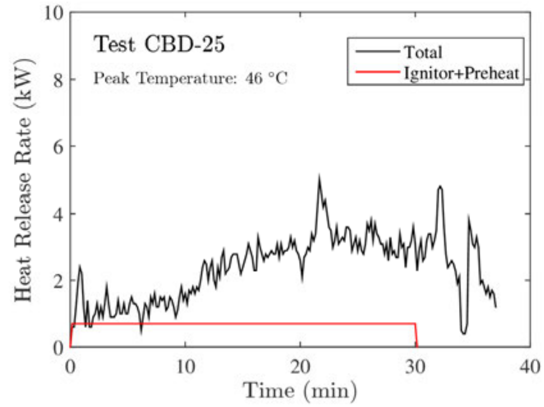
Fuel Load: 768 m (2520 ft) insulated conductors (#834) connected to center board and running down both sides of enclosure

Ignition Source: 0.7 kW propane burner

Ventilation: Door closed, opened briefly

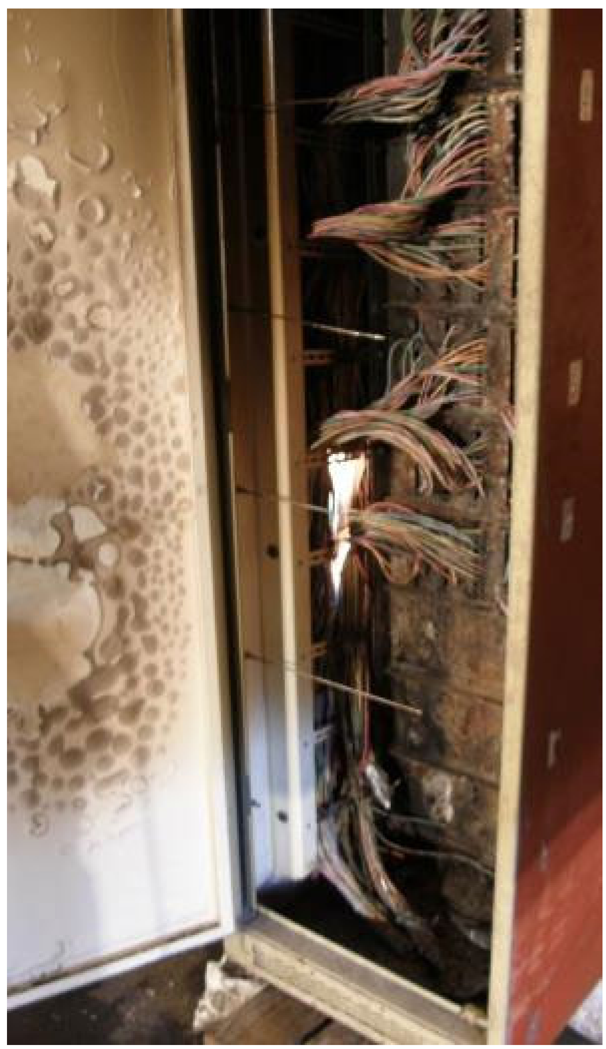
Notes: The fire spread approximately 20 cm (8 in) above the burner. The door was opened at approximately 20 min for 1 min to check progress. The fire did not spread beyond the vicinity of the burner. Based on observation, 36 cables were consumed 20 cm (8 in) above the burner.

</td>
<td>



</td>
</tr>
<tr>
<td>

</td>
<td>



</td>
</tr>
</table>

Table 5-28. Summary of Test 26

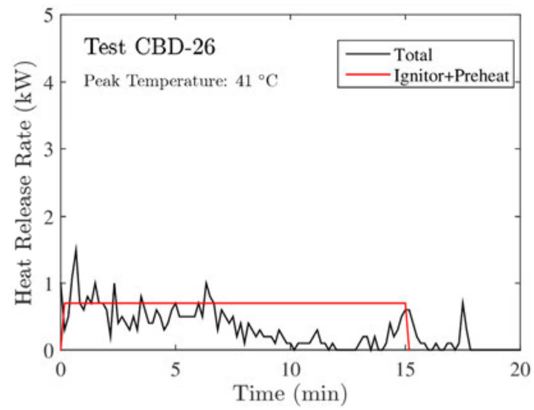
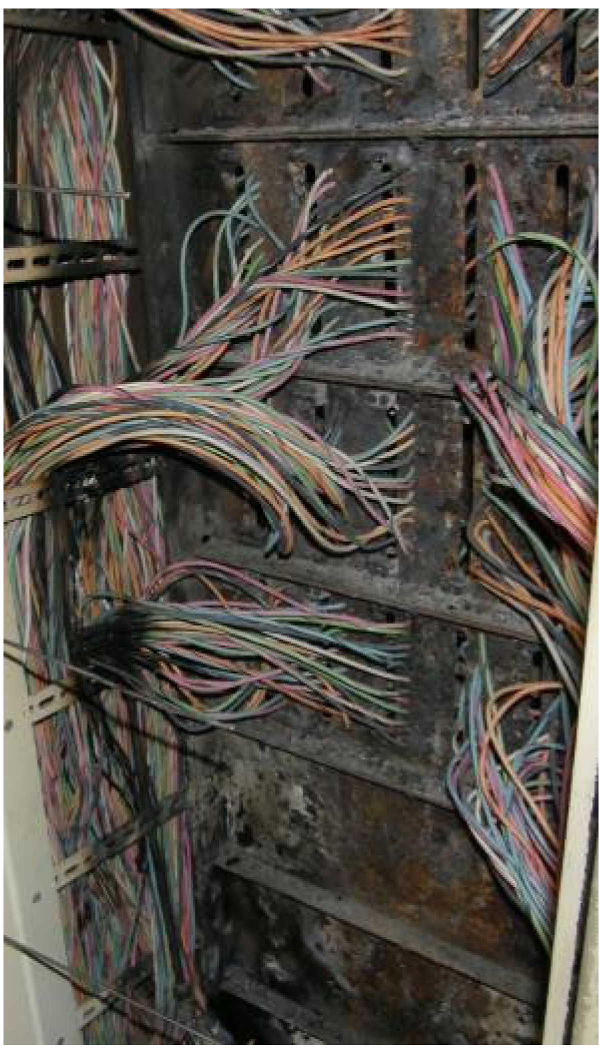
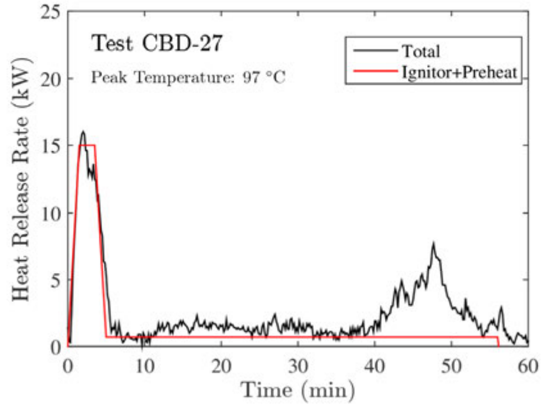
Test: 26 **Enclosure:** 1 **Fuel Load:** Same as Test 25 **Ignition Source:** 0.7 kW propane burner **Ventilation:** Door closed then opened **Notes:** This test made use of the mostly unburned wire from Test 25. The propane burner was placed in a different position, near unburned wire. The door was opened at approximately 15 min and the test was ended at 17 min. The fire did not spread. Based on observation, 36 conductors were consumed 10 cm (4 in) above the burner.	
	

Table 5-29. Summary of Test 27

<table>
<tr>
<td>

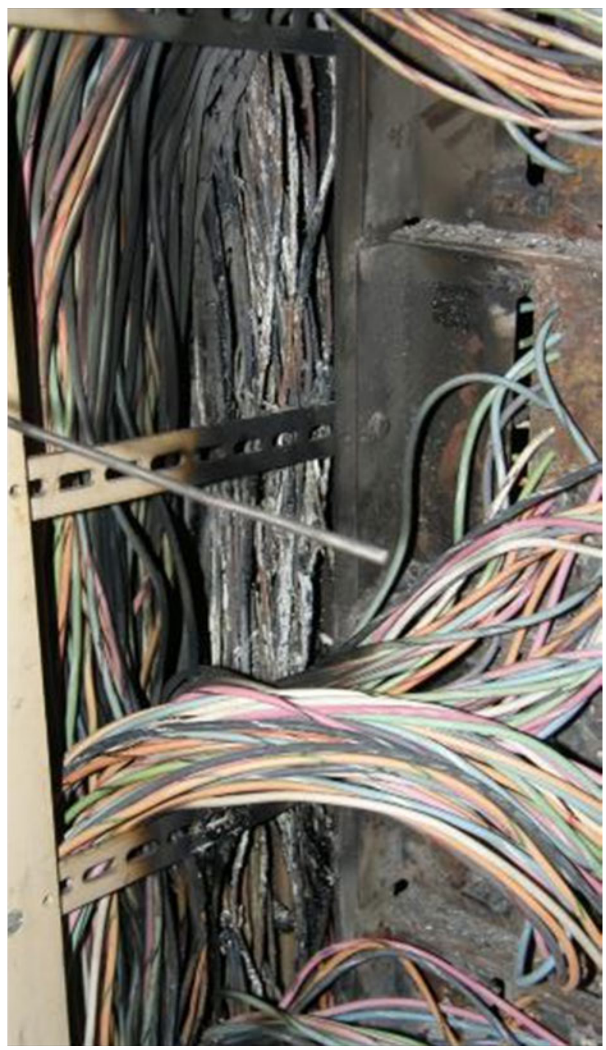
Test: 27 (A,B)
Enclosure: 1
Fuel Load: 2.99 kg
Ignition Source: 0.7 kW propane burner
Preheating Source: 150 mL ethanol pan fire
Ventilation: Door closed, opened briefly
Notes: The ethanol was exhausted at approximately 7 min, at which time the propane burner was lit. The door was opened at 27 min and at 40 min (B), for approximately 1 min. Each time the door was opened, the cables were jostled with a crowbar. The burner was turned off at 56 min. Based on observation, 36 conductors were consumed 30 cm (1 ft) above the burner.

</td>
<td>



</td>
</tr>
<tr>
<td>

</td>
<td>



</td>
</tr>
</table>

Table 5-30. Summary of Test 28

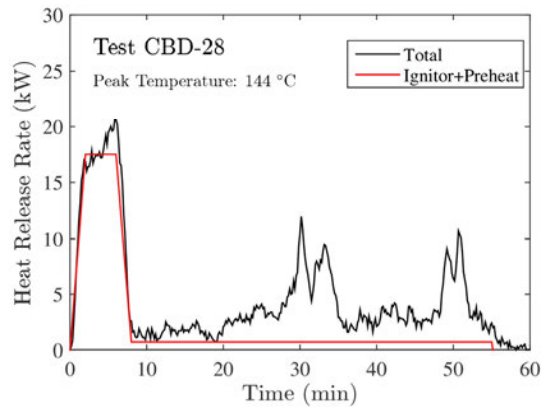
Test: 28 (A,B,C) **Enclosure:** 1 **Fuel Load:** 2.87 kg **Ignition Source:** 0.7 kW propane burner **Preheating Source:** 300 mL ethanol pan fire **Ventilation:** Door closed, opened briefly **Notes:** The ethanol fire was exhausted at approximately 9 min after which the propane burner was ignited. At 19 min (B), the door was opened and the wires in the vicinity of the burner were jostled with a crowbar, and the door was closed. The fire then spread upwards, approximately 0.6 m (2 ft) above the burner. The crowbar process was repeated at 40 min (C).	
	

Table 5-31. Summary of Test 29

Test: 29
Enclosure: 1
Fuel Load: 2.64 kg
Ignition Source: 500 mL acetone pan fire
Ventilation: Door closed
Notes: The bottom ends of 3 bundles, each consisting of 37 insulated conductors, were placed in the 15 cm by 23 cm (6 in by 9 in) steel baking pan at the lower left side of the enclosure. The acetone burned for approximately 12 min, 30 s. The fire spread up one side of the enclosure. Half of the combustible material was consumed.

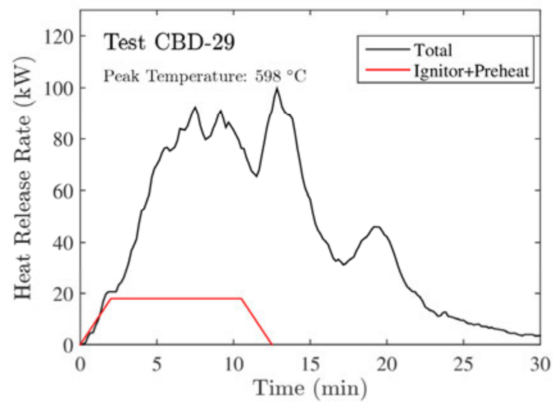


Table 5-32. Summary of Test 30

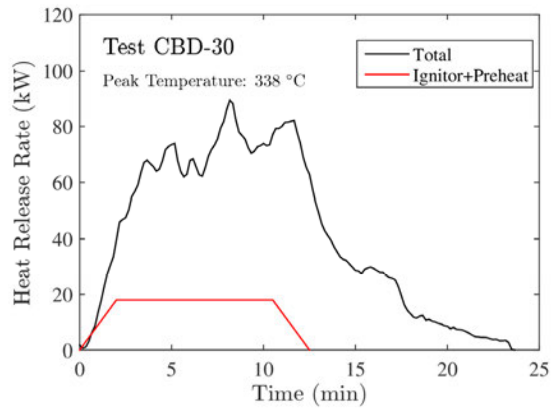
Test: 30 **Enclosure:** 1 **Fuel Load:** 1.32 kg **Ignition Source:** 500 mL acetone pan fire **Ventilation:** Door closed **Notes:** This test was similar to Test 29, where the acetone pan was placed on the unburned right side of the enclosure. The test was terminated at approximately 23 min.	
	

Table 5-33. Summary of Test 31

Test: 31

Enclosure: 4

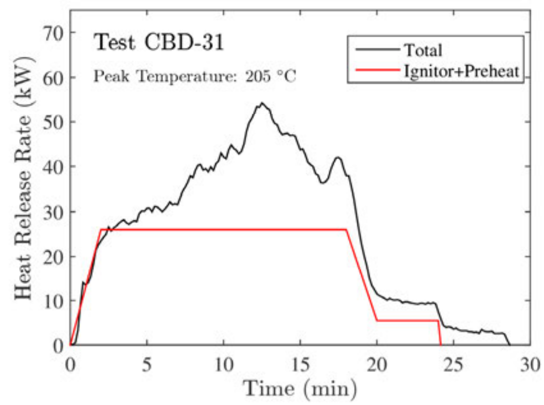
Fuel Load: 37. insulated conductors extracted from Cable #834, loosely bundled, 1.8 m (6 ft) along right side of enclosure

Ignition Source: 5.5 kW propane burner

Preheating Source: 1 L acetone pan fire

Ventilation: Door closed

Notes: The acetone pan was placed in the rear of the enclosure for the purpose of pre-heating. The acetone was exhausted at 20 min. The door was opened and the propane burner was turned off at 23 min.



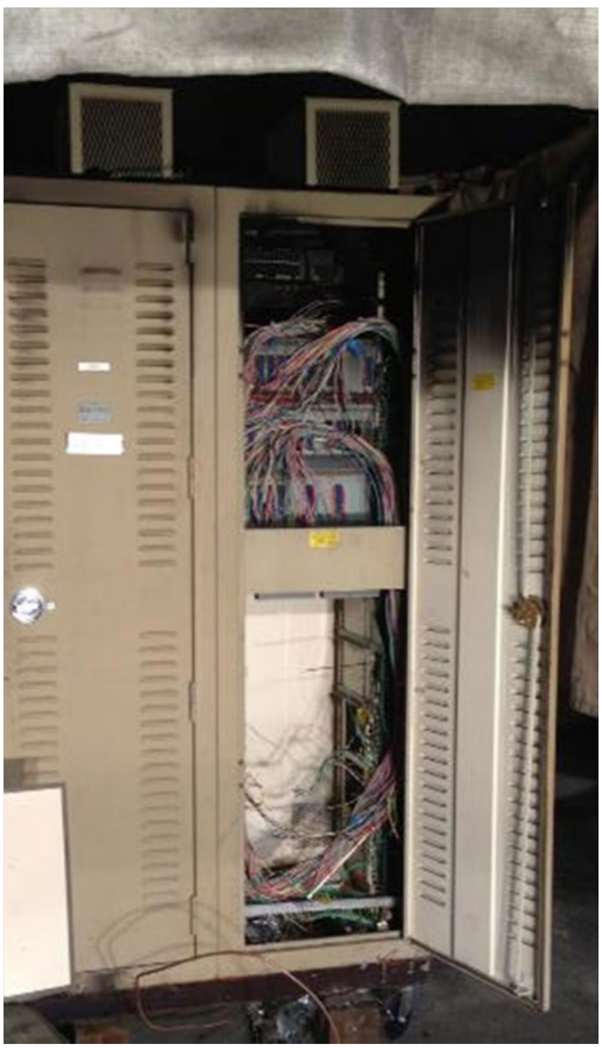


Table 5-34. Summary of Test 32

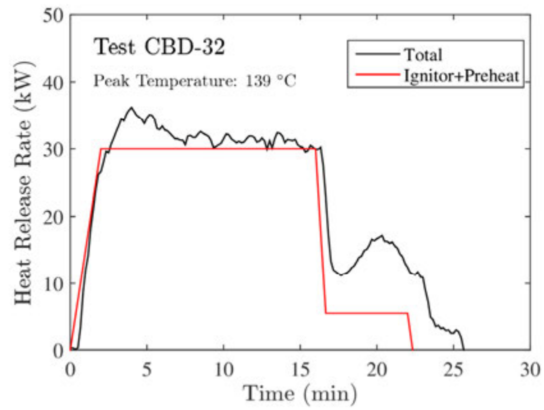
Test: 32 (A,B) **Enclosure:** 4 **Fuel Load:** 37 insulated conductors (#834), loosely bundled, 1.8 m (6 ft) along left side of enclosure **Ignition Source:** 5.5 kW propane burner **Preheating Source:** 1 L acetone pan fire **Ventilation:** Door closed, then opened **Notes:** The acetone was exhausted at approximately 16 min, and the propane burner was turned off at 22 min. The door was opened at 16 min (B) and remained open. The fire did not spread beyond the vicinity of the propane burner.	
	

Table 5-35. Summary of Test 33

Test: 33

Enclosure: 5

Fuel Load: 74 insulated conductors (#834), loosely bundled, 1.8 m (6 ft)

Ignition Source: 5.5 kW propane burner and 1 L acetone pan fire at the overlap region of left and right side bundles

Ventilation: Door closed

Notes: This was an attempt to burn the wiring on both sides of the enclosure. The fire spread about one-third of the way up the left side, but within 10 min the only fuel burning was the acetone and propane. The acetone was exhausted and the burner turned off just after 20 min. Based on observation, 37 conductors were consumed 0.6 m (2 ft).

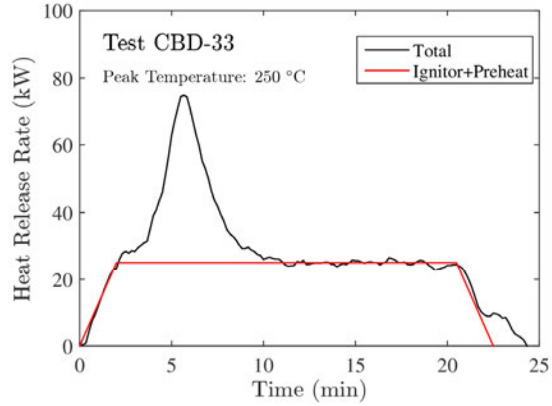


Table 5-36. Summary of Test 34

<table>
<tr>
<td>

Test: 34

Enclosure: 5

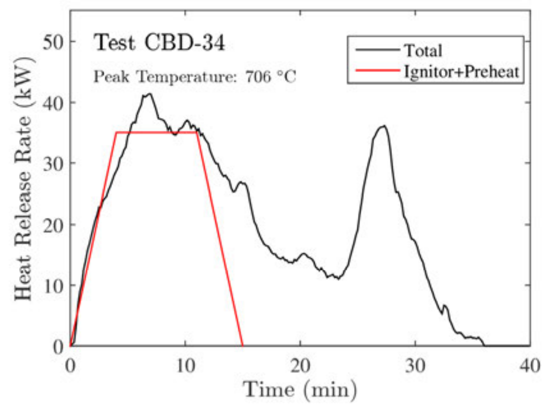
Fuel Load: 62 insulated conductors (#834), loosely bundled, 1.8 m (6 ft) long, 1.22 kg

Ignition Source: 2 pans of acetone, 500 mL each

Ventilation: Door closed

Notes: This was an attempt to burn wire bundles left over from previous tests. The fire spread up the left side of the enclosure, and halfway up the right.

</td>
<td>



</td>
</tr>
<tr>
<td>

</td>
<td>

</td>
</tr>
</table>

Table 5-37. Summary of Test 35

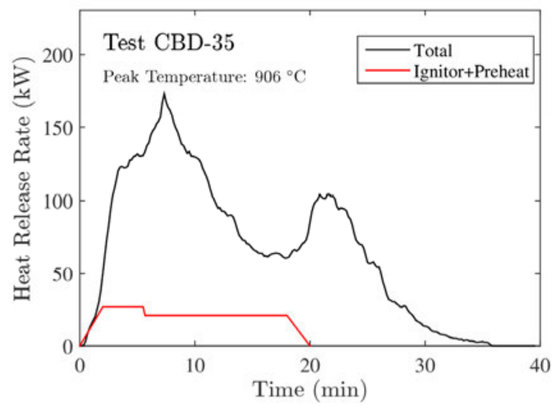
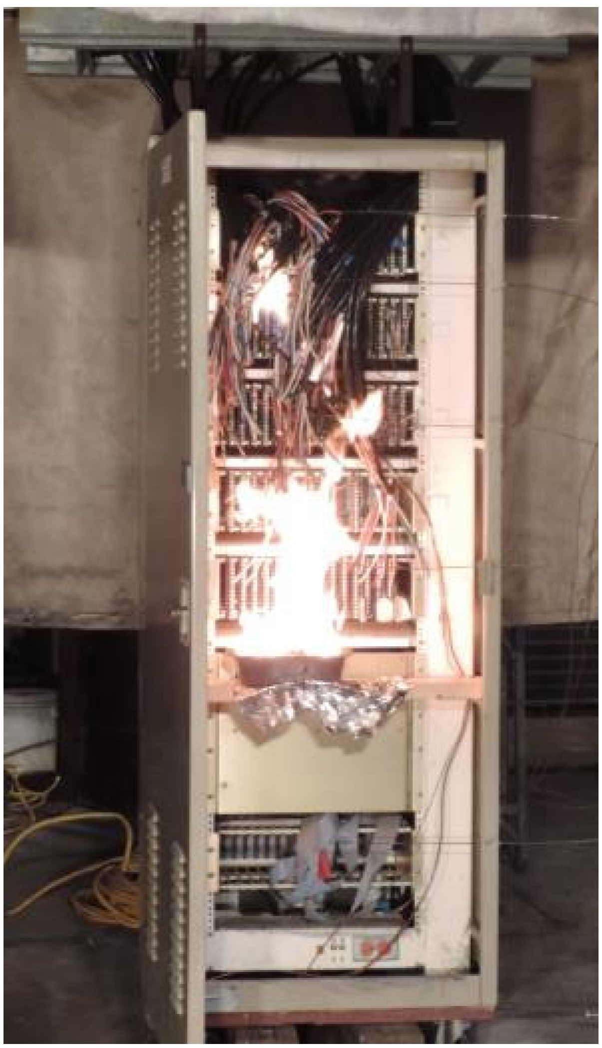
Test: 35 **Enclosure:** 8 **Fuel Load:** 42 control cables (#807), 1.8 m (6 ft) long, routed through vertical conduits on top of enclosure into cable tray 45 cm (18 in) above **Ignition Source:** 5.5 kW propane burner within the bundled cable and 1 L acetone pan fire 60 cm (2 ft) below base of cable bundle **Ventilation:** Door closed, then opened **Notes:** The door popped open at 3 min, 20 s, due to the rapid increase in the HRR. The propane burner was turned off at 5 min, 30 s. At approximately 20 min the fire spread through the 10 conduits and burned the cables in the tray above.	
	

Table 5-38. Summary of Test 36

Test: 36 (A,B)

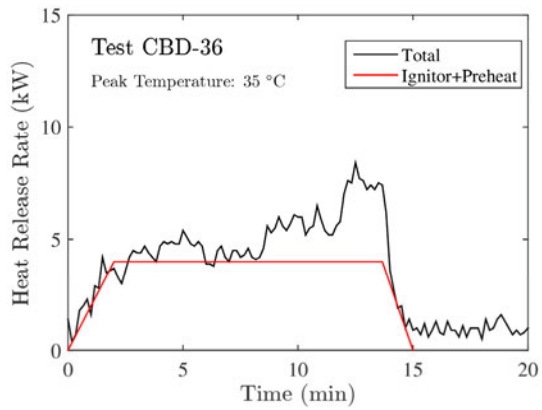
Enclosure: 2

Fuel Load: Bundle of 10 control cables (#807), 1.8 m (6 ft) long, 2.71 kg

Ignition Source: 4 kW propane burner

Ventilation: Door closed, then opened

Notes: The fire did not spread beyond its point of origin near the base of the bundle. The front door was opened at 12 min (B). The burner was turned off at approximately 14 min.



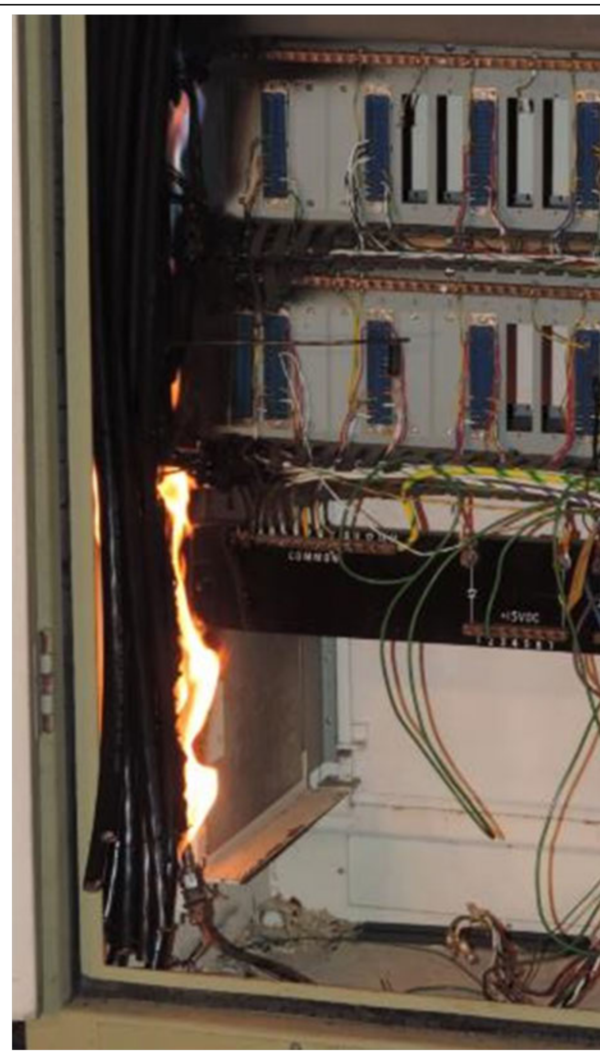


Table 5-39. Summary of Test 37

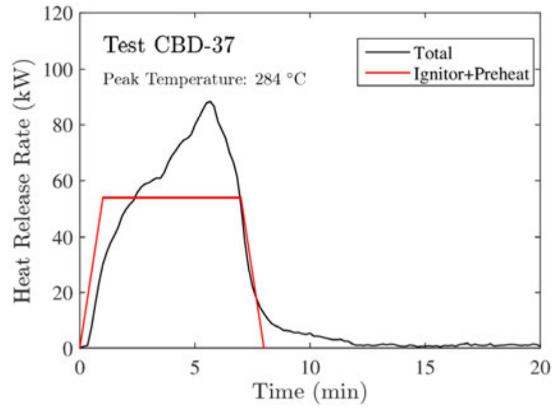
Test: 37 **Enclosure:** 2 **Fuel Load:** Two bundles of 10 control cables (#807); 1.8 m (6 ft) long, one on each side of enclosure **Ignition Source:** Two pans of acetone, each containing 500 mL **Ventilation:** Door closed **Notes:** The fire spread upwards on the left side bundle, but did not spread upwards on the right. 10 control cables approximately 0.46 m (1.5 ft) on the right side were consumed,.	
	

Table 5-40. Summary of Test 38

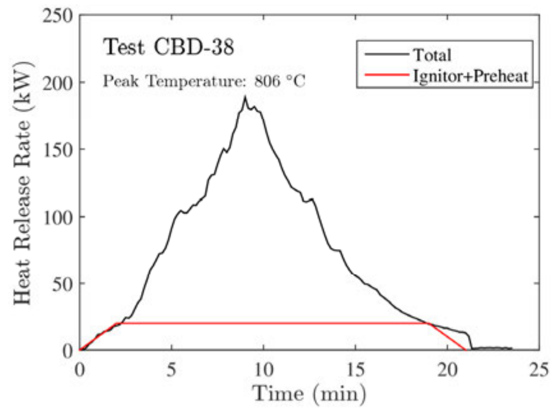
Test: 38 **Enclosure:** 2 **Fuel Load:** Same cables from Test 37, with both left and right bundles gathered together in front of central partition with the ends terminating in the fuel pan. 4.74 kg **Ignition Source:** 1 L acetone pan fire **Ventilation:** Door closed **Notes:** The fire consumed all of the cables within the enclosure. Flames extended outside of the access openings, reaching a height approximately 30 cm (1 ft) above the top of the enclosure. The acetone was exhausted at 21 min.	
	

Table 5-41. Summary of Test 39

<table>
<tr>
<td>

Test: 39

Enclosure: 8

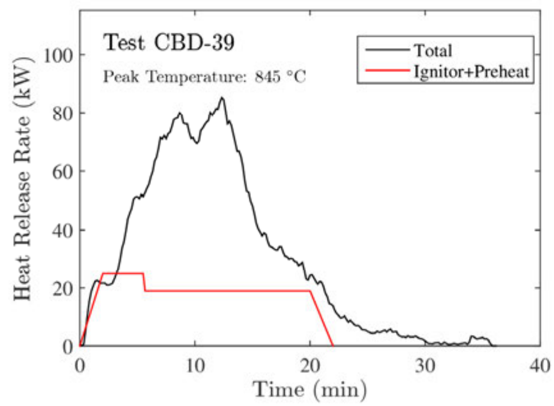
Fuel Load: 21 control cables (#807), 1.8 m (6 ft) long

Ignition Source: 5.5 kW propane burner within the bundled cable and 1 L acetone pan fire 60 cm (2 ft) below base of cable bundle

Ventilation: Door closed

Notes: The fire spread upwards through the 10 conduits in the top of the enclosure and consumed the cables in the tray directly above.

</td>
<td>



</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</table>

Table 5-42. Summary of Test 40

<table>
<tr>
<td>

Test: 40

Enclosure: 3

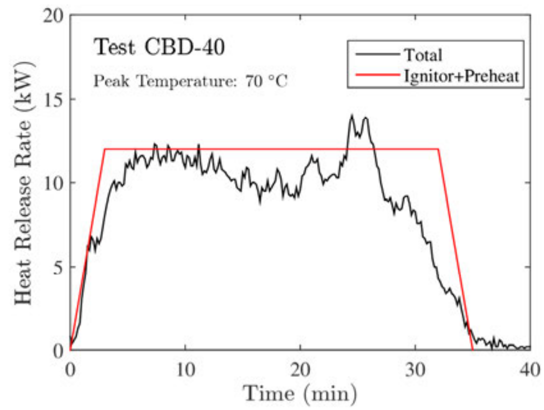
Fuel Load: Various bundles of fine, coated relay wire in middle section of enclosure

Ignition Source: 1 L acetone pan fire

Ventilation: Door closed; side panel open

Notes: The wire and connectors were stuffed into the fuel pan. The fire did not spread beyond the pan. The wire coating appeared to blacken but did not generate any measurable heat.

</td>
<td>



</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</table>

Table 5-43. Summary of Test 41

<table>
<tr>
<td>

Test: 41 (A,B)

Enclosure: 3

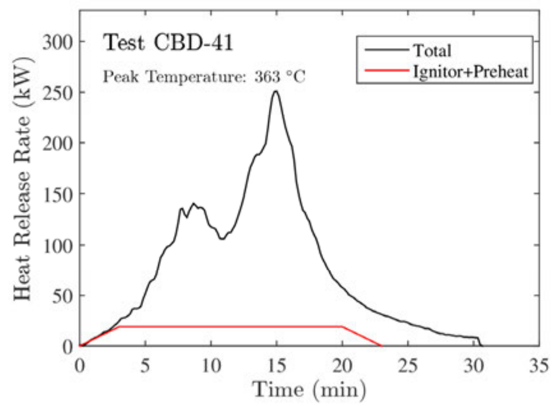
Fuel Load: 36 circuit boards, 28 cm by 23 cm (11 in by 9 in)

Ignition Source: 1 L acetone pan fire

Ventilation: Door closed

Notes: The fire spread rapidly through the circuit boards, which were arranged in multiple racks above the pan. The clear plastic panel in the front door burned through at 11 min (B), and the fire grew rapidly afterwards. The coated relay wiring on the back side of the partition between the front and middle sections burned.

</td>
<td>



</td>
</tr>
<tr>
<td>

</td>
<td>

</td>
</tr>
</table>

Table 5-44. Summary of Test 42

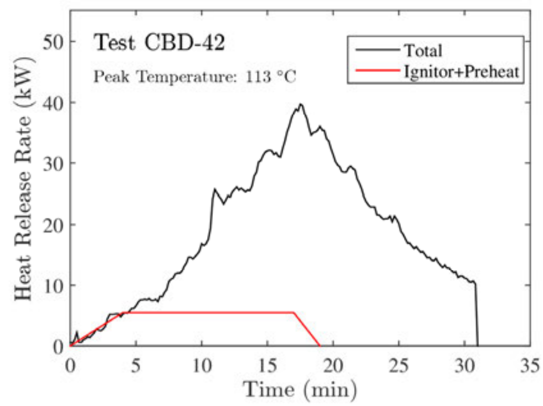
Test: 42 **Enclosure:** 4 **Fuel Load:** 10 cables (#813), 1.8 m (6 ft) long, routed up right side of enclosure **Ignition Source:** 5.5 kW propane burner **Ventilation:** Door closed then opened at 10 min **Notes:** The fire spread upwards along the cables in the right side of the enclosure. The door was opened at approximately 10 min and it was left open for the remainder of the test. The burner was turned off at 17 min.	
	

Table 5-45. Summary of Test 43

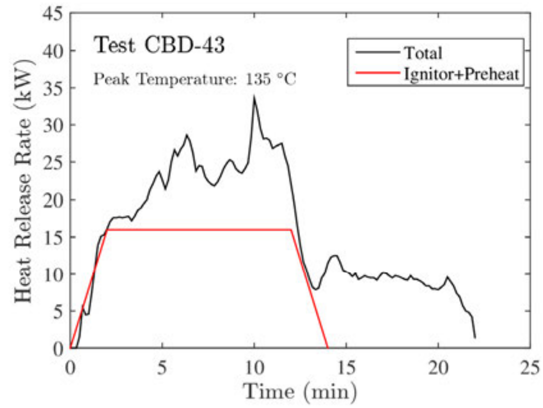
Test: 43 **Enclosure:** 4 **Fuel Load:** 10 cables (#813), 1.8 m (6 ft) long, routed up left side of enclosure **Ignition Source:** 500 mL acetone pan fire **Ventilation:** Door closed then opened **Notes:** Even though the cables were immersed in the acetone, the fire did not spread upwards. The door was opened at 9.5 min and remained open. The acetone was exhausted at approximately 14 min.	
	

Table 5-46. Summary of Test 44

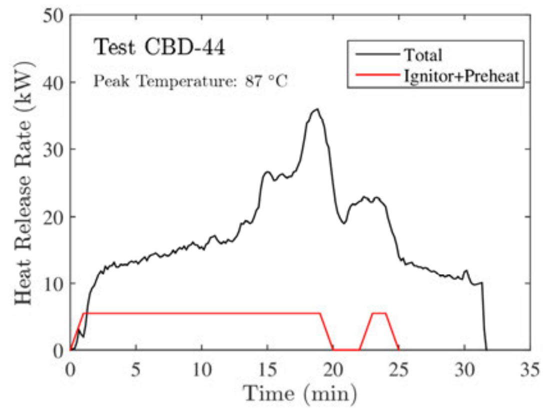
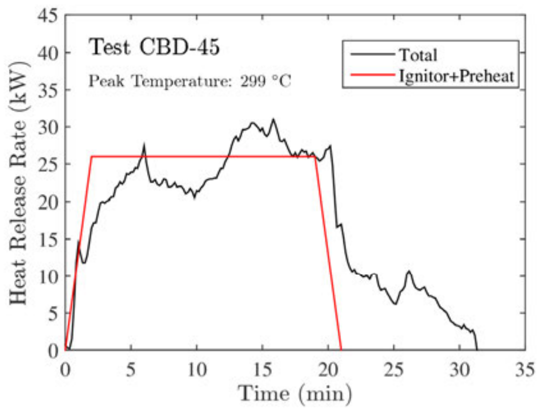
Test: 44 **Enclosure:** 5 **Fuel Load:** 10 cables (#813), 1.8 m (6 ft) long, routed up right side of enclosure **Ignition Source:** 5.5 kW propane burner **Ventilation:** Door closed, then opened **Notes:** The door was opened at approximately 14 min. The propane burner was turned off at approximately 19 min; turned back on at 22 min; and finally off at 23 min. This was done to test the influence of the burner.	
	

Table 5-47. Summary of Test 45

<table>
<tr>
<td>

Test: 45
Enclosure: 5
Fuel Load: 10 cables (#813), 1.8 m (6 ft) long, routed up left side of enclosure
Ignition Source: 5.5 kW propane burner
Preheating Source: 1 L acetone pan fire
Ventilation: Door closed, then opened
Notes: The pan fire was placed away from the cables. The acetone was exhausted by 20 min, at which time the door was opened. The propane burner was turned off and the fire sustained itself for a few minutes.

</td>
<td>



</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</table>

Table 5-48. Summary of Test 46

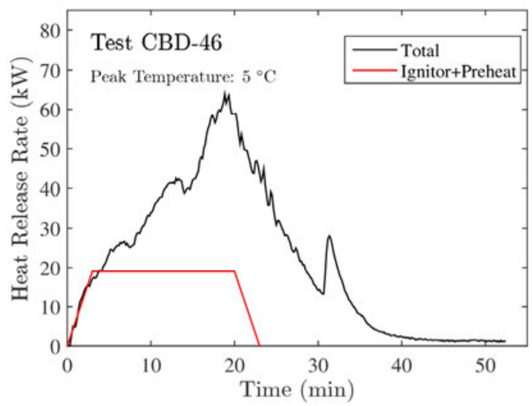
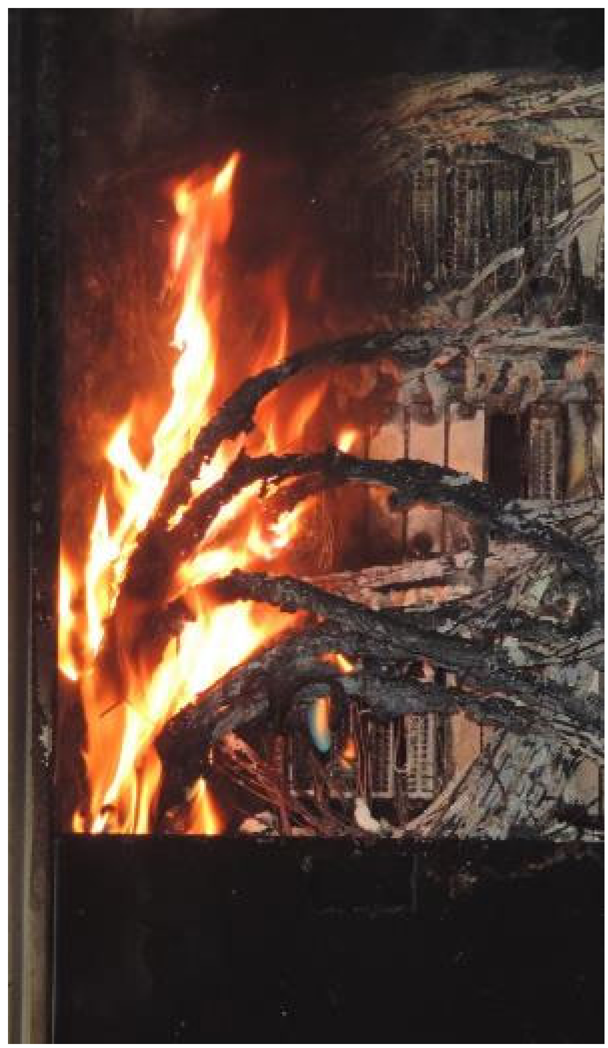
Test: 46 **Enclosure:** 4 **Fuel Load:** Two cable bundles; one on each side. Each bundle contained 10 cables (#807), 1.8 m (6 ft) long, stripped 20 cm (8 in) and overlapping near the top **Ignition Source:** 1 L acetone pan fire **Ventilation:** Door closed **Notes:** The pan was placed on the right side of the enclosure with the base of the cable bundle soaked in the liquid fuel. The fire spread upwards; across the top, and partially down the left side (see photo below right). The door was opened at approximately 30 min.	
	

Table 5-49. Summary of Test 47

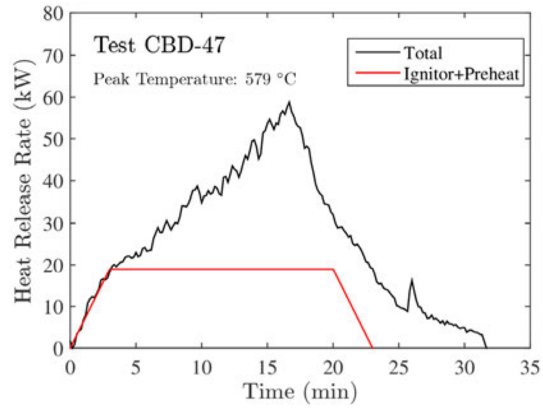
Test: 47 **Enclosure:** 4 **Fuel Load:** Two cable bundles; one on each side. Each bundle contained 5 cables (#807), 1.8 m (6 ft) long, stripped 20 cm (8 in) and overlapping near the top **Ignition Source:** 1 L acetone pan fire **Ventilation:** Door closed **Notes:** The fire behaved in a similar manner as Test 46. The door was opened at 25 min, at which point the fire had spread to the top of the bundle on the right side and was burning the top of the left bundle.	
	

Table 5-50. Summary of Test 48

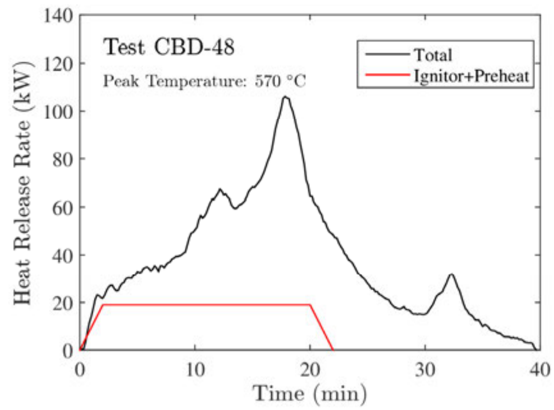
Test: 48 **Enclosure:** 4 **Fuel Load:** Two cable bundles; one on each side. Each bundle contained 10 cables (#807), 1.8 m (6 ft) long, stripped 20 cm (8 in) and overlapping near the top **Ignition Source:** 1 L acetone pan fire **Ventilation:** Door open **Notes:** This test was the same as Test 46, except with the door open.	
	

Table 5-51. Summary of Test 49

<table>
<tr>
<td>

Test: 49

Enclosure: 4

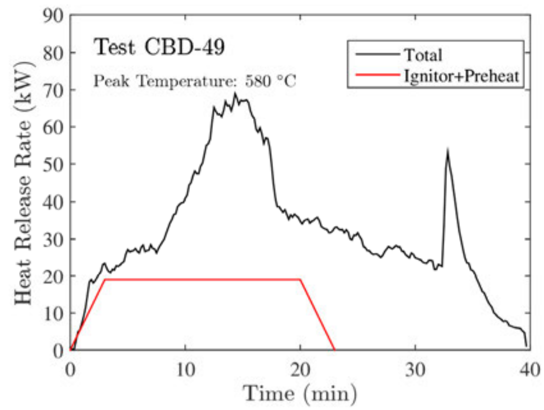
Fuel Load: Two cable bundles; one on each side. Each bundle contained 10 cables (#807), 1.8 m (6 ft) long, stripped 20 cm (8 in) and overlapping near the top

Ignition Source: 1 L acetone pan fire

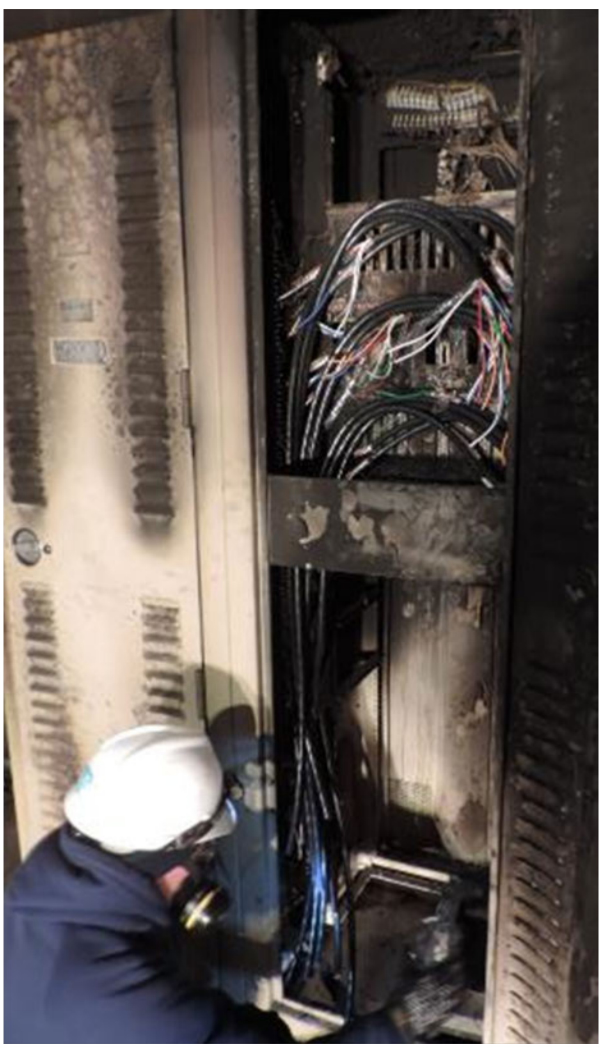
Ventilation: Door closed

Notes: This test was a repeat of Test 46 because there was a concern that the calorimetry might have been faulty in Test 46. The door was opened at 32 min. The fire spread from the right side of the enclosure to the left side following overlapping cable bundles. The fire burned halfway down the left side.

</td>
<td>



</td>
</tr>
<tr>
<td>



</td>
<td>

</td>
</tr>
</table>

Table 5-52. Summary of Test 50

<table>
<tr>
<td>

Test: 50

Enclosure: 4

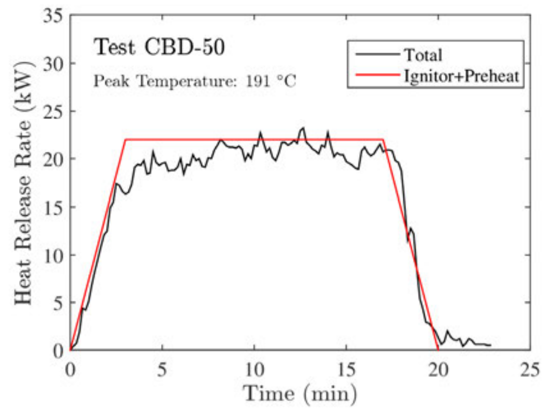
Fuel Load: Two cable bundles; one on each side. Each bundle contained 10 cables (#805), 1.8 m (6 ft) long, stripped 20 cm (8 in) near the top

Ignition Source: 1 L acetone pan fire

Ventilation: Door closed, then opened

Notes: Even though the cables were immersed in the liquid fuel, the fire did not spread upwards. The door was opened at 18 min and remained open. The acetone was exhausted at 20 min.

</td>
<td>



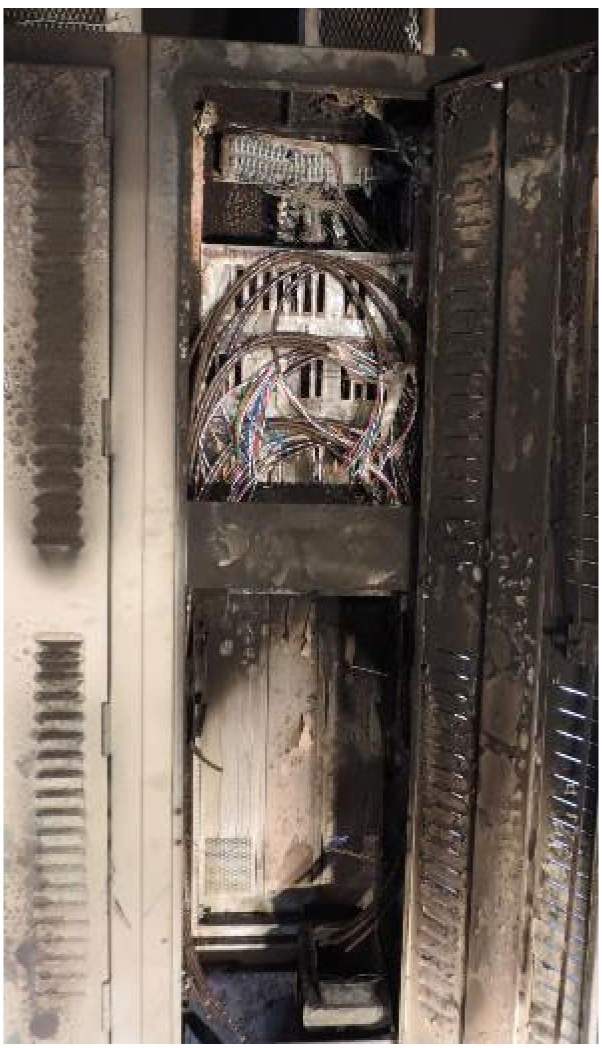
</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</table>

Table 5-53. Summary of Test 51

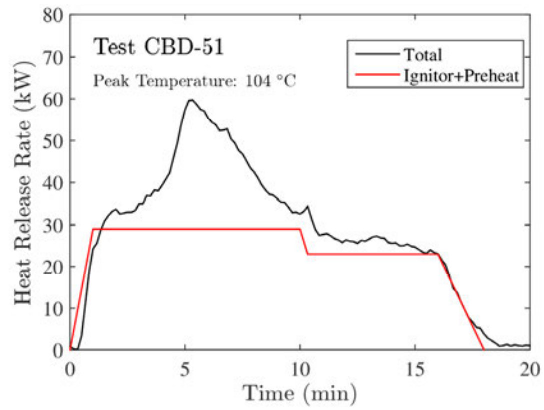
Test: 51 **Enclosure:** 4 **Fuel Load:** The unburned left side bundle from Test 50, 10 cables (#805), 1.8 m (6 ft) long, stripped 20 cm (8 in) near top **Ignition Source:** 5.5 kW propane burner and 1 L acetone pan fire **Ventilation:** Door open **Notes:** The fire spread halfway to the top of the enclosure. The propane burner was turned off at 10 min.	
	

Table 5-54. Summary of Test 52

Test: 52

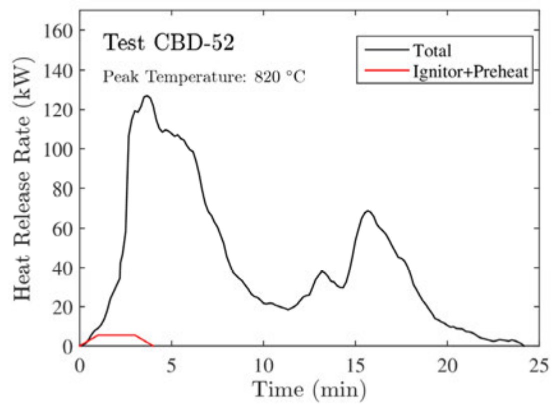
Enclosure: 4

Fuel Load: Two cable bundles; one on each side. Each bundle contained 70 insulated conductors stripped from Cable #807, 1.8 m (6 ft) long

Ignition Source: 5.5 kW propane burner

Ventilation: Door open

Notes: The fire spread upwards along the right side of the enclosure. The burner was turned off at 3 min. The second peak in HRR was due to the spread of the fire across a horizontal bundle of wire which ignited a fire on the left side.



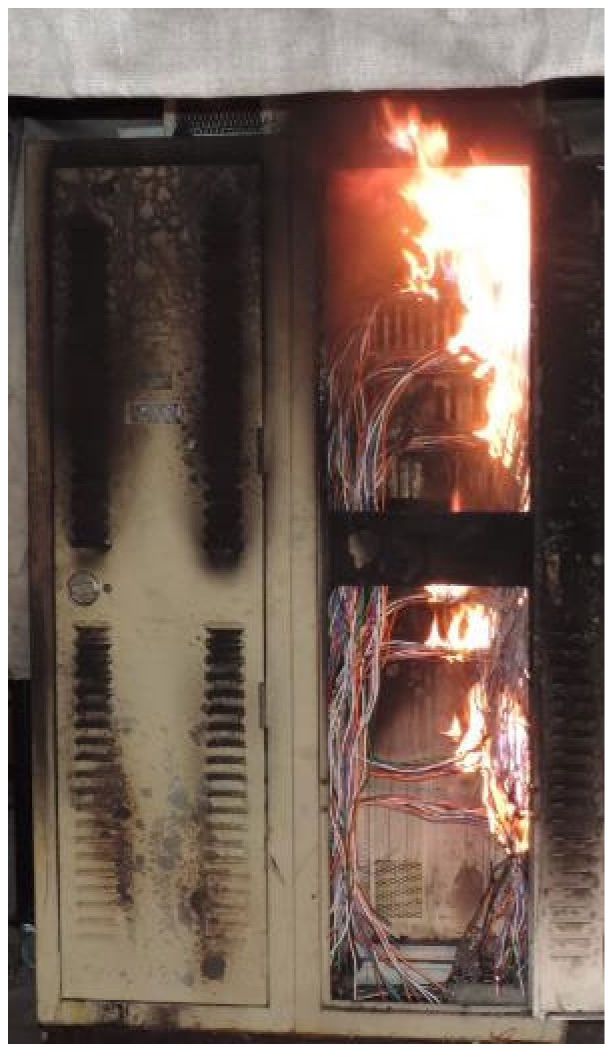


Table 5-55. Summary of Test 53

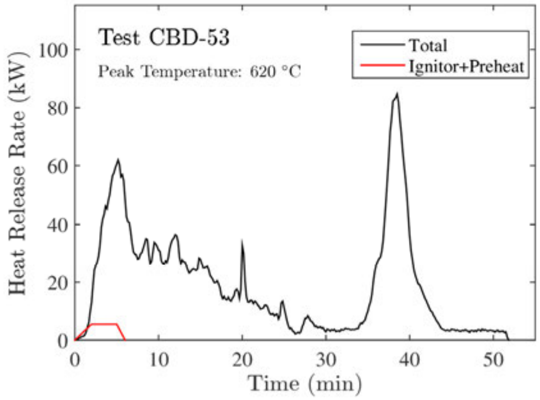
Test: 53 (A,B) **Enclosure:** 4 **Fuel Load:** Two cable bundles; one on each side. Each bundle contained 70 insulated conductors stripped from Cable #807, 1.8 m (6 ft) long **Ignition Source:** 5.5 kW propane burner **Ventilation:** Door closed, then opened **Notes:** This test was a repeat of Test 52, except with the door closed. The fire spread rapidly along the right side of the enclosure. The burner was turned off after 5 min. The door was opened at 20 min and then closed. At 30 min (B), a blow torch was used to ignite the unburned wire on the left side of the enclosure. The fire spread upwards with the door remaining open. Approximately, one-fourth of the initial fuel remained before the blow torch was applied	
	

Table 5-56. Summary of Test 54

<table>
<tr>
<td>

Test: 54

Enclosure: 4

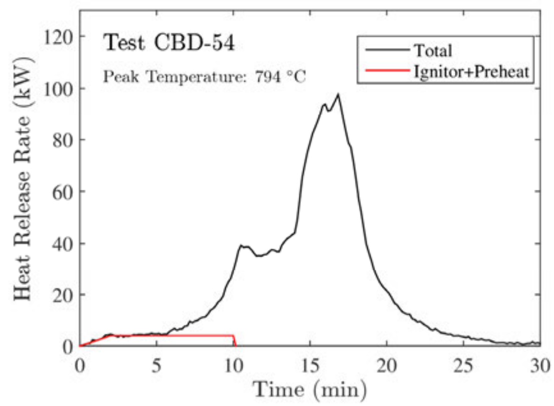
Fuel Load: 2 bundles of surplus power cord (#841); one per side; 10 cords per bundle, 1.8 m (6 ft) long

Ignition Source: 4 kW propane burner

Ventilation: Door open

Notes: The fire spread up the right side of the enclosure and then spread along the top of the enclosures where the two bundles overlapped. The burner was turned off at 10 min.

</td>
<td>



</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</table>

Table 5-57. Summary of Test 55

<table>
<tr>
<td>

Test: 55

Enclosure: 4

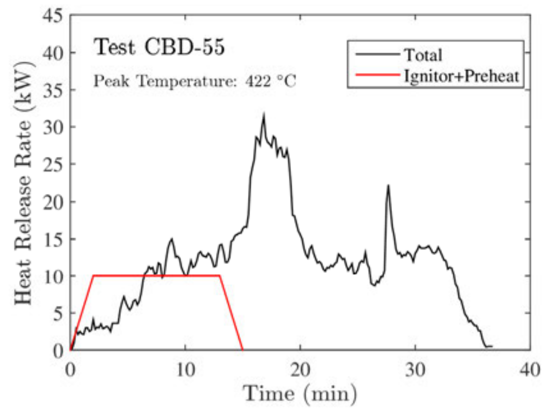
Fuel Load: 2 bundles of surplus power cord (#841), one per side, 10 cords per bundle, 1.8 m (6 ft) long

Ignition Source: 4 kW propane burner and 200 mL of acetone in a stainless steel cup 10 cm in diameter

Ventilation: Door closed, then opened

Notes: The two ignition sources were positioned beneath the two bundles, but the fire only spread upwards on the side of the propane burner. The propane burner was turned off and the acetone exhausted at 15 min. The door was opened at 27 min.

</td>
<td>



</td>
</tr>
<tr>
<td>

</td>
<td>

</td>
</tr>
</table>

Table 5-58. Summary of Test 56

<table>
<tr>
<td>

Test: 56

Enclosure: 5

Fuel Load: 10 cable bundle (#844) routed up right side of enclosure, 1.8 m (6 ft) long

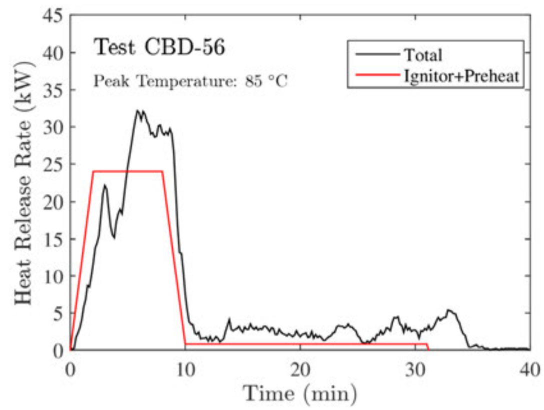
Ignition Source: 0.8 kW propane burner

Preheating Source: 500 mL acetone pan fire

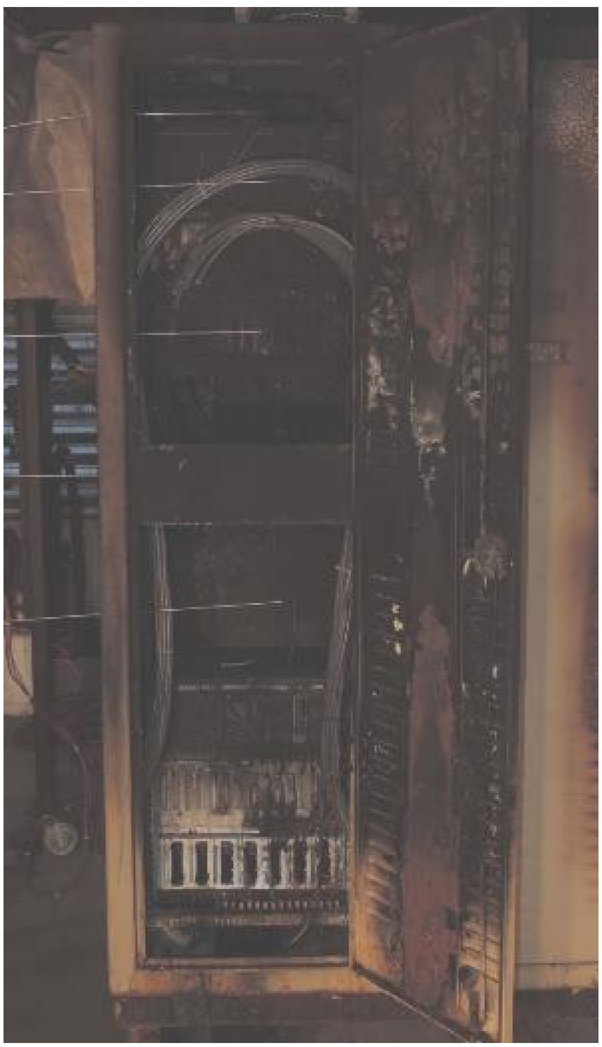
Ventilation: Door closed

Notes: The acetone pan fire was used for pre-heating only and burned for about 10 min, at which time the propane burner was turned on. The propane burner was turned off at 31 min. The door was opened several times and the cables were jostled with a crowbar (photo, lower right). The fire did not spread beyond the vicinity of the burner.

</td>
<td>



</td>
</tr>
<tr>
<td>



</td>
<td>

</td>
</tr>
</table>

Table 5-59. Summary of Test 57

<table>
<tr>
<td>

Test: 57

Enclosure: 5

Fuel Load: 10 cable bundle (#844) routed up left side of enclosure, 1.8 m (6 ft) long

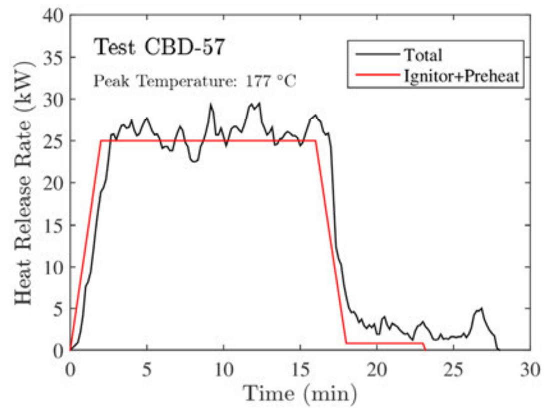
Ignition Source: 0.8 kW propane burner

Preheating Source: 1 L acetone pan fire

Ventilation: Door closed

Notes: The acetone pan fire was used for pre-heating only and burned for about 18 min. The propane burner was lit at the start of the test. The propane burner was turned off at 23 min. The fire did not spread beyond the vicinity of the propane burner.

</td>
<td>



</td>
</tr>
<tr>
<td>

</td>
<td>

</td>
</tr>
</table>

Table 5-60. Summary of Test 58

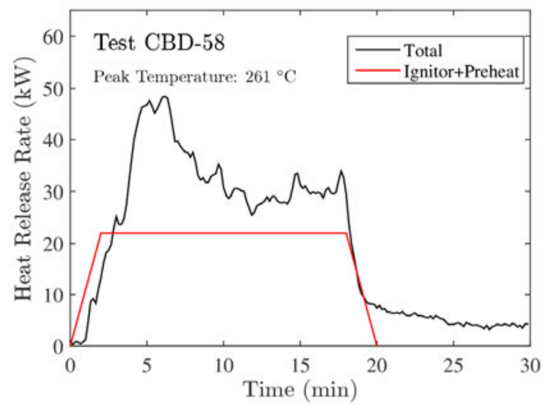
Test: 58 **Enclosure:** 5 **Fuel Load:** 10 jacketed cables and 10 stripped cables (#844), 1.8 m (6 ft) long. The jacketed cable was left over from Tests 56 and 57. **Ignition Source:** 0.8 kW propane burner **Preheating Source:** 1 L acetone pan fire **Ventilation:** Door closed **Notes:** The acetone pan fire burned for about 17 min, at which point the propane burner was turned off. The fire spread to the top of the bundle, burning mainly the stripped cable.	
	

Table 5-61. Summary of Test 59

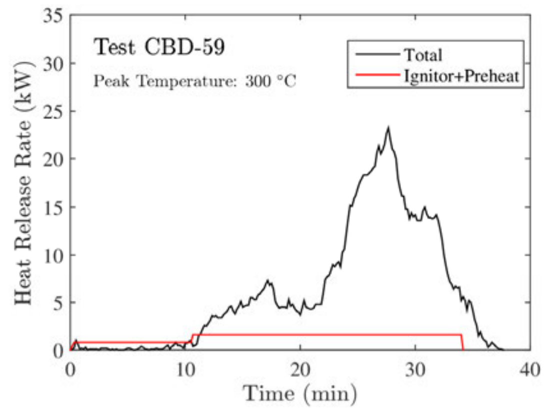
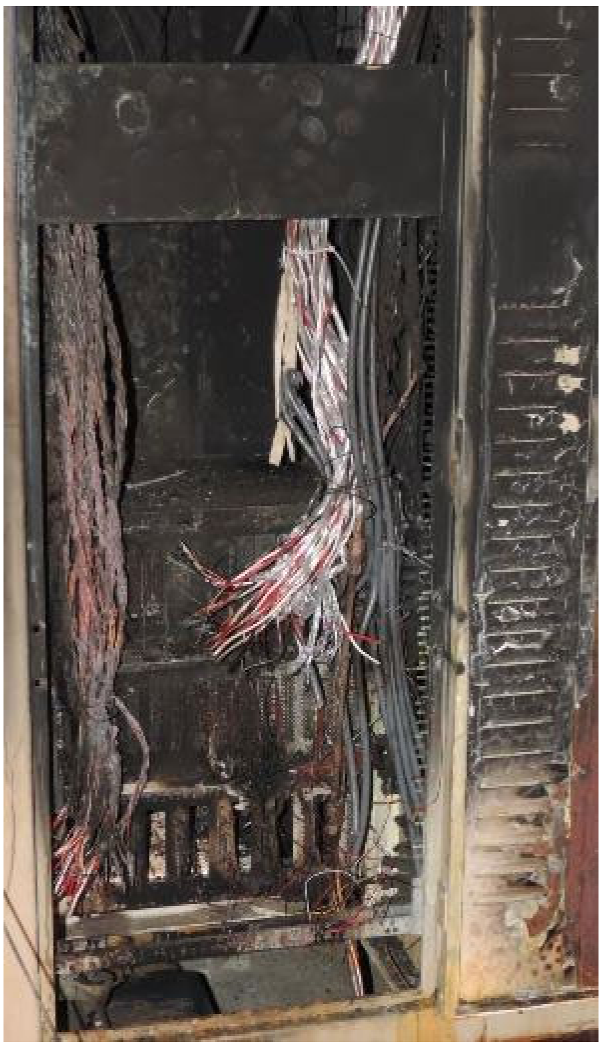
Test: 59 (A,B) **Enclosure:** 5 **Fuel Load:** 10 jacketed cables and 10 stripped cables (#844), 1.8 m (6 ft) long. The jacketed cable was left over from Tests 56 and 57. **Ignition Source:** 0.8 kW propane burner **Ventilation:** Door open **Notes:** The propane burner was increased to 2 kW after 10 min, 30 s, at which point the fire began to spread upwards, extending about 60 cm above the burner by 20 min. At 21 min (B), the cable bundle was loosened with a crowbar, and the fire spread to the top of the enclosure. The burner was turned off at 34 min.	
	

Table 5-62. Summary of Test 60

<table>
<tr><td>

Test: 60

Enclosure: 1

Fuel Load: 72 cables (#844) of various lengths, 73 m (240 ft) total

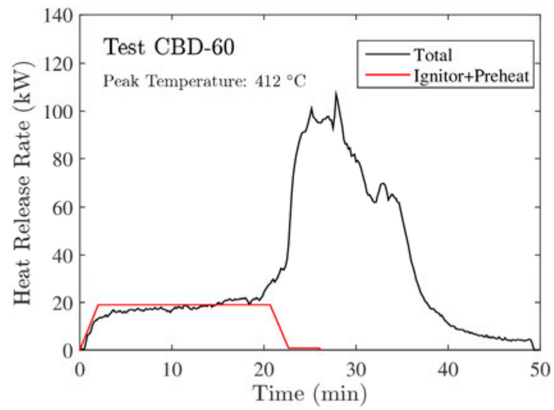
Ignition Source: 0.8 kW propane burner

Preheating Source: 1 L acetone pan fire

Ventilation: Door closed

Notes: The acetone pan fire was placed in the back of the enclosure, behind a steel partition. The acetone was exhausted at 22 min, 40 s. The propane burner was turned off at 26 min.

</td><td>



</td></tr>
<tr><td>

</td><td>

</td></tr>
</table>

Table 5-63. Summary of Test 61

<table>
<tr>
<td>

Test: 61

Enclosure: 1

Fuel Load: 60 cables (#807) of various lengths; 63 m (208 ft) total

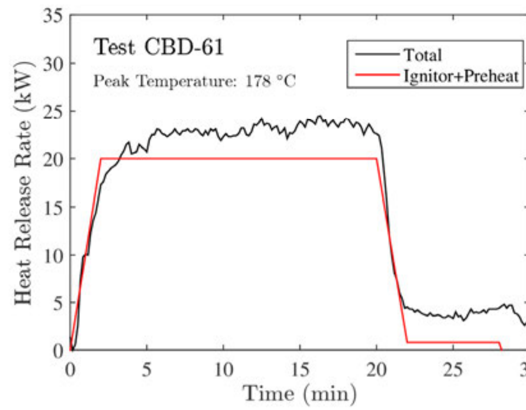
Ignition Source: 0.8 kW propane burner

Preheating Source: 1 L acetone pan fire

Ventilation: Door closed

Notes: The acetone pan was placed at the back of the enclosure behind a steel partition, and it burned for 20 min. At 21 min, the cables were jostled with a crowbar. At 25 min, the door was opened. The propane burner was turned off at 28 min. The fire did not spread beyond the vicinity of the propane burner. No appreciable combustible material lost.

</td>
<td>



</td>
</tr>
<tr>
<td>

</td>
<td>

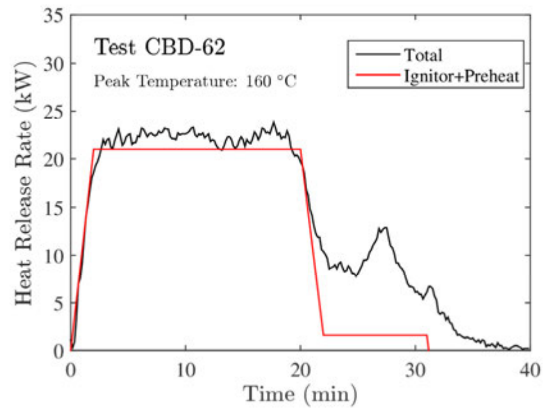
</td>
</tr>
</table>

Table 5-64. Summary of Test 62

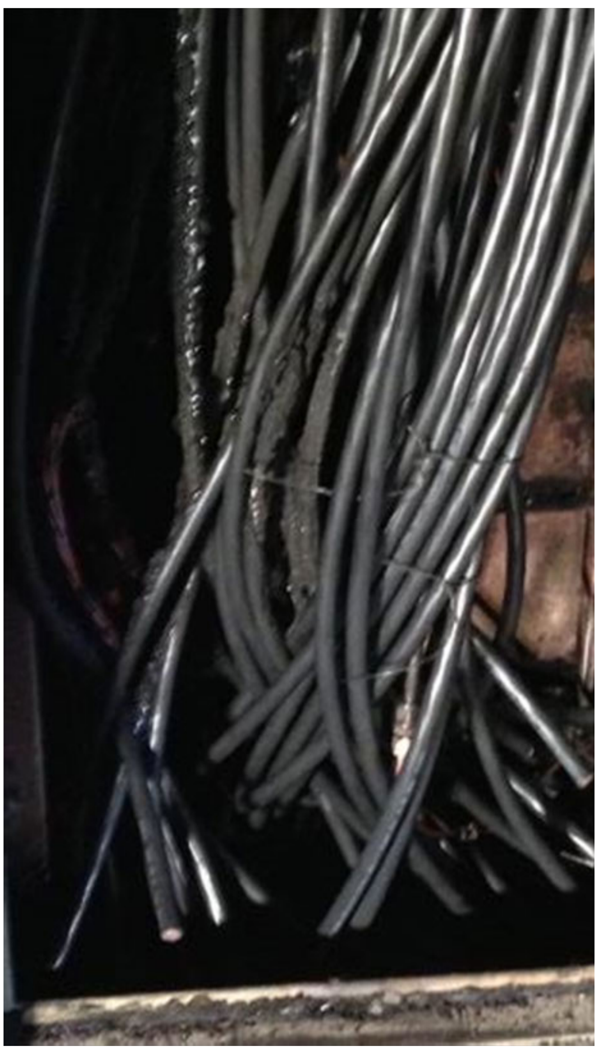
<table>
<tr>
<td>

Test: 62
Enclosure: 1
Fuel Load: 60 cables (#807) of various lengths; 63 m (208 ft) total
Ignition Source: 1.6 kW propane burner
Preheating Source: 1 L acetone pan fire
Ventilation: Door closed
Notes: The acetone pan was placed at the back of the enclosure behind a steel partition, and it burned for 20 min. At 30 min, the door was opened. The propane burner was turned off at 31 min. The fire did not spread beyond the vicinity of the propane burner.

</td>
<td>



</td>
</tr>
<tr>
<td>



</td>
<td>

No picture available

</td>
</tr>
</table>

Table 5-65. Summary of Test 63

Test: 63

Enclosure: 1

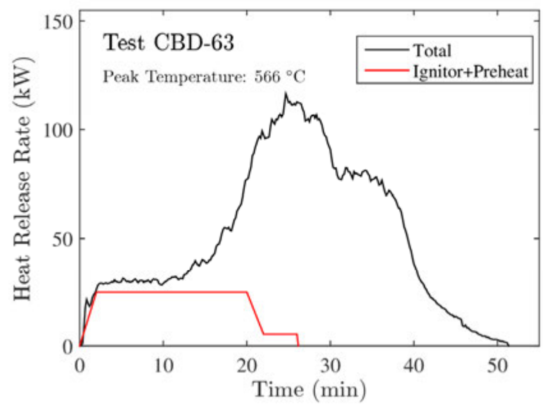
Fuel Load: 60 cables (#807) of various lengths; 63 m (208 ft) total

Ignition Source: 5.5 kW propane burner

Preheating Source: 1 L acetone pan fire

Ventilation: Door closed

Notes: The acetone pan was placed at the back of the enclosure behind a steel partition, and it burned for 20 min. The propane burner was turned off at 26 min. The door was opened at 46 min and it was observed that all the cables had burned.



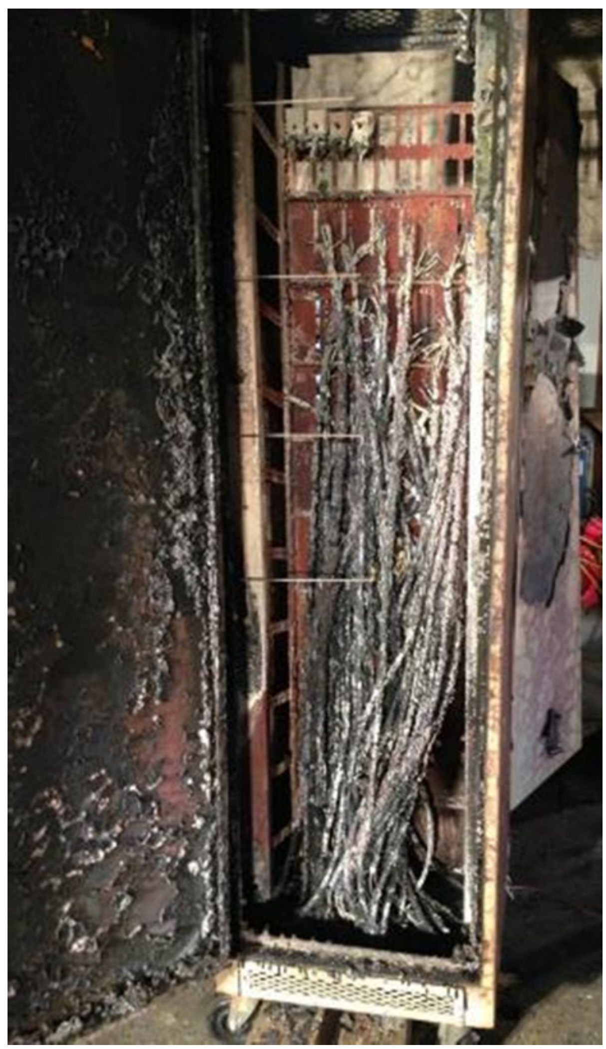
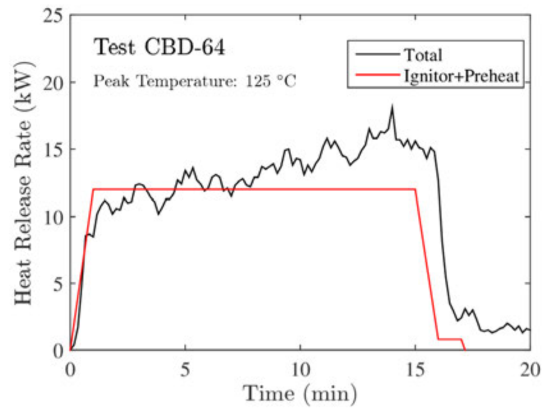


Table 5-66. Summary of Test 64

<table>
<tr>
<td>
Test: 64
Enclosure: 8
Fuel Load: 21 cables (#813), each 1.8 m (6 ft) long, routed through channels in top of enclosure and onto a cable tray 30 cm (1 ft) above
Ignition Source: 0.8 kW propane burner
Preheating Source: 500 mL acetone pan fire
Ventilation: Door closed
Notes: The acetone pan was placed at the back of the enclosure such that the fire did not directly impinge on cables. The acetone was exhausted at 16 min, at which time the door was opened. The propane burner was turned off at 17 min. The fire did not spread beyond the propane burner. No appreciable combustible mass lost.
</td>
<td>


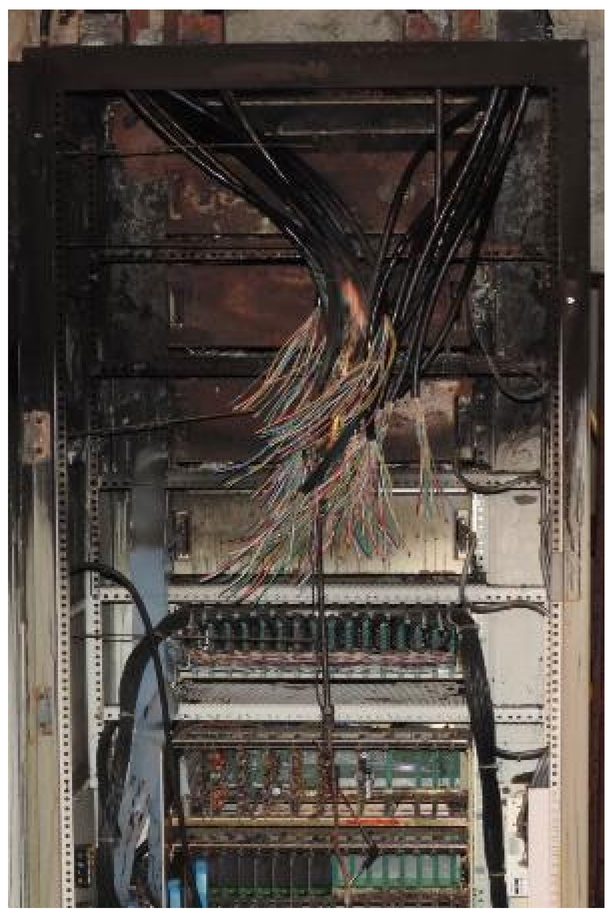
</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</table>

Table 5-67. Summary of Test 65

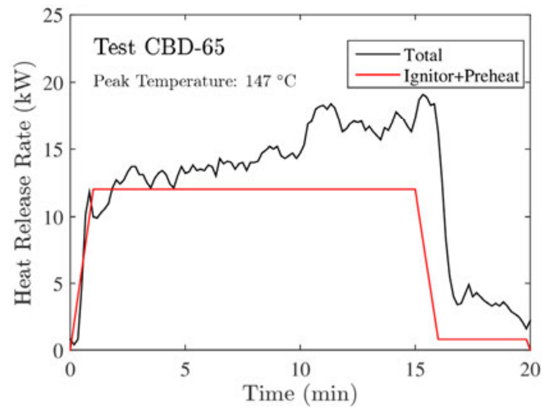
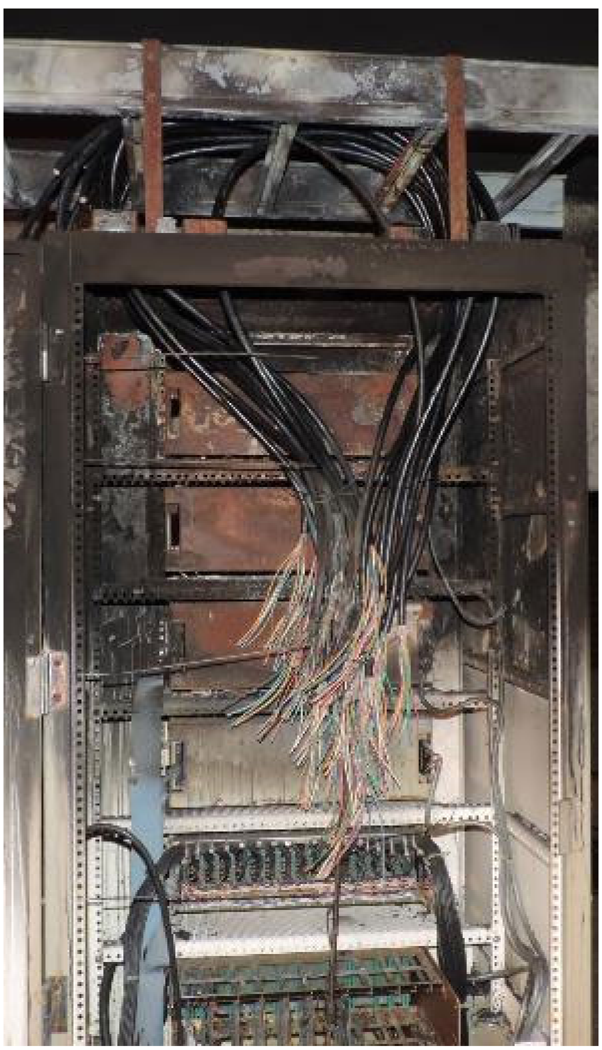
Test: 65 **Enclosure:** 8 **Fuel Load:** Same as Test 64 **Ignition Source:** 0.8 kW propane burner **Preheating Source:** 500 mL acetone pan fire **Ventilation:** Door closed **Notes:** The acetone pan was placed at the back of the enclosure and the fire did not directly impinge on cables. The acetone was exhausted at 16 min. The propane burner was turned off at 20 min. The fire did not spread beyond igniter. No appreciable combustible mass lost.	
	

Table 5-68. Summary of Test 66

Test: 66 (A,B)

Enclosure: 4

Fuel Load: 20 cable bundle (#844), 1.8 m (6 ft) long, routed up right side of enclosure

Ignition Source: 5.5 kW propane burner

Preheating Source: 1 L acetone pan fire

Ventilation: Door closed then opened

Notes: The acetone pan was placed at the rear of the enclosure, out of direct contact with the cables. The acetone was exhausted at 17 min, and the propane burner was turned off at 18 min. At 23 min (B), the door was opened and the cables were jostled with a crowbar. The fire then spread to within 30 cm (1 ft) of top.

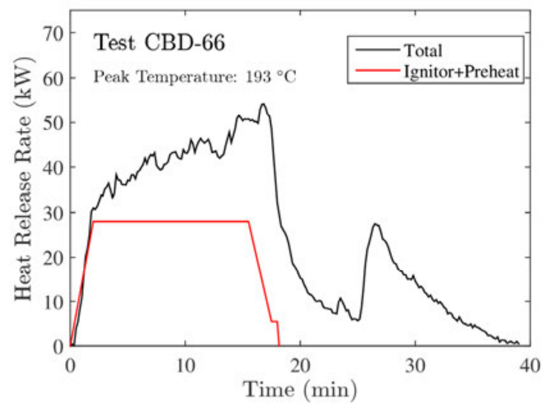
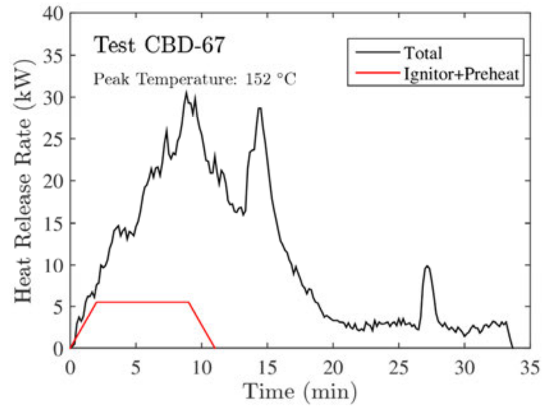


Table 5-69. Summary of Test 67

<table>
<tr>
<td>

Test: 67 (A,B)
Enclosure: 4
Fuel Load: 20 cable bundle (#844); 1.8 m (6 ft) long, routed up left side of enclosure
Ignition Source: 5.5 kW propane burner
Ventilation: Door closed, then open
Notes: The propane burner was turned off at 9 min. At 13 min (B), the door was opened and the cables were jostled with a crowbar. The fire then spread to within 30 cm (1 ft) of the top of the bundle.

</td>
<td>



</td>
</tr>
<tr>
<td>

</td>
<td>

</td>
</tr>
</table>

Table 5-70. Summary of Test 68

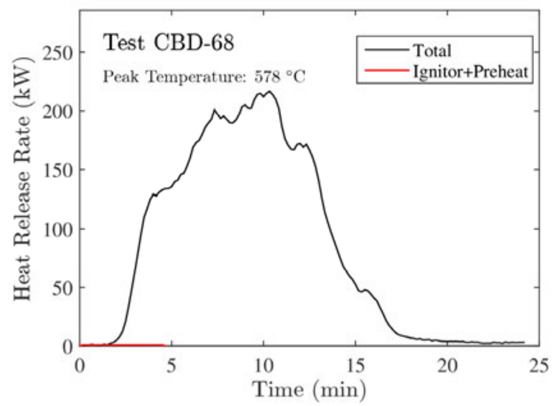
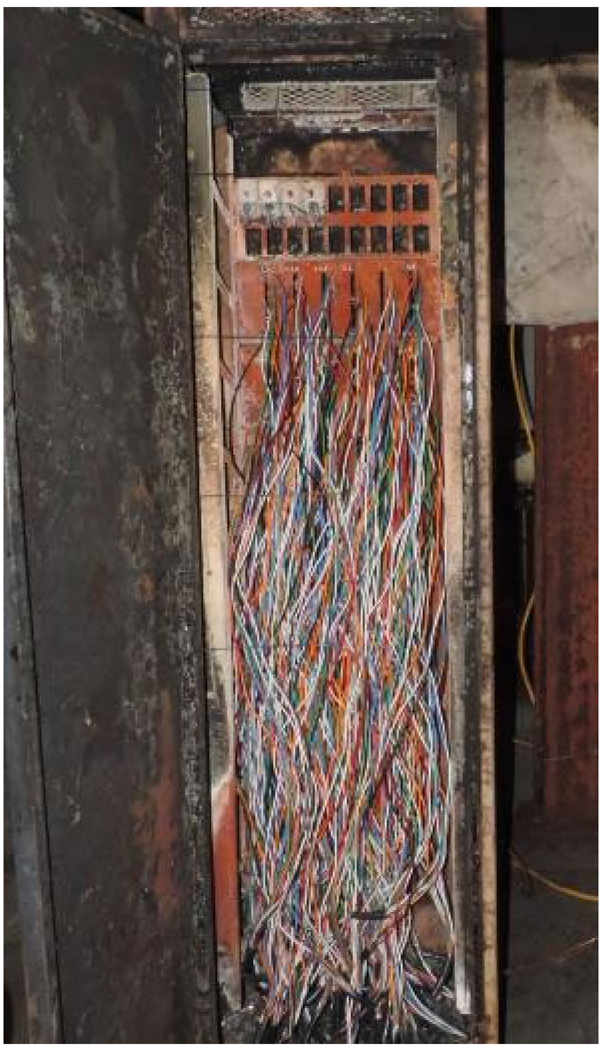
Test: 68 **Enclosure:** 1 **Fuel Load:** 420 insulated conductors extracted from Cable #807; 540 m (1770 ft) total **Ignition Source:** 0.8 kW propane burner **Ventilation:** Door closed **Notes:** The burner was turned off at 4 min, 30 s. The door was opened at 15 min and it was observed that all the cable had burned.	
	

Table 5-71. Summary of Test 69

<table>
<tr>
<td>

Test: 69

Enclosure: 8

Fuel Load: 21 cables, 1.8 m (6 ft) long, routed through conduits in top of enclosure onto a cable tray

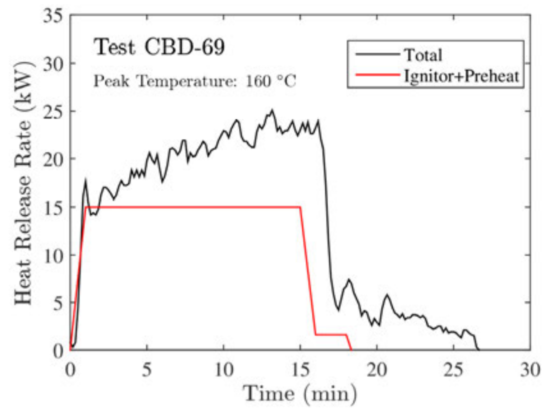
Ignition Source: 1.6 kW propane burner

Preheating Source: 500 mL acetone pan fire

Ventilation: Door closed

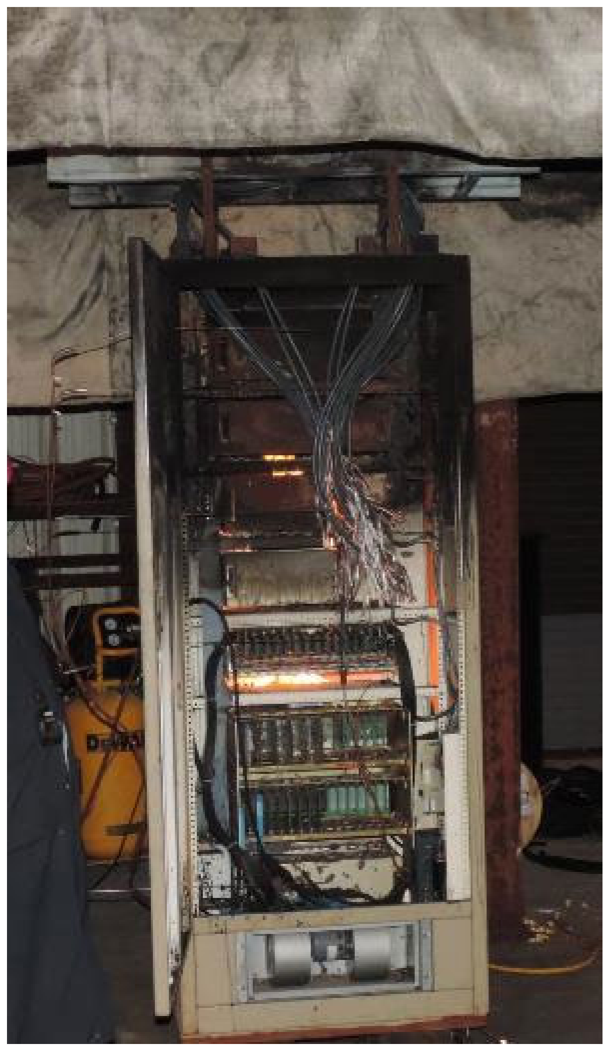
Notes: The acetone pan was located in the rear of the enclosure and did not directly impinge on the cables. The acetone was exhausted in 16 min. The door was opened at 17 min and the propane was turned off at 18 min. The fire did not spread beyond vicinity of igniter.

</td>
<td>



</td>
</tr>
<tr>
<td>

</td>
<td>



</td>
</tr>
</table>

Table 5-72. Summary of Test 70

<table>
<tr>
<td>

Test: 70

Enclosure: 1

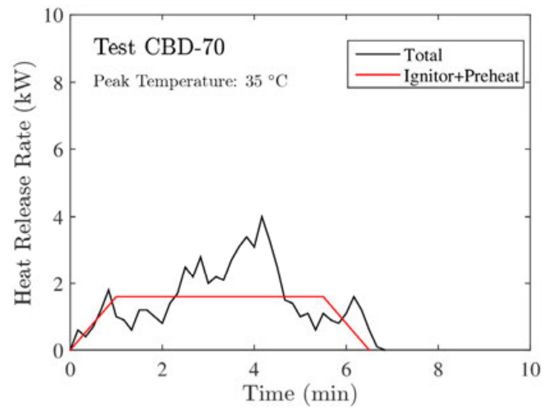
Fuel Load: 420 insulated conductors extracted from Cable #834; 540 m (1770 ft) total

Ignition Source: 1.6 kW propane burner

Ventilation: Door closed

Notes: The door was opened at 5 min, 30 s and left open. The propane was turned off at this time. The fire did not spread beyond the vicinity of the igniter. No appreciable combustible mass lost.

</td>
<td>



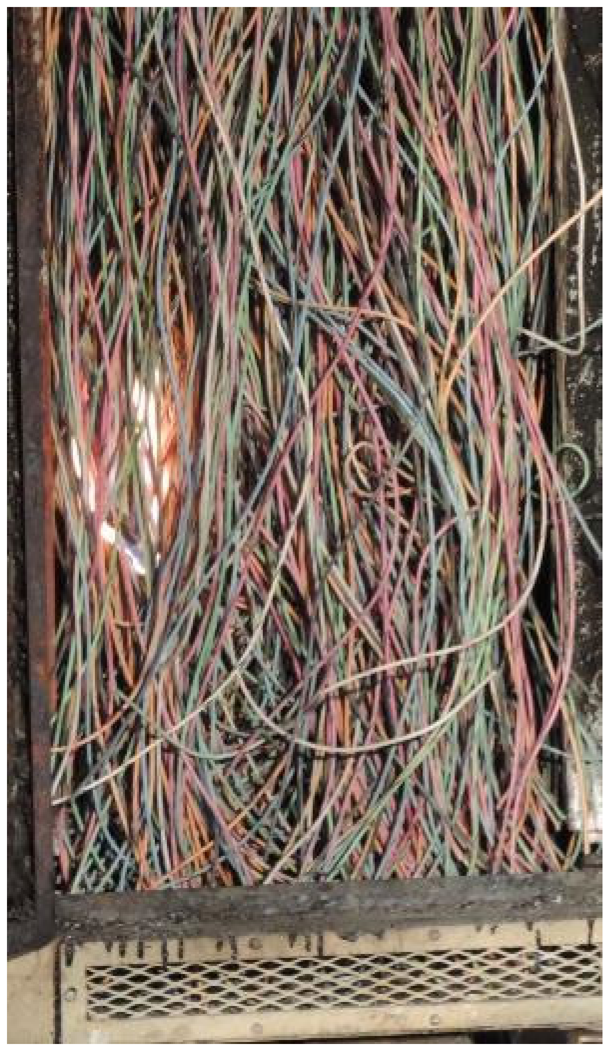
</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</table>

Table 5-73. Summary of Test 71

Test: 71
Enclosure: 1
Fuel Load: Same as Test 70
Ignition Source: 5.5 kW propane burner
Preheating Source: 1 L acetone pan fire
Ventilation: Door closed
Notes: The acetone pan was placed in the rear of the enclosure, behind a steel partition. The acetone was exhausted at 18 min. The propane was turned off at 18 min. The door was opened at 23 min, when it was observed that the cables were completely burned.

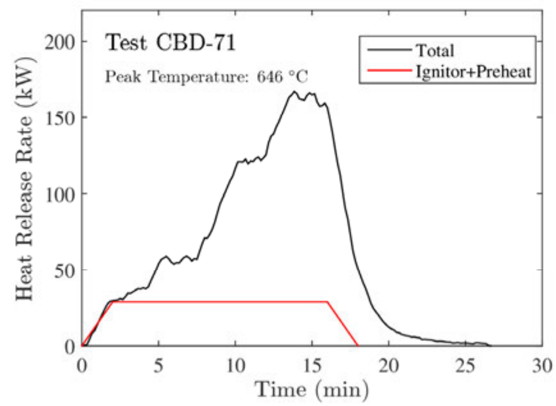


Table 5-74. Summary of Test 72

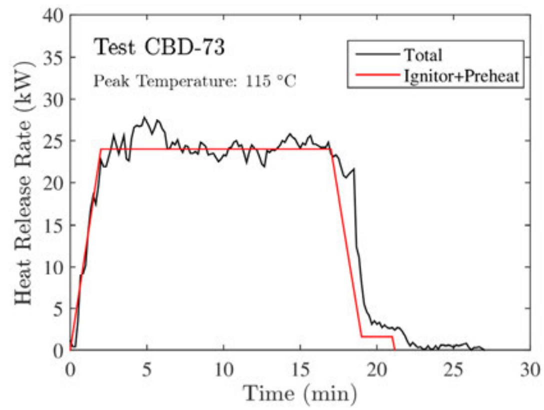
Test: 72 **Enclosure:** 4 **Fuel Load:** 10 cable bundle (#813), 1.8 m (6 ft) long **Ignition Source:** 0.8 kW propane burner **Ventilation:** Door closed, then opened **Notes:** The door was opened at 12 min and the cables were jostled with a crowbar. The propane was turned off at 16 min. The fire did not spread beyond the vicinity of the burner. The HRR oxygen measurement malfunctioned during this experiment, and it is assumed that the HRR is only that of the ignition source.	The oxygen consumption calorimeter malfunctioned. No HRR data available.
	

Table 5-75. Summary of Test 73

<table>
<tr>
<td>

Test: 73
Enclosure: 4
Fuel Load: 10 cable bundle (#813), 1.8 m (6 ft) long
Ignition Source: 1.6 kW propane burner
Preheating Source: 1 L acetone pan fire
Ventilation: Door closed, then opened
Notes: The acetone pan fire did not directly impinge upon the cables. The acetone was exhausted at 19 min, at which time the door was opened and the cables were jostled with a crowbar. The door remained open. The propane burner was turned off at 21 min. The fire spread approximately 45 cm (18 in) above the burner.

</td>
<td>



</td>
</tr>
<tr>
<td>

</td>
<td>

</td>
</tr>
</table>

Table 5-76. Summary of Test 74

<table>
<tr>
<td>

Test: 74

Enclosure: 5

Fuel Load: 10 cable bundle (#809), 1.8 m (6 ft) long

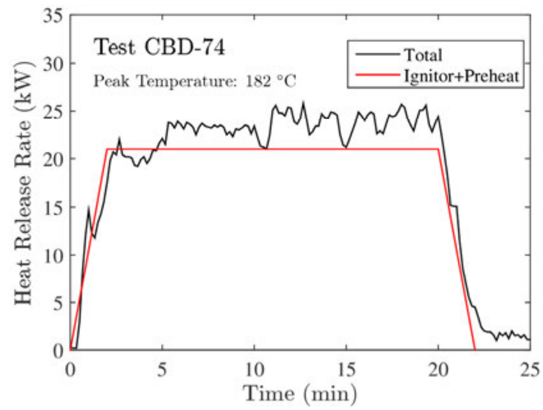
Ignition Source: 1.6 kW propane burner

Preheating Source: 1 L acetone pan fire

Ventilation: Door closed, then opened

Notes: The acetone pan fire did not directly impinge upon the cables. The acetone was exhausted at 22 min, at which time the door was opened and remained open. The propane burner was turned off at 22 min. The fire spread approximately 60 cm (2 ft) above the burner.

</td>
<td>



</td>
</tr>
<tr>
<td>

</td>
<td>

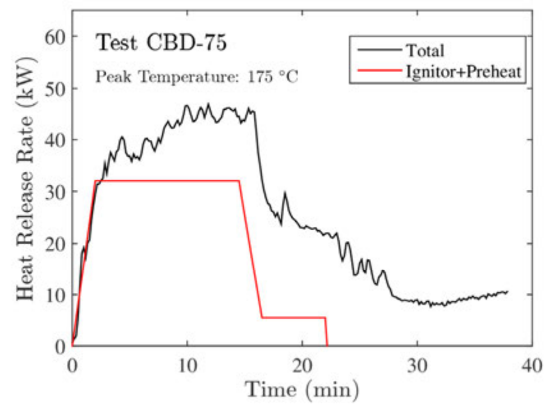
</td>
</tr>
</table>

Table 5-77. Summary of Test 75

<table>
<tr>
<td>

Test: 75
Enclosure: 4
Fuel Load: 10 cable bundle (#813), 1.8 m (6 ft) long
Ignition Source: 5.5 kW propane burner
Preheating Source: 1 L acetone pan fire
Ventilation: Door closed, then opened
Notes: The acetone pan fire did not directly impinge upon the cables. The acetone was exhausted at 16 min, 30 s. The door was open at 18 min and left open. The propane was turned off at 22 min, 30 s. The fire spread 0.9 m (3 ft) above the burner.

</td>
<td>



</td>
</tr>
<tr>
<td>

</td>
<td>

</td>
</tr>
</table>

Table 5-78. Summary of Test 76

Test: 76

Enclosure: 5

Fuel Load: 10 cable bundle (#813), 1.8 m (6 ft) long

Ignition Source: 1 L acetone pan fire

Ventilation: Door closed and opened multiple times

Notes: The acetone pan was placed directly under the cable bundle so that the ends of the cables were immersed in the liquid. The door was opened at 8 min, 30 s and then closed 30 s later. The door was opened again at 17 min and the cables were jostled with a crowbar. The acetone was exhausted at 19 min. The fire never spread beyond the vicinity of the acetone flames.

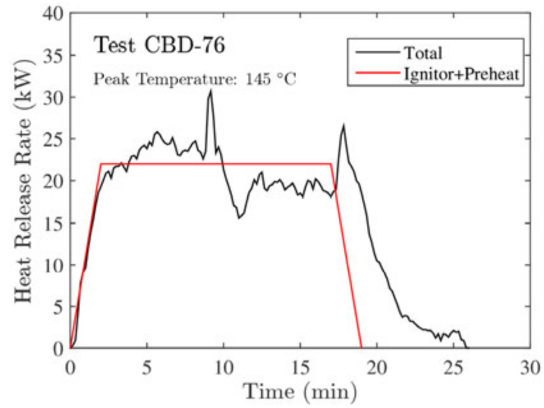


Table 5-79. Summary of Test 77

Test: 77 (A,B)

Enclosure: 5

Fuel Load: 10 cable bundle (#809), 1.8 m (6 ft) long

Ignition Source: 5.5 kW propane burner

Preheating Source: 1 L acetone pan fire

Ventilation: Door closed, then opened

Notes: The acetone pan fire did not directly impinge upon the cables. The door was opened at 16 min, 30 s (B), and was left open until 28 min. The propane burner was turned off at 18 min and the acetone was exhausted at 18 min, 30 s. Over the next 20 min, the fire spread slowly upwards, with occasional door openings and jostling with a crowbar.

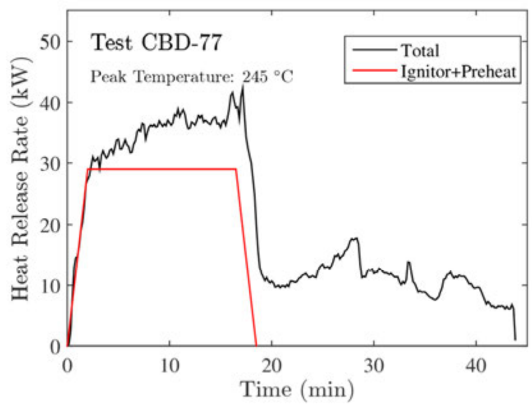


Table 5-80. Summary of Test 78

Test: 78 (A,B)

Enclosure: 5

Fuel Load: 10 cable bundle (#809), 1.8 m (6 ft) long

Ignition Source: 5.5 kW propane burner

Ventilation: Door closed, then opened

Notes: The fire spread steadily to the top of the bundle. The burner was turned off at 15 min. The door was opened at 12 min 30 sec (B), and remained open.

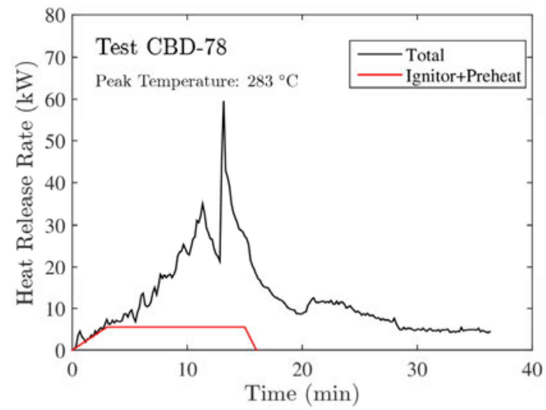


Table 5-81. Summary of Test 79

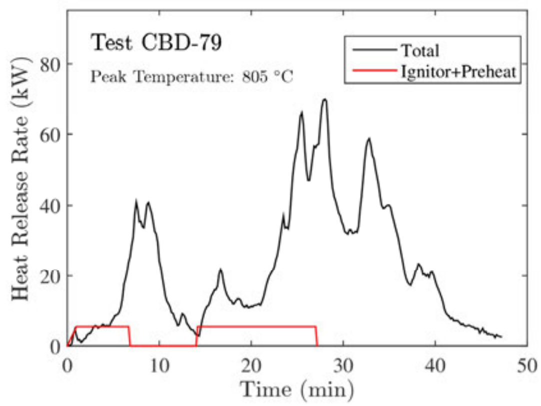
Test: 79 (A,B) **Enclosure:** 4 **Fuel Load:** 310 insulated wires stripped from Cable #834, 1.8 m (6 ft) long, arranged in 4 loose bundles **Ignition Source:** 5.5 kW propane burner **Ventilation:** Door closed, then opened **Notes:** The propane burner was turned off at 6 min, 40 s. The door was opened at 12 min (B). The propane burner was relit at 14 min and the door was left open. The wires were jostled at 19 min with a crowbar, after which the fire spread to the top of the bundle. The propane burner was turned off at 27 min.	
	

Table 5-82. Summary of Test 80

<table>
<tr>
<td>

Test: 80 (A,B)

Enclosure: 4

Fuel Load: 70 insulated wires (#834), arranged in 2 loose bundles along right side of enclosure

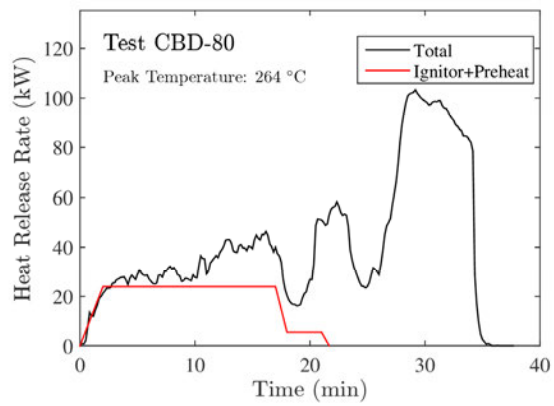
Ignition Source: 5.5 kW propane burner

Preheating Source: 1 L acetone pan fire

Ventilation: Door closed, then opened

Notes: The acetone pan fire did not directly impinge upon the wires. The propane burner was initially set to 1 kW and then increased to 5.5 kW at 17 min, 30 s. The door was opened at 10 min and a crowbar was used. The door was opened again at 20 min. The acetone was exhausted at 18 min (B), and the propane burner was turned off at 21 min. The fire spread to the top of the bundles.

</td>
<td>



</td>
</tr>
<tr>
<td>

</td>
<td>

</td>
</tr>
</table>

Table 5-83. Summary of Test 81

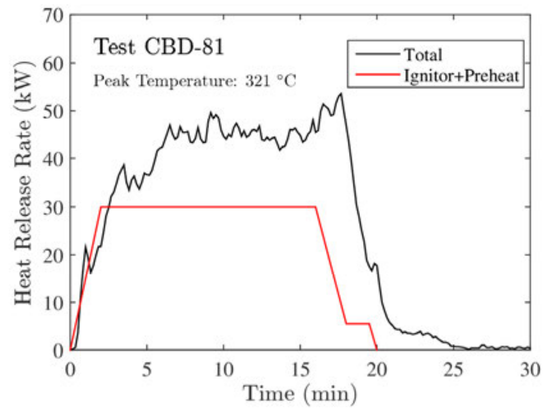
Test: 81 **Enclosure:** 5 **Fuel Load:** 10 cable bundle (#813), 1.8 m (6 ft) long **Ignition Source:** 5.5 kW propane burner and 1 L acetone pan fire **Ventilation:** Door closed, then opened **Notes:** The acetone pan fire was placed near the base of the cable bundle. The acetone was exhausted at 18 min. The door was opened at 19 min and the propane burner was turned off at 19 min, 30 s. The fire spread approximately 30 cm (1 ft) above burner.	
	

Table 5-84. Summary of Test 82

<table>
<tr>
<td>

Test: 82 (A,B)

Enclosure: 1

Fuel Load: 72 cables (#844) of various lengths; 73 m (240 ft) total

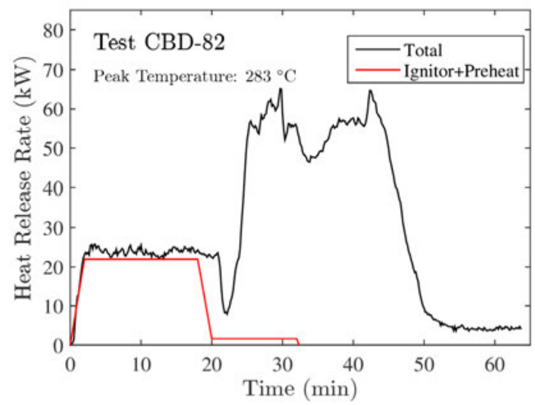
Ignition Source: 1.6 kW propane burner

Preheating Source: 1 L acetone pan fire

Ventilation: Door closed, then opened

Notes: The acetone pan was placed in the rear of the compartment behind a steel partition. The acetone was exhausted at 20 min, at which time the propane burner was increased from 0.8 kW to 1.6 kW. The door was opened at 22 min (B) and left open. The propane burner was turned off at 32 min.

</td>
<td>



</td>
</tr>
<tr>
<td>

</td>
<td>

</td>
</tr>
</table>

Table 5-85. Summary of Test 83

<table>
<tr>
<td>

Test: 83

Enclosure: 1

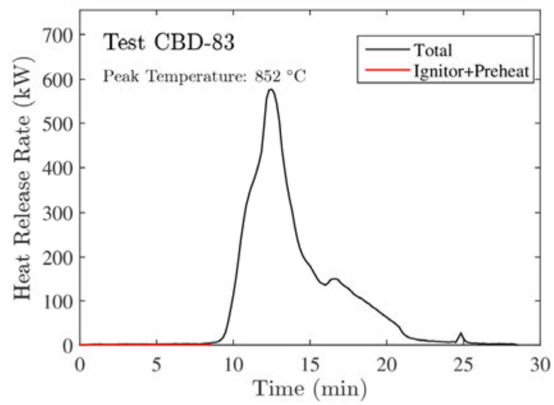
Fuel Load: 420 loose, insulated wires of various lengths, stripped from Cable #807. 540 m (1768 ft) total

Ignition Source: 0.8 kW propane burner

Ventilation: Door open

Notes: This experiment was similar to Test 68, but with the door open. The fire spread rapidly upwards after a roughly 10 min warm-up period.

</td>
<td>



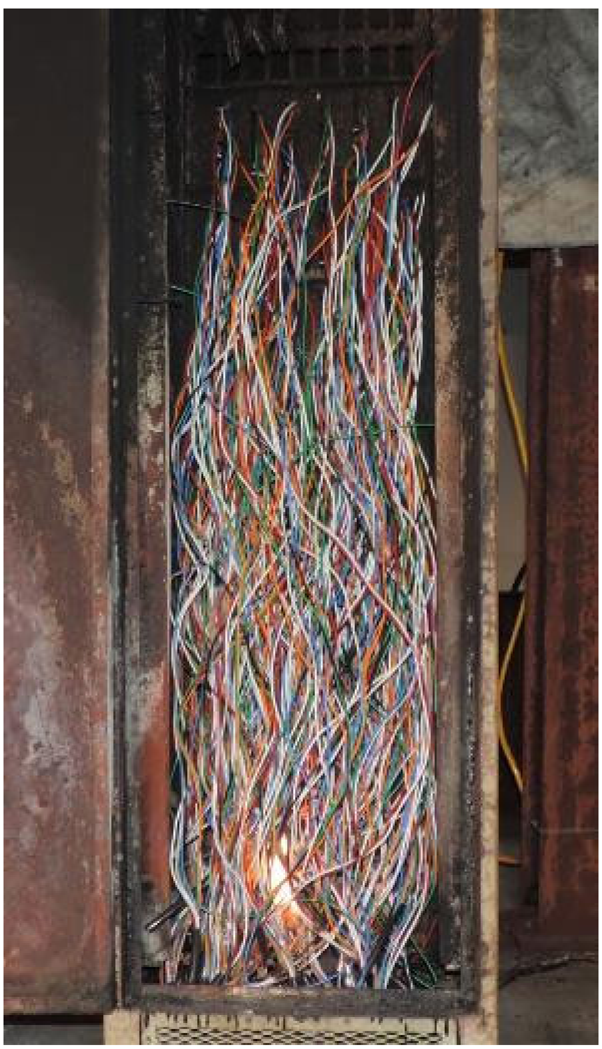
</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</table>

Table 5-86. Summary of Test 84

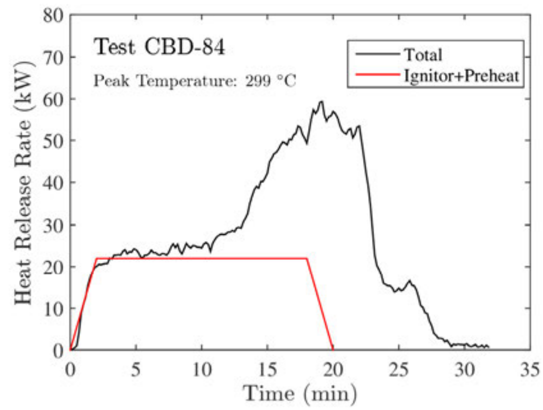
Test: 84 **Enclosure:** 7 **Fuel Load:** 36 cable bundle (#818), 2.4 m (8 ft) long **Ignition Source:** 0.8 kW propane burner **Preheating Source:** 1 L acetone pan fire **Ventilation:** Door open **Notes:** The acetone pan fire did not directly impinge on the cables. The burner was placed within a coiled bundle of cable inside of a small box whose front panel had been removed. The fire eventually spread upwards through access holes in the top of the box. The fire reached the top of the enclosure but did not spread horizontally.	
	

Table 5-87. Summary of Test 85

<table>
<tr>
<td>

Test: 85

Enclosure: 7

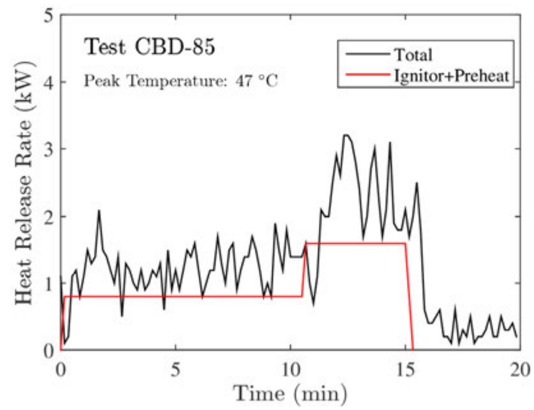
Fuel Load: 10 cables (#817) routed up the left side of the enclosure, 2.4 m (8 ft) long

Ignition Source: 0.8 kW propane burner

Ventilation: Door closed

Notes: The cables originated in a small box whose side panel had been removed. The propane burner was tied to the cables inside of the enclosure. The burner was increased to 1.6 kW at 10 min, 30 s. The burner was turned off at 15 min. No appreciable combustible mass lost.

</td>
<td>



</td>
</tr>
<tr>
<td>

</td>
<td>

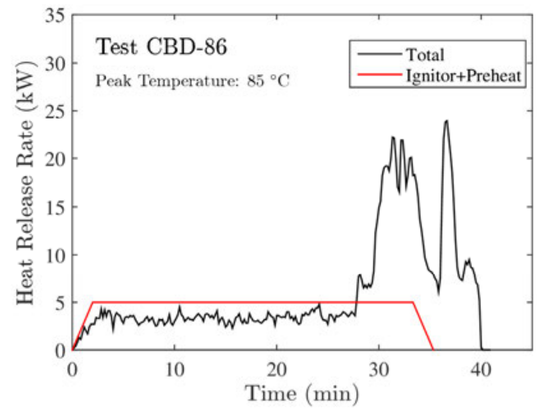
</td>
</tr>
</table>

Table 5-88. Summary of Test 86

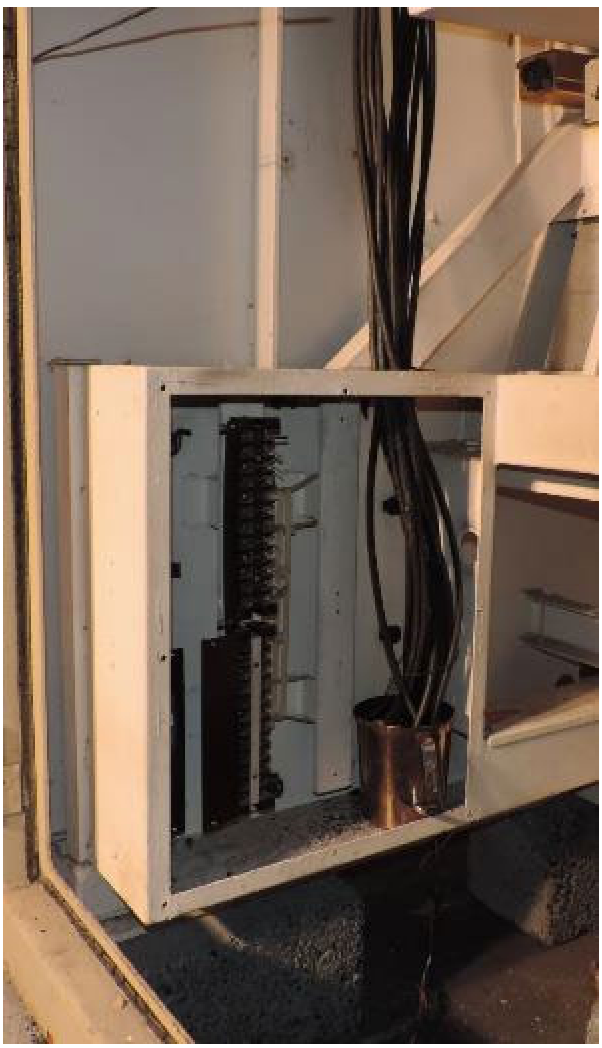
<table>
<tr>
<td>

Test: 86 (A,B)
Enclosure: 7
Fuel Load: Same as Test 85
Ignition Source: 500 mL acetone pan fire
Ventilation: Door open
Notes: The acetone was poured into a stainless steel beaker with a 10 cm (4 in) opening. The cables inside the small box burned, but the fire did not spread through the conduits at the top. The cables were jostled with a crowbar at 27 min 30 sec (B), 29 min, and 31 min.

</td>
<td>



</td>
</tr>
<tr>
<td>



</td>
<td>

</td>
</tr>
</table>

Table 5-89. Summary of Test 87

<table>
<tr>
<td>

Test: 87

Enclosure: 7

Fuel Load: 36 cables (#818), 2.4 m (8 ft) long, routed up left right side of enclosure

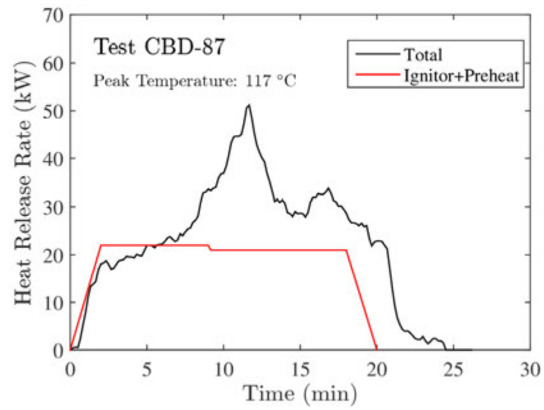
Ignition Source: 0.8 kW propane burner

Preheating Source: 1 L acetone pan fire

Ventilation: Door closed

Notes: The acetone pan fire did not directly impinge upon the cables. The propane burner was turned off at 9 min. The door was opened at 21 min, 20 s, at which time the fire was out. The cable burned 1.2 m (4 ft) above the burner.

</td>
<td>



</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</table>

Table 5-90. Summary of Test 88

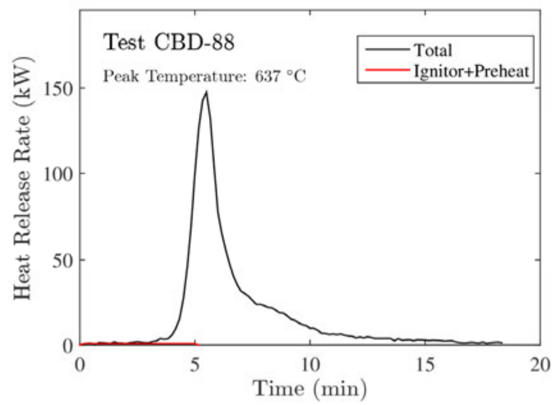
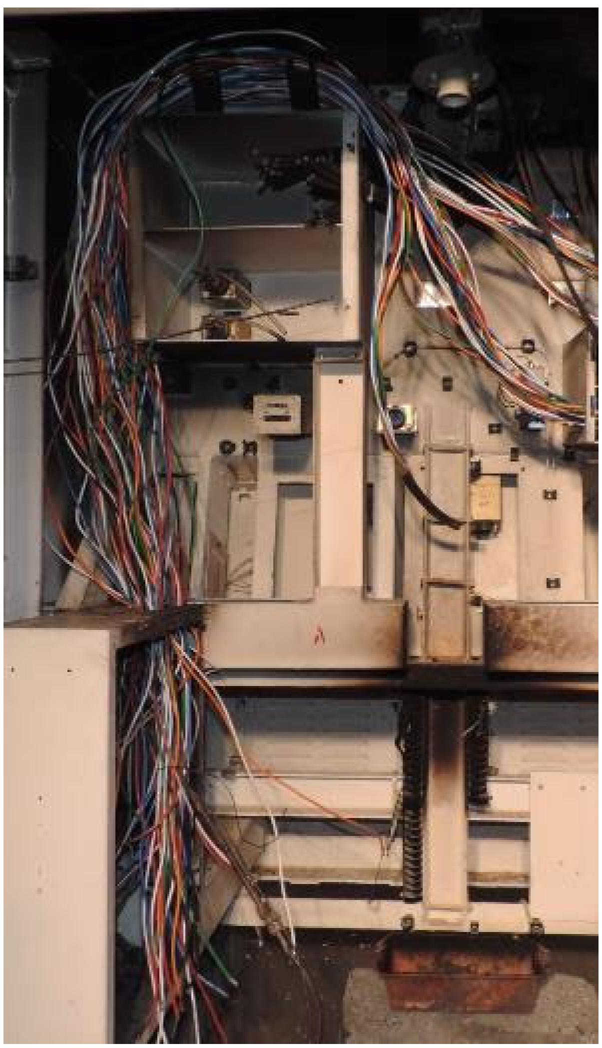
Test: 88 **Enclosure:** 7 **Fuel Load:** 56 insulated conductors extracted from Cable #807, 2.4 m (8 ft) long, routed from enclosed box up left side of enclosure **Ignition Source:** 0.8 kW propane burner **Ventilation:** Door closed, then opened **Notes:** The propane burner was turned off at 5 min. The fire spread upwards and horizontally over all of the wire except a small amount hanging down at the end. The door was opened at 13 min 30 sec.	
	

Table 5-91. Summary of Test 89

Test: 89

Enclosure: 7

Fuel Load: Same set-up as Test 88, except the wires were left tightly bundled in groups of 7

Ignition Source: 0.8 kW propane burner

Ventilation: Door closed, then opened

Notes: The burner was turned off at 11 min, 30 s. The fire spread more slowly than Test 88, and it consumed only the vertical portion of the bundles. The door was opened at 20 min 45 sec and left open.

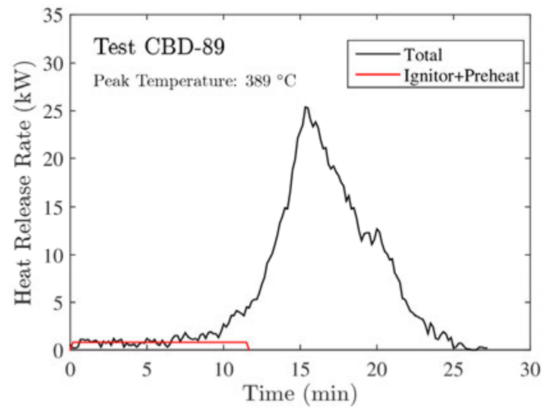


Table 5-92. Summary of Test 90

<table>
<tr>
<td>

Test: 90

Enclosure: 7

Fuel Load: 10 cables (#809) routed up the left side of the enclosure, 2.4 m (8 ft) long

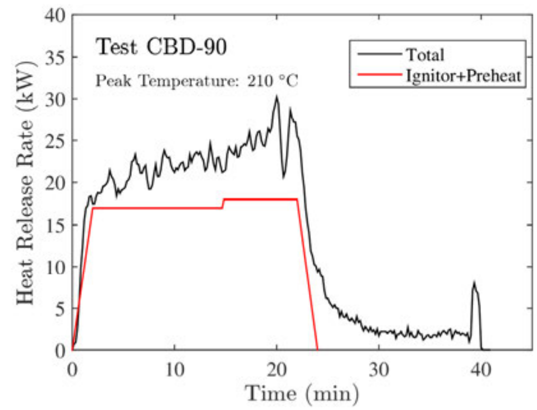
Ignition Source: 0.8 kW propane burner

Preheating Source: 1 L acetone pan fire

Ventilation: Door closed, opened briefly

Notes: The acetone pan fire did not impinge upon the cables. The propane burner was increased to 1.6 kW at 14 min, 40 s. The door was opened at 15 min and again at 23 min. The fire spread slowly upwards, but only burned the vertical portion of the bundle, approximately 1.2 m (4 ft) above the burner.

</td>
<td>



</td>
</tr>
<tr>
<td>

</td>
<td>

</td>
</tr>
</table>

Table 5-93. Summary of Test 91

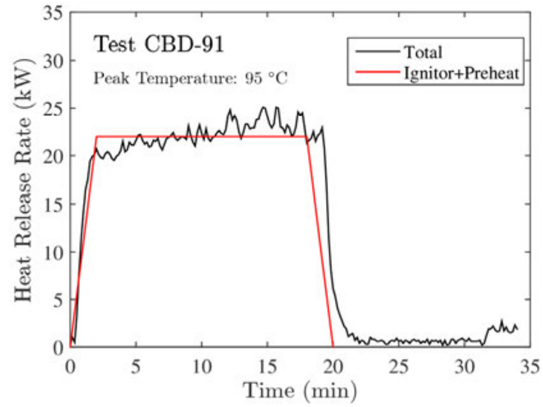
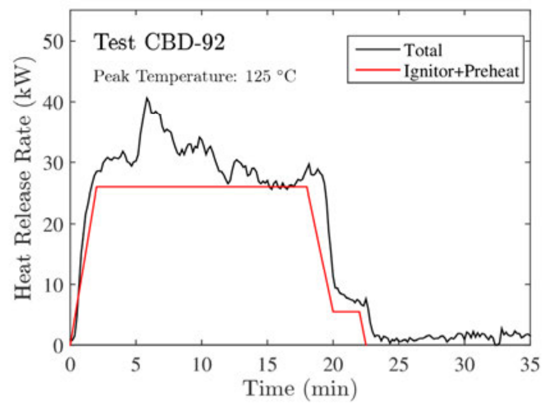
Test: 91 **Enclosure:** 7 **Fuel Load:** 5.9 kg of SIS wire hung along top and right side of enclosure **Ignition Source:** 1.6 kW propane burner **Preheating Source:** 1 L acetone pan fire **Ventilation:** Door closed, open briefly **Notes:** The acetone pan fire did not directly impinge upon the wire. The door was opened at 10 min to check the burner. The acetone was exhausted and the burner turned off at 20 min. No appreciable combustible mass lost.	
	

Table 5-94. Summary of Test 92

<table>
<tr>
<td>
Test: 92
Enclosure: 7
Fuel Load: Same as Test 91
Ignition Source: 5.5 kW propane burner
Preheating Source: 1 L acetone pan fire
Ventilation: Door closed
Notes: The test set-up was the same as Test 92, only with the larger propane burner. The fire spread vertically, but did not spread horizontally. The acetone was exhausted at 20 min and the propane burner was turned off at 22 min.
</td>
<td>


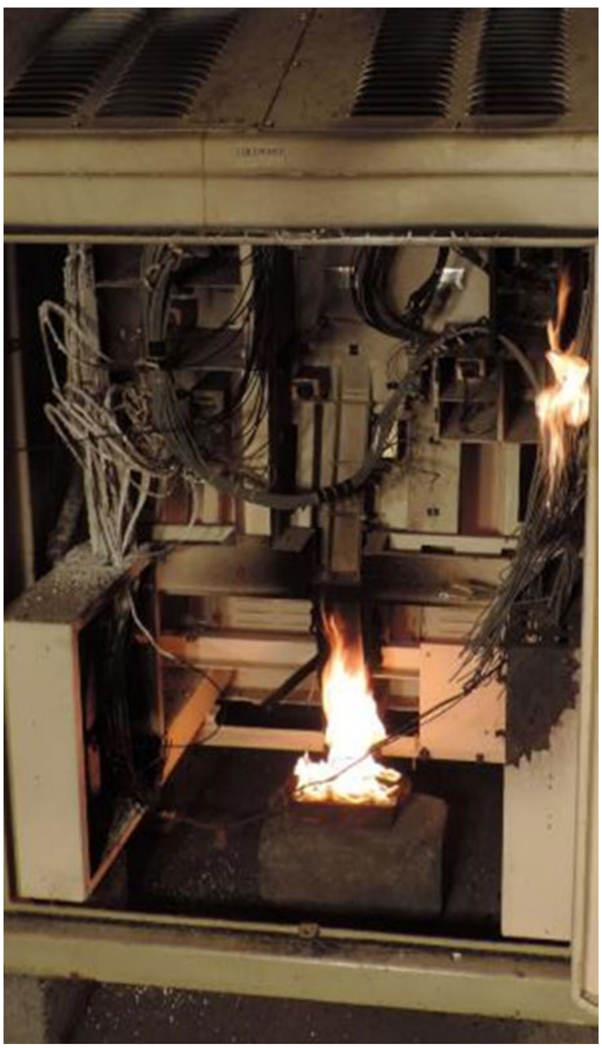
</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</table>

Table 5-95. Summary of Test 93

<table>
<tr>
<td>

Test: 93

Enclosure: 7

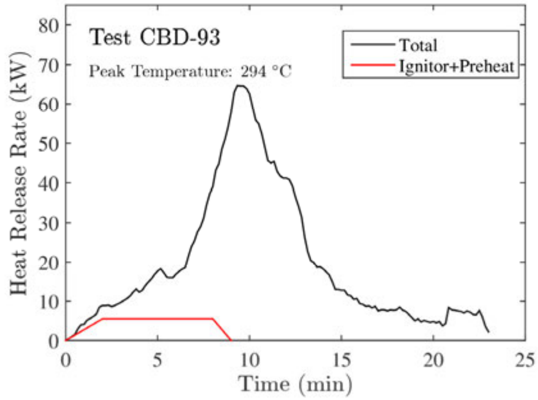
Fuel Load: 72 cables (#833), arranged in 4 bundles, 2.4 m (8 ft) long, originating in open box on right side of enclosure

Ignition Source: 5.5 kW propane burner

Ventilation: Door closed, then opened

Notes: The propane burner was turned off at 8 min. The door was opened at 14 min, 30 s, and left open after that time. The fire spread vertically but not horizontally. A few flames were seen extending just beyond the louvers at the top of the enclosure.

</td>
<td>



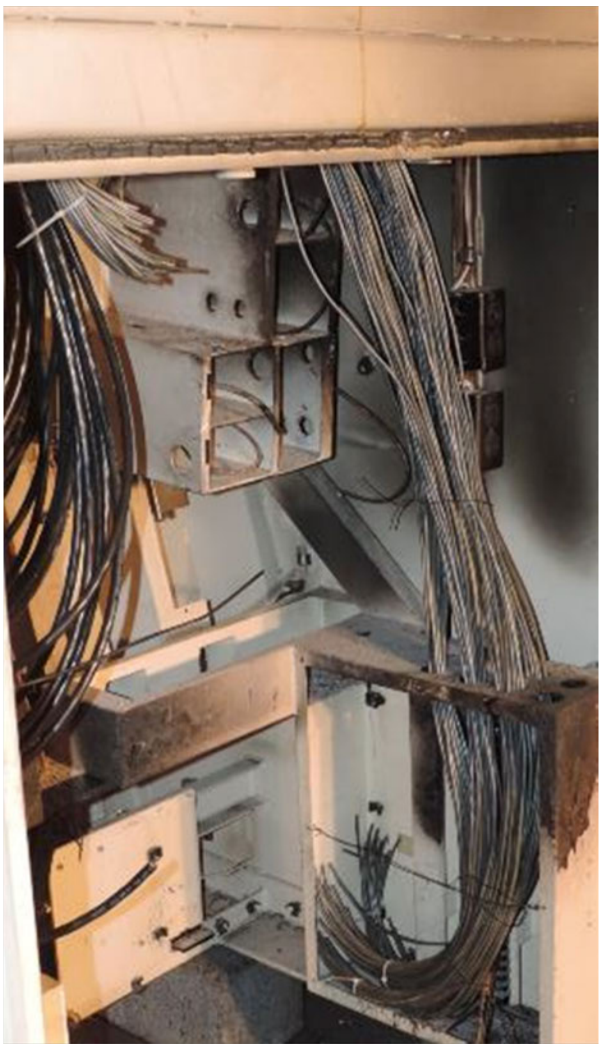
</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</table>

Table 5-96. Summary of Test 94

Test: 94

Enclosure: 7

Fuel Load: 24 cables (#814) in 4 bundles of 6, 2.4 m (8 ft) long, routed up the left side and across brackets running along the top

Ignition Source: 5.5 kW propane burner

Ventilation: Door closed, then opened

Notes: The door was opened at 20 min and left open. The propane burner was turned off at 21 min. The fire spread vertically and approximately 30 cm (1 ft) horizontally.

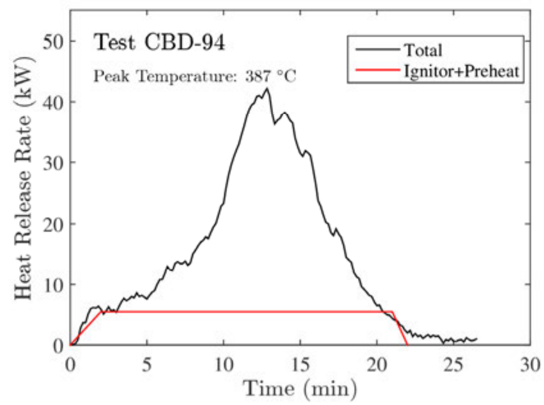


Table 5-97. Summary of Test 95

<table>
<tr>
<td>

Test: 95

Enclosure: 7

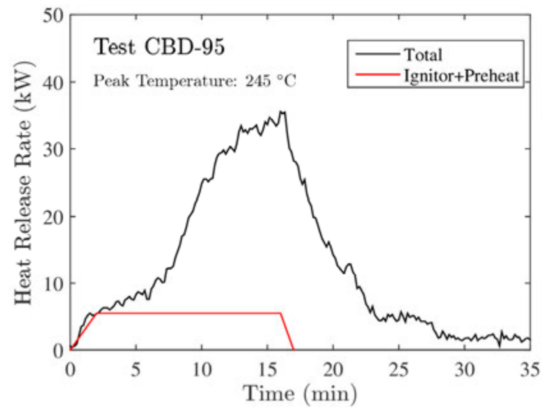
Fuel Load: 24 cables (#844) in 4 bundles of 6, 2.4 m (8 ft) long, routed up the left side and across brackets running along the top

Ignition Source: 5.5 kW propane burner

Ventilation: Door closed, then opened

Notes: The burner was turned off at 16 min. The door was opened at 22 min and left open. The fire spread vertically and approximately 30 cm (1 ft) horizontally.

</td>
<td>



</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</table>

Table 5-98. Summary of Test 96

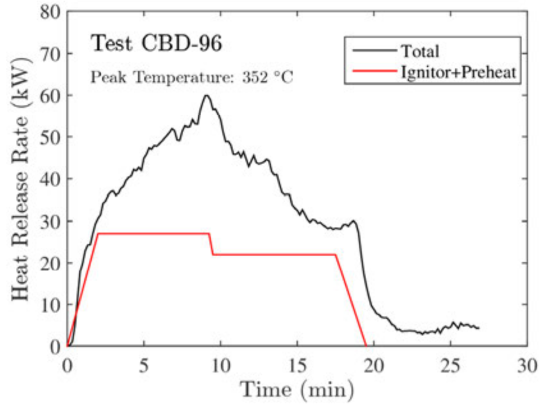
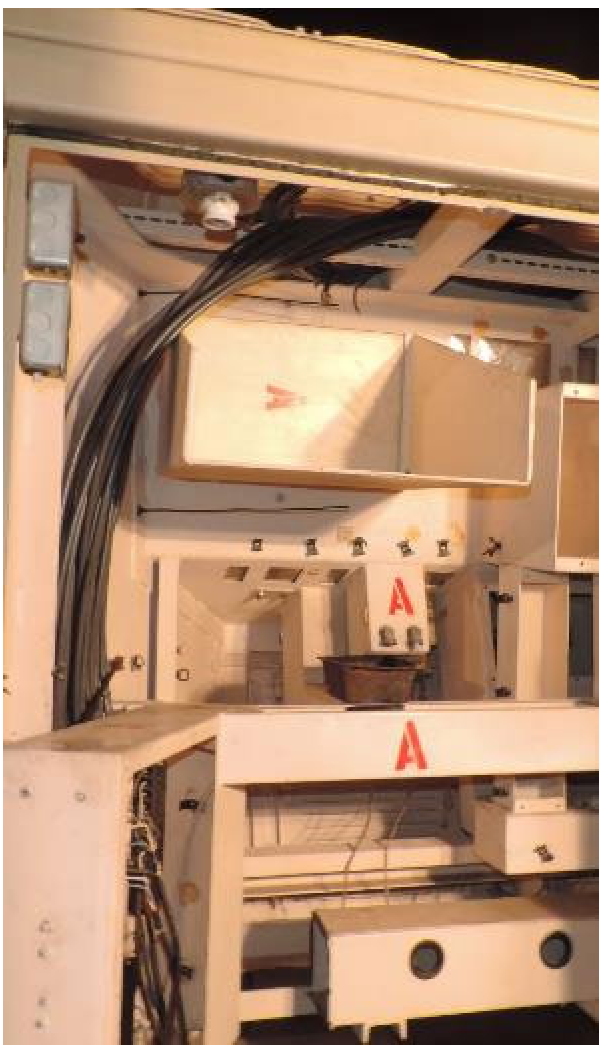
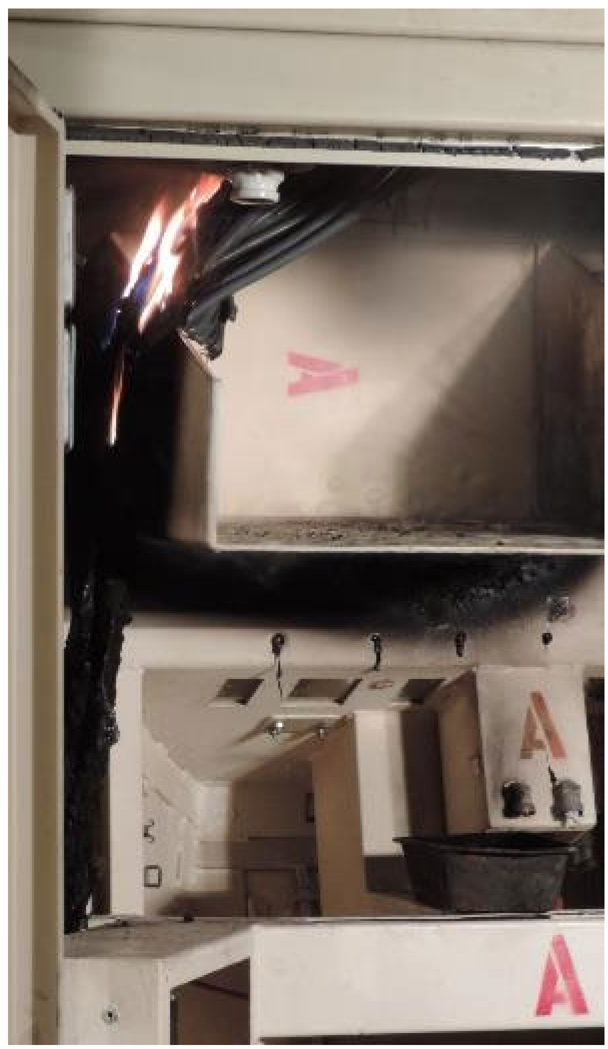
Test: 96 **Enclosure:** 6 **Fuel Load:** 24 cables (#844), 2.4 m (8 ft) long, routed up left side and across brackets running along the top **Ignition Source:** 5.5 kW propane burner **Preheating Source:** 1 L acetone pan fire **Ventilation:** Door closed, then opened **Notes:** The acetone pan fire did not impinge upon the cables. The propane burner was turned off at 9 min and the acetone was exhausted at 19 min, 30 s, when the door was opened. The fire spread vertically but not horizontally.	
	

Table 5-99. Summary of Test 97

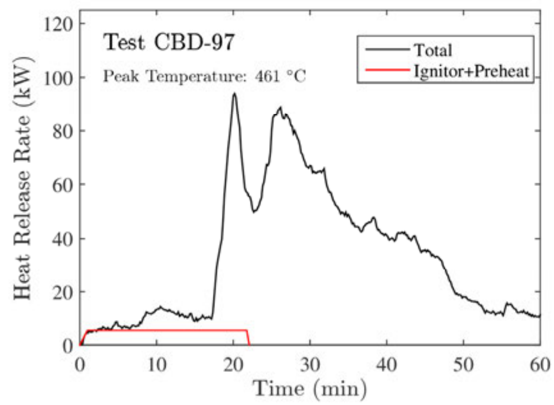
Test: 97 (A,B) **Enclosure:** 6 **Fuel Load:** 108 cables (#833), arranged in 6 bundles, 2.4 m (8 ft) long, originating in a junction box in the center of the enclosure, running vertically, then horizontally **Ignition Source:** 5.5 kW propane burner **Ventilation:** Door closed **Notes:** The door was opened at 16 min, 30 s (B), and the cables were jostled with a crow bar, leading to a rapid increase in the HRR and spread. The propane burner was turned off at 21 min, 45 s. The door was opened at 38 min and left open. The fire spread both vertically and horizontally.	
	

Table 5-100. Summary of Test 98

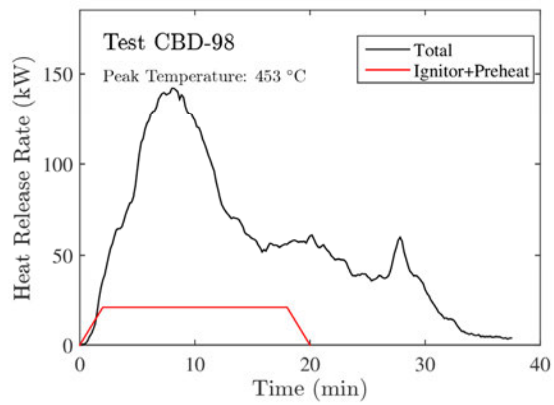
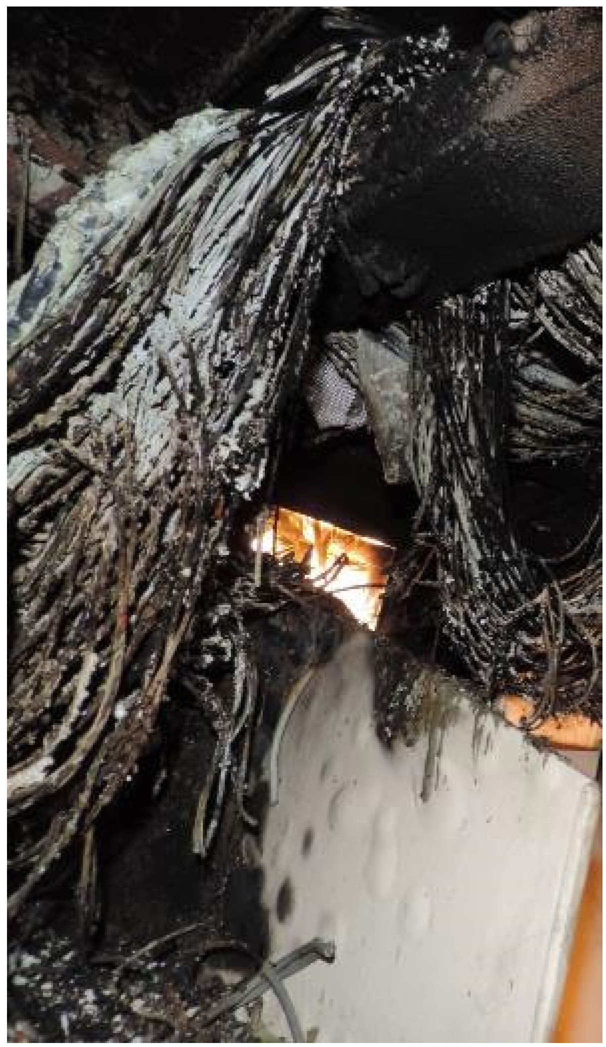
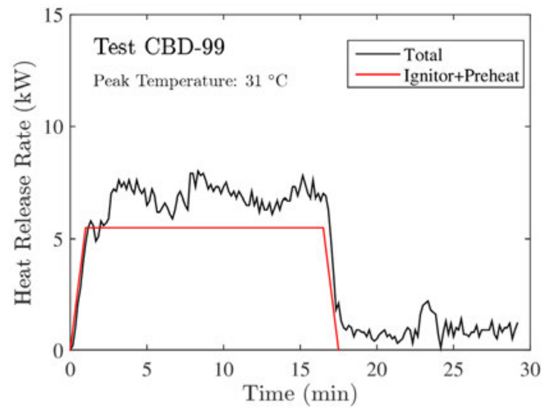
Test: 98 **Enclosure:** 6 **Fuel Load:** 21.9 kg of SIS wire (#831) spread over brackets running along the top of enclosure **Ignition Source:** 1 L acetone pan fire **Ventilation:** Door closed, then opened **Notes:** A bundle of the wire was placed directly in the fuel pan. The acetone was exhausted after 20 min. The doors were opened at 25 min and left open after that time. Most of the wire insulation was consumed.	
	

Table 5-101. Summary of Test 99

<table>
<tr>
<td>
Test: 99
Enclosure: 6
Fuel Load: 20 coaxial cables (#832), 2.4 m (8 ft) long, routed through a narrow, open-topped steel duct
Ignition Source: 5.5 kW propane burner
Ventilation: Door open
Notes: This experiment was to determine if a fire could propagate from the box at the left of the first photo below along the horizontal channel to the right. The cables were jostled periodically during the test, but the fire did not spread beyond the vicinity of the burner, which was turned off at 16 min, 20 s.
</td>
<td>


</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</table>

Table 5-102. Summary of Test 100

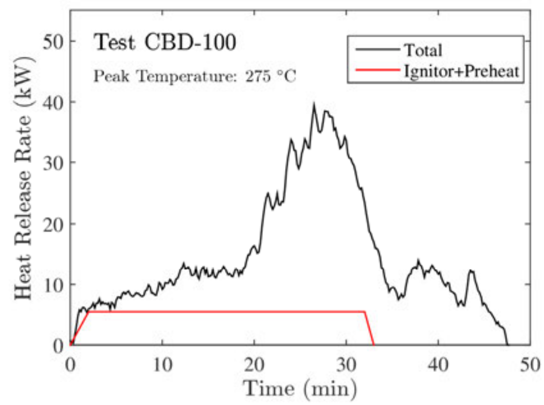
Test: 100 **Enclosure:** 6 **Fuel Load:** 80 cables (#845), arranged in 8 bundles of 10, 2.4 m (8 ft) long, running along the top of the enclosure **Ignition Source:** 5.5 kW propane burner **Ventilation:** Door closed, opened briefly multiple times **Notes:** The door was opened periodically to check on progress. The propane burner was turned off at 32 min. The cables were jostled at 35 min and at 43 min with a crowbar. The fire consumed approximately 1 m (3 ft) of the 80 cables. Roughly half of the combustible load.	
	

Table 5-103. Summary of Test 101

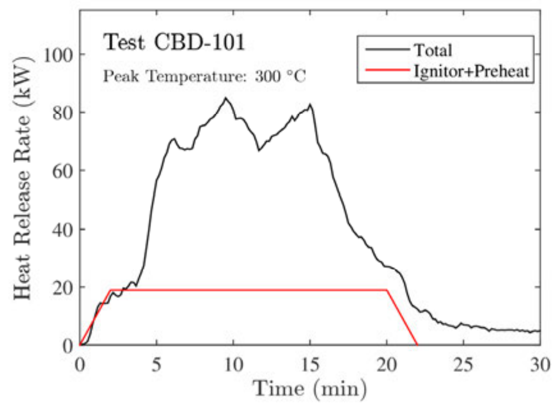
Test: 101 **Enclosure:** 6 **Fuel Load:** The unburned right side portion of the cables from Test 100, approximately 1.2 m (4 ft) of horizontal cable extending downward into fuel pan. Approximately 3.9 kg. **Ignition Source:** 1 L acetone pan fire **Ventilation:** Door closed, then opened **Notes:** The fire spread rapidly upwards and then horizontally. The right hand photo below shows the fire spreading in the horizontal direction when looking through an opening on the front side of the enclosure. The door was opened at 19 min and left open. The acetone was exhausted at 22 min.	
	

Table 5-104. Summary of Test 102

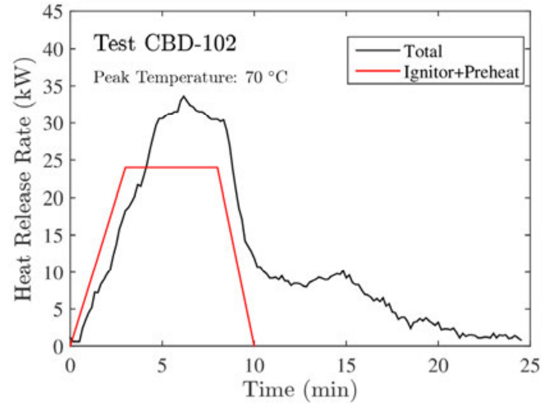
Test: 102 **Enclosure:** 6 **Fuel Load:** 60 insulated wires extracted from Cable #834, routed through a horizontal duct with 20 cm (8 in) square cross section and 5 cm (2 in) openings every 30 cm (1 ft) **Ignition Source:** 500 mL acetone pan fire **Ventilation:** Door open **Notes:** The acetone pan was placed 5 cm (2 in) below an opening in the bottom of the duct (below left). The acetone was exhausted by 10 min, and the fire continued to spread slowly inside the duct. The fire spread to the end of the duct (below right) but did not burn the wire outside the duct.	
	

Table 5-105. Summary of Test 103

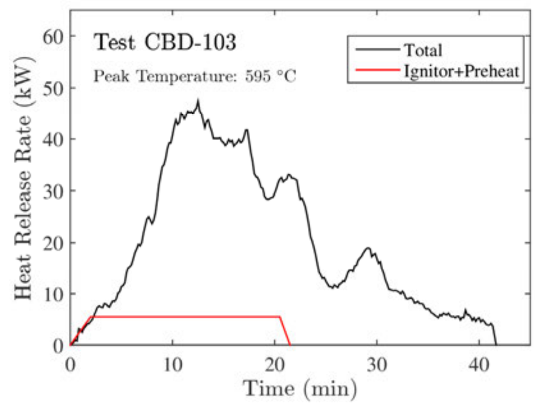
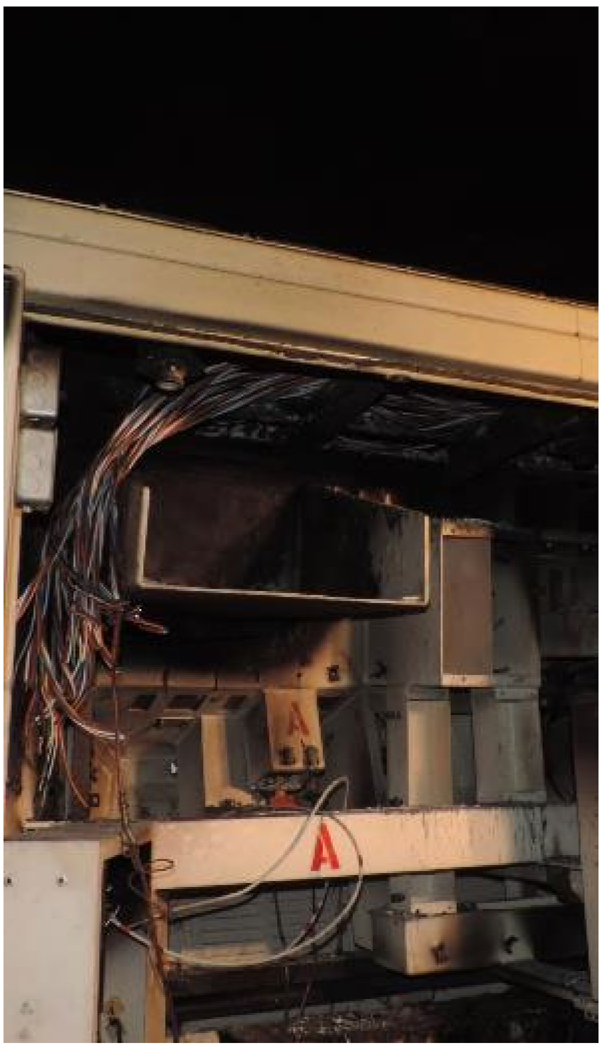
Test: 103 **Enclosure:** 6 **Fuel Load:** 56 insulated conductors extracted from Cable #807, tightly bound in bundles of 7, 2.4 m (8 ft) long, routed along top of enclosure **Ignition Source:** 5.5 kW propane burner **Ventilation:** Door closed **Notes:** The propane burner was turned off at 20 min, 30 s. The doors were opened at 37 min. The fire spread approximately 2 m (6 ft) from left to right along the top of the enclosure. The photo at right shows the furthest extent of the fire.	
	

Table 5-106. Summary of Test 104

Test: 104

Enclosure: 1

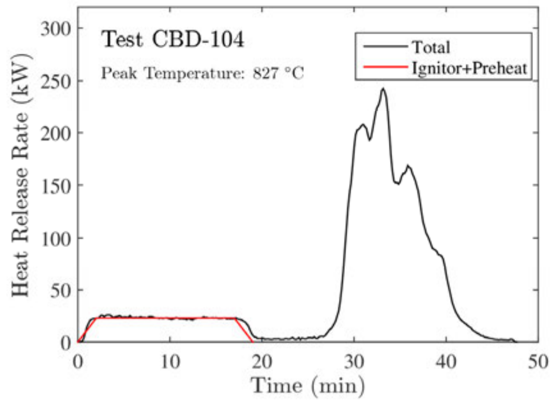
Fuel Load: 420 insulated conductors extracted from Cable #807, tightly bound in groups of 7, various lengths, 540 m (1768 ft) total

Ignition Source: 0.8 kW propane burner

Preheating Source: 1 L acetone pan fire

Ventilation: Door open

Notes: The acetone pan fire was placed in the back of the enclosure, behind a steel partition. The burner was increased to 1.6 kW at 17 min. The acetone was exhausted at 19 min, but the fire had not spread. The cables were jostled at 24 min with a crowbar, after which the fire grew and spread.



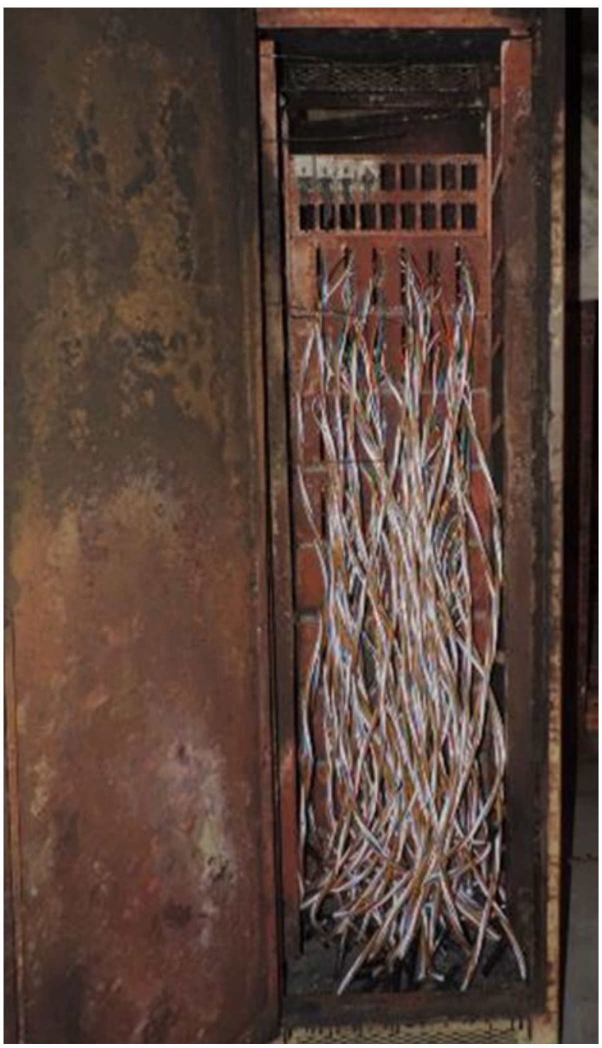


Table 5-107. Summary of Test 105

Test: 105

Enclosure: 1

Fuel Load: A variety of cable remnants, approximately 6.1 kg

Ignition Source: 5.5 kW propane burner

Ventilation: Door closed

Notes: The burner was positioned among the cables routed up the right side of the enclosure. The fire spread to the top of the enclosure in 6 min. The burner was turned off at 7 min, 30 s. The door was opened at 9 min. The fire did not spread to the left side of the enclosure. Approximately half of the combustible mass was consumed.

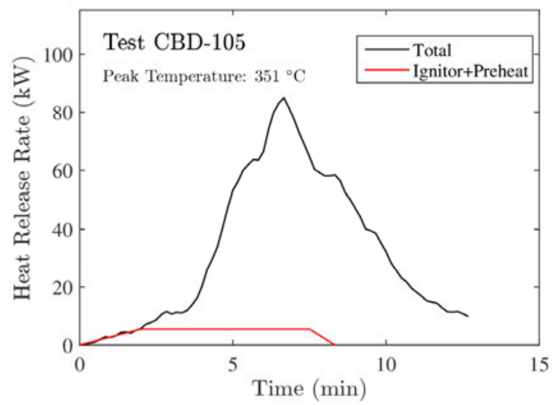
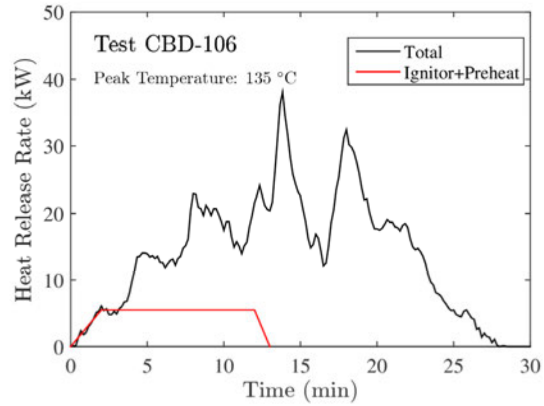


Table 5-108. Summary of Test 106

<table>
<tr>
<td>
Test: 106 (A,B)
Enclosure: 1
Fuel Load: Unburned portion of Test 105 along left side of enclosure, approximately 3.05kg
Ignition Source: 5.5 kW propane burner
Ventilation: Door closed, then opened
Notes: The door was opened at 9 min and left open (B). The propane burner was turned off at 12 min. The cables were jostled with a crowbar at 14 min (below right). The fire spread to the top of the left side of the enclosure.
</td>
<td>


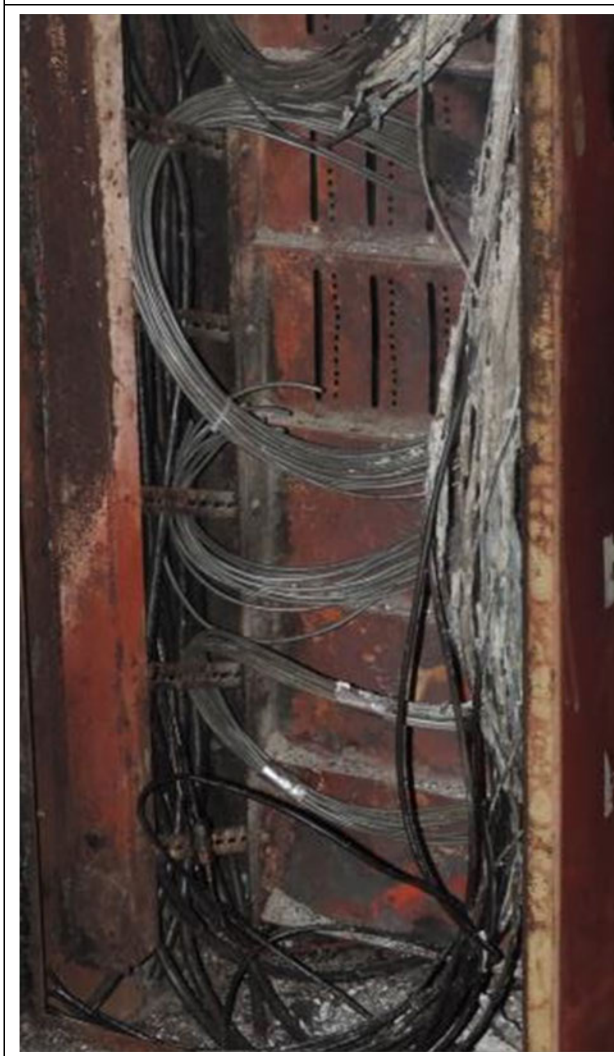
</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</table>

Table 5-109. Summary of Test 107

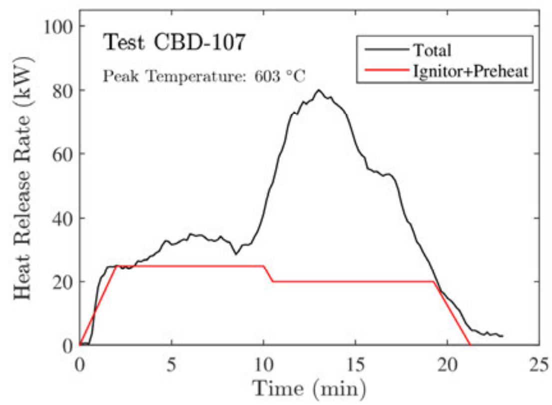
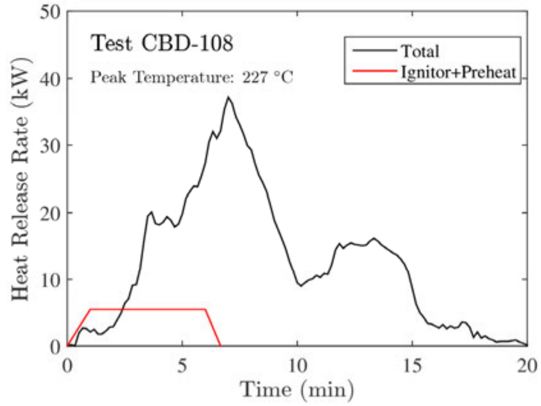
Test: 107 **Enclosure:** 1 **Fuel Load:** 280 insulated conductors (#834), arranged in 4 bundles, 1.8 m (6 ft) long, hanging in front of steel partition **Ignition Source:** 5.5 kW propane burner **Ventilation:** Door open **Notes:** The acetone pan was placed in the back of the enclosure behind a steel partition. The propane burner was turned off at 10 min. The fire consumed the insulation of the two left bundles completely, and burned some of the right two bundles. Approximately, three-quarters of the combustible material was burned.	
	

Table 5-110. Summary of Test 108

<table>
<tr>
<td>

Test: 108
Enclosure: 1
Fuel Load: Unburned wire from Test 107, approximately 1.38 kg
Ignition Source: 5.5 kW propane burner
Ventilation: Door closed, then opened
Notes: The propane burner was turned off at 6 min. The door was opened at 11 min. All of the remaining cable insulation from Test 107 was consumed.

</td>
<td>



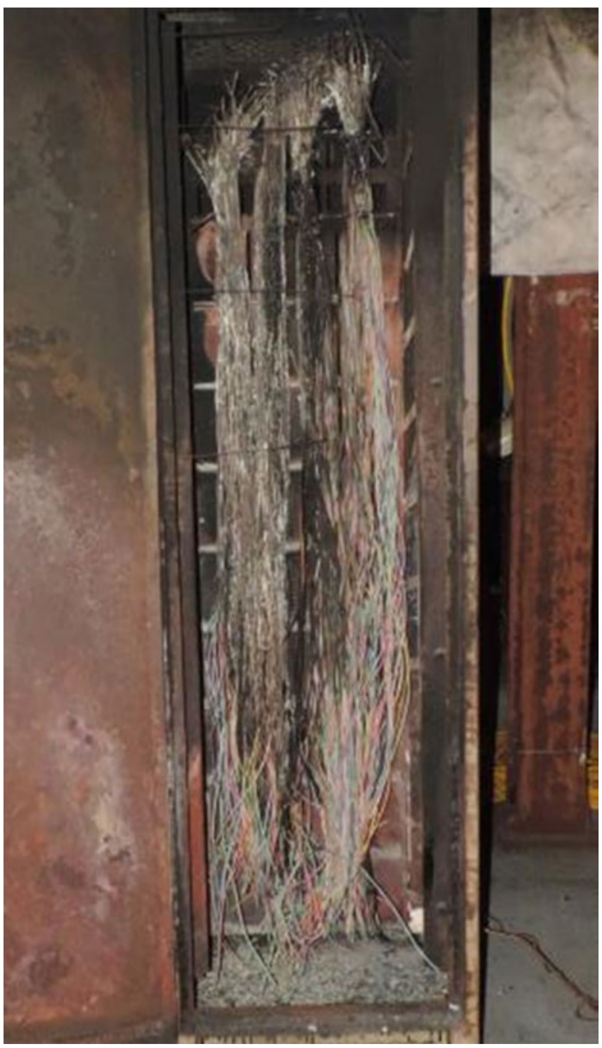
</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</table>

Table 5-111. Summary of Test 109

<table>
<tr>
<td>

Test: 109

Enclosure: 8

Fuel Load: 30 cables (#814), 2.4 m (8 ft) long, routed through 10 conduits in top of enclosure into a tray 45 cm (18 in) above

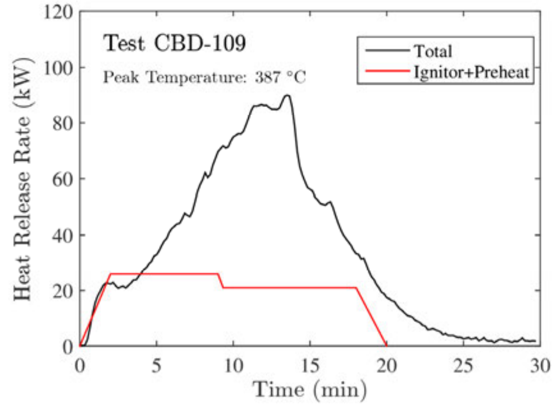
Ignition Source: 5.5 kW propane burner

Preheating Source: 1 L acetone pan fire

Ventilation: Door closed, then opened

Notes: The acetone pan was placed in the back of the enclosure, away from the cables. The propane burner was turned off at 9 min. The door was opened at 20 min and left open. The fire consumed the cable within the enclosure, and scorched approximately 15 cm (6 in) of cable outside.

</td>
<td>



</td>
</tr>
<tr>
<td>

</td>
<td>

</td>
</tr>
</table>

Table 5-112. Summary of Test 110

<table>
<tr>
<td>

Test: 110 (A,B)

Enclosure: 4

Fuel Load: 10 cables (#844), 1.8 m (6 ft) long, routed up right side of enclosure

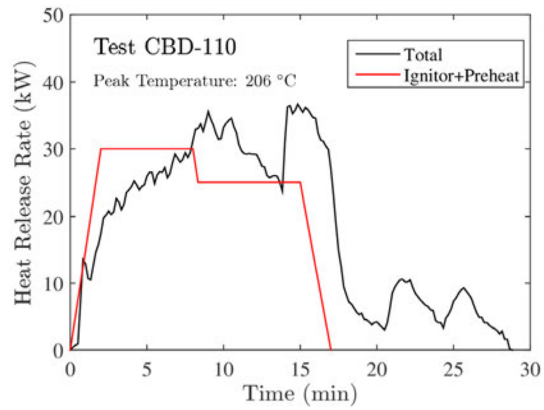
Ignition Source: 5.5 kW propane burner

Preheating Source: 1 L acetone pan fire

Ventilation: Door closed, then opened

Notes: The acetone pan fire did not directly impinge upon the cables. The propane burner was turned off at 8 min. The door was opened at 13 min, 30 s (B). The acetone was exhausted at 17 min. The cables were jostled at 20 min and at 24 min, at which times the fire spread upward, gradually reaching within 30 cm (1 ft) of the top.

</td>
<td>



</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</table>

Table 5-113. Summary of Test 111

Test: 111 (A,B)

Enclosure: 5

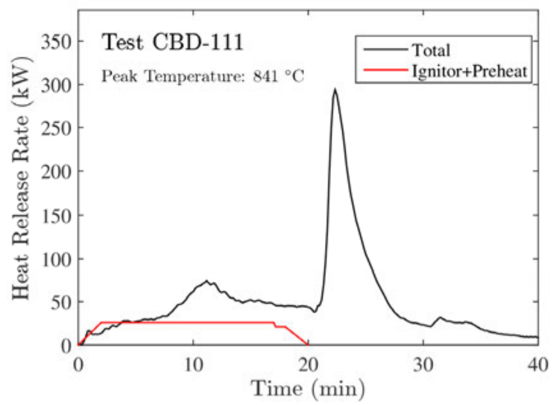
Fuel Load: 2 bundles of 20 cables each (#845), one on each side of enclosure, 2.4 m (8 ft) long

Ignition Source: 5.5 kW propane burner

Preheating Source: 1 L acetone pan fire

Ventilation: Door closed, then opened

Notes: The acetone pan was placed on a ledge at the mid-height of the enclosure. It did not directly impinge upon the cables. The propane burner was positioned at intersection of two bundles at base of enclosure. It was turned off at 17 min. The door was opened at 20 min and left open (B). The fire spread rapidly on both sides following the door opening. All of the cable insulation was consumed.



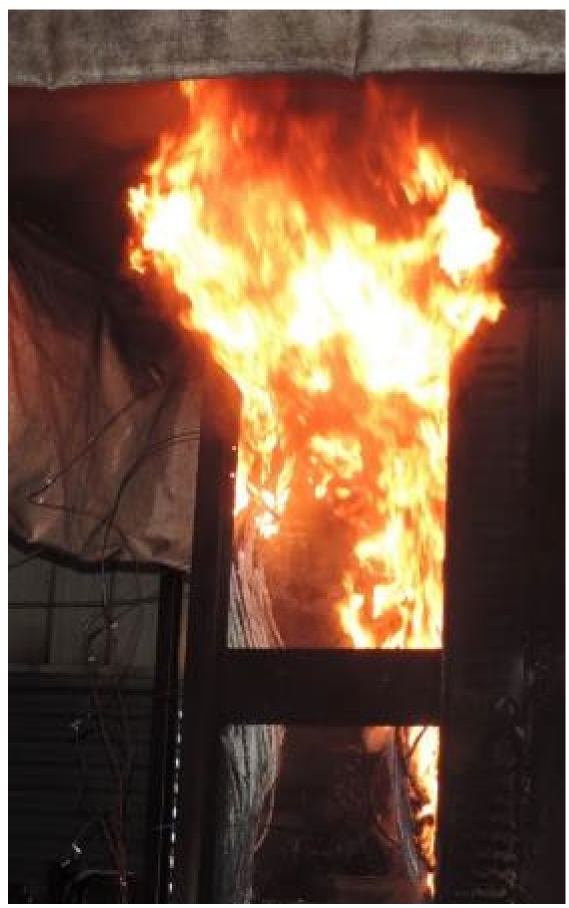
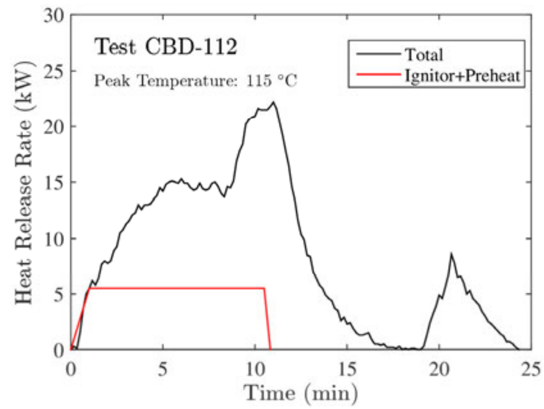


Table 5-114. Summary of Test 112

Test: 112 **Enclosure:** 4 **Fuel Load:** 10 cables (#844), 1.8 m (6 ft) long, routed up left side of enclosure **Ignition Source:** 5.5 kW propane burner **Ventilation:** Door open **Notes:** The propane burner was turned off at 10 min, 30 s. The fire sustained itself, but gradually weakened and stopped spreading 1.2 m (4 ft) above the burner. The cables were jostled with a crowbar at 19 min and the fire spread approximately 30 cm (1 ft) further.	
	

5.3 General Observations

The test report documenting the full-scale electrical enclosure experiments conducted by Sandia National Laboratories (Chavez, 1987) has five general conclusions. Briefly:

1. “Cabinet fires can be ignited and propagate in either unqualified or qualified cable… However, the qualified cable is much more difficult to ignite and propagate.”

2. “It is possible to have a rapidly developing cabinet fire in either type of cable… Although, fires with qualified cable do not become very large.”

3. “Ignition, development rate, and spread of a cabinet fire are dependent on ‘critical’ ignition sources, in situ fuel type, geometries, cabinet style, and ventilation… 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, the thermal environment … was not severe enough to cause auto-ignition of materials…. Furthermore, it appears that a fire will not spread from the burning cabinet to adjacent cabinets.”

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

These same general conclusions apply to the enclosure fire experiments described above. This is not surprising given that the enclosure geometries and cable construction have not significantly changed since the early 1980s.

5.3.1 Ignition

There were three types of ignition sources used in the experiments, although one of these, the cartridge heater, proved unreliable and was only used for one experiment. The other two, a propane line burner or an acetone pan fire, were used either separately or together depending on the type of cables in the enclosure. A propane line burner was used in the VTT experiments (Mangs), and a bucket of acetone was used in some of the Sandia experiments (Chavez, 1987). In general, the propane burner with a roughly 1 kW flame could ignite loosely bound single conductor wiring insulated with thermoplastic materials like polyethylene. Stronger propane flames, 2 kW to 8 kW, were required to ignite unqualified jacketed cable or loosely bundled single conductor thermoset wiring. Acetone pan fires, with HRRs on the order of 20 kW, were required to ignite jacketed thermoset cable. Chavez (1987) reports similar observations.

Past experimental programs at Sandia, VTT, and IRSN focused on generating relatively large fires to better understand the fire dynamics. However, in the experiments described above, the various test parameters (ignition source, fuel load, ventilation, etc.) were varied randomly so that the resulting distribution of fire sizes would not be skewed towards larger fires.

5.3.2 Fire Spread

Regardless of ignition source, the cables in each experiment were heated sufficiently to ignite. However, in many cases the fire did not spread beyond the point of origin, and the fire generally self-extinguished when the propane igniter was removed. In some cases the fire spread upwards beyond the flame height of the igniter, but stopped because it could not support itself without the assist of the heat from the igniter. In cases where the fire spread to the top of the enclosure, it typically did not ignite cables on the opposite side of the enclosure. Chavez (1987) notes the same phenomenon when he says that the fires were not severe enough to cause auto-ignition. In a few instances, the fire spread to the top of the enclosure and burned the top end of some of the cables from the opposite side, but in general the fire spread was vertical in a vertical enclosure. In bench board enclosures, the fire sometimes spread horizontally near the top of the enclosure.

Two vertical enclosures (#4 and #5) were connected together, and there was a fairly wide opening connecting the two. In none of the experiments did the fire spread from one enclosure to the other. However, enclosure to enclosure spread was not the focus of this test series and no conclusions should be drawn from the results.

5.3.3 Ventilation

The most obvious way of controlling the ventilation in the enclosures was to either open or close the door(s). In addition, some enclosures had a removable steel plate covering the bottom, and some had cooling fans mounted at the top. These fans blew air downwards, and could not be operated during the experiments. Smoke from the fire would have been blown outside of the exhaust product collection hood and adversely impacted the HRR measurements. The removable plates did not seem to have much of an impact on the fire behavior, probably because the variation in the fire dynamics test to test was such that the effect of the plate could not be distinguished. Since only two of the fires reached peak heat release rates where ventilation would be expected to have a significant influence, this test series has limited value for analyzing the impact of ventilation.

5.3.4 Peak Heat Release Rate

In an effort to expand the data available for analysis, some test conditions were altered during the tests. For example, doors that were initially closed were opened and remained open for the duration of a test to examine ventilation effects. A crowbar was used to “jostle some of the cable bundles during some tests to examine the impact of cable bundling on peak HRR rate.

The peak HRR is calculated by subtracting off the estimated HRR of the ignition and preheating sources from the total measured HRR. Of the 112 experiments, the peak HRR varied from 0 kW to 576 kW. The mean was 43 kW; the median was 19 kW. Eleven of the 112 fires had a peak HRR greater than 100 kW. Six had a peak HRR between 100 kW and 200 kW. Four had a peak HRR between 200 kW and 300 kW. The highest peak HRR was nearly 600 kW in Test 83. This particular experiment had all the elements that lead to a high HRR: a relatively large fuel load of relatively thin, unqualified, thermoplastic wiring loosely hung in an open enclosure. This essentially produced a wall of flame that quickly consumed virtually all of the combustibles. The experiments with peak HRRs between 100 kW and 300 kW all had relatively large amounts of loose, thin wiring, but some were performed with the doors closed, and some contained thermoset rather than thermoplastic insulation.

6 CONCLUSION AND FUTURE WORK

During the Heat Release Rates of Electrical Enclosure Fires (HELEN-FIRE) program, 112 full-scale experiments were conducted in which the heat release rate of fires in a variety of electrical enclosures was measured using oxygen consumption calorimetry. This data can be used in the development of energy source terms for fire models used to assess the potential consequences of fires within nuclear power plants (NPPs).

Future work in this program is to develop simplified models of fires within electrical cabinets. The 112 experiments in the HELEN-FIRE test program can be used to support development of statistical distributions of HRRs that can be input into fire models. However, simplified fire models that rely on empirical correlations of plume and ceiling jet temperatures do not contain the physical mechanisms to account for the geometry of the electrical enclosure itself. In other words, even if the HRR of the fire is specified, there is no physical mechanism within the model to account for the fact that a significant fraction of the fire's heat is trapped within the enclosure and not transported upwards to damage ceiling targets. In the HELEN-FIRE experiments, the overall HRR of the fire was inferred from the measured rate of oxygen consumption, but it was not possible to measure the fraction of the energy that was absorbed by the steel walls of the enclosure and the fraction that was transported into the exhaust duct.

Computational fluid dynamics (CFD) models can account for the geometry of the enclosure, but even these models require validation. For this reason, experiments are being planned in which a simple gas burner is to be placed in various locations within a few different kinds of electrical enclosures and surface and gas temperatures are to be measured on and above the enclosure. The results of the experiments will be used to develop guidance for applying the HRRs to simplified models and to validate CFD models used to assess other enclosure geometries.

7 REFERENCES

Chavez, J.M. (1987), *An Experimental Investigation of Internally Ignited Fires in Nuclear Power Plant Control Enclosures: Part I: Enclosure Effects Tests,* NUREG/CR-4527/V1, US Nuclear Regulatory Commission, Washington, DC.

Chavez, J.M. and S.P. Nowlen (1988), *An Experimental Investigation of Internally Ignited Fires in Nuclear Power Plant Control Enclosures: Part II: Room Effects Tests,* NUREG/CR-4527/V2, US Nuclear Regulatory Commission, Washington, DC.

Coutin, M., W. Plumecocq, S. Melis and L. Audouin (2012), "Energy balance in a confined fire compartment to assess the heat release rate of an electrical enclosure fire," *Fire Safety Journal*, **52**: 34-45.

IEEE-383 (1974) *Standard for Qualifying Class 1E Electric Cables and Field Splices for Nuclear Power Generating Stations*, IEEE Standards Association.

Mangs, J., J. and O. Keski-Rahkonen (1994), "Full scale fire experiments on electronic enclosures," VTT Publications 186, VTT Technical Research Centre of Finland, Espoo, Finland.

Mangs, J., J. and O. Keski-Rahkonen (1996), "Full scale fire experiments on electronic enclosures II," VTT Publications 269, VTT Technical Research Centre of Finland, Espoo, Finland.

Mangs, J., J. Paananen and O. Keski-Rahkonen (2003), "Calorimetric fire experiments on electronic enclosures," *Fire Safety Journal*, 38: 165-186.

Mangs, J., J. (2004), "On the fire dynamics of vehicles and electrical equipment," VTT Publications 521, VTT Technical Research Centre of Finland, Espoo, Finland.

McGrattan, K., A. Lock, N. Marsh, M. Nyden, S. Bareham, and M. Price (2012), *Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE)*, NUREG/CR-7010, Vol. 1, National Institute of Standards and Technology, Gaithersburg, Maryland.

Nowlen, S.P. (1989), *A Summary of Nuclear Power Plant Fire Safety Research at Sandia National Laboratories, 1975-1987*, NUREG/CR-5384, SAND89-1359, Sandia National Laboratories, Albuquerque, New Mexico.

Nowlen, S.P. and Wyant, F.J. (2007a), *CAROLFIRE Test Report Volume 1: General Test Descriptions and the Analysis of Circuit Response Data,* NUREG/CR-6931/V1, US Nuclear Regulatory Commission, Washington, DC.

Nowlen, S.P. and Wyant, F.J. (2007b), *CAROLFIRE Test Report Volume 2: Cable Fire Response Data for Fire Model Improvement*, NUREG/CR-6931/V2, US Nuclear Regulatory Commission, Washington, DC.

Plumecocq, W., M. Coutin, S. Melis and L. Rigollet (2011), Characterization of closed-doors electrical enclosure fires in compartments," *Fire Safety Journal*, **46**: 243-253.

SFPE (2008) *SFPE Handbook of Fire Protection Engineering*, Fourth Edition, National Fire Protection Association, Quincy, Massachusetts.

Taylor, B.N. and C.E. Kuyatt (1994), *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*, NIST Technical Note 1297, National Institute of Standards and Technology, Gaithersburg, Maryland.

U.S. NRC and EPRI (2004), *Fire PRA Methodology for Nuclear Power Facilities*, NUREG/CR-6850, U.S. Nuclear Regulatory Commission, Washington, DC.

Wachowiak, R. and A. Lindeman (2013), *The Updated Fire Events Database: Description of Content and Fire Event Classification Guidance*, EPRI Report 1025284, Electric Power Research Institute, Palo Alto, CA.

Appendix A TEMPERATURE DATA

Near-ceiling temperature measurements for each experiment are listed on the following pages. Shown is the measurement nearest to the ceiling of the enclosure, typically about 15 cm (6 in) below and centered from left to right.

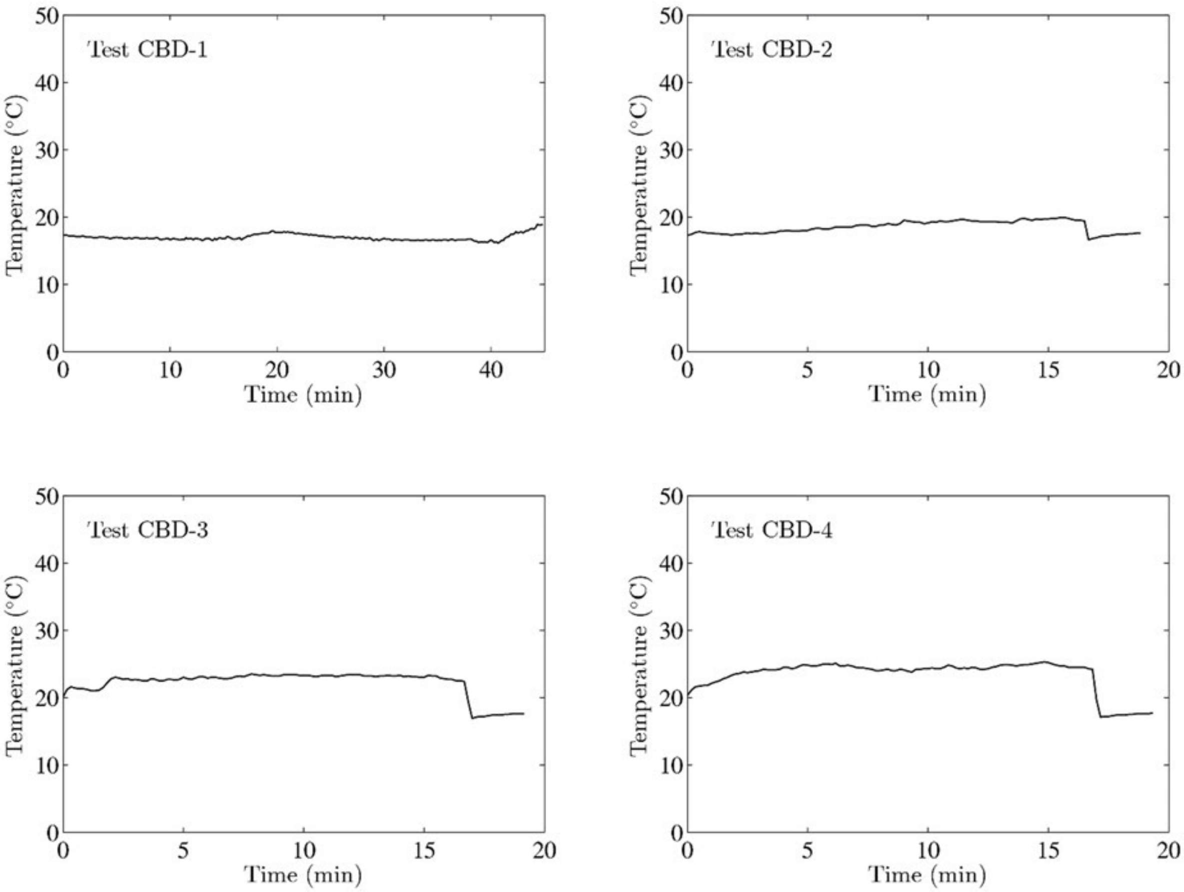


Figure A-1. Enclosure temperatures, Tests 1-4.

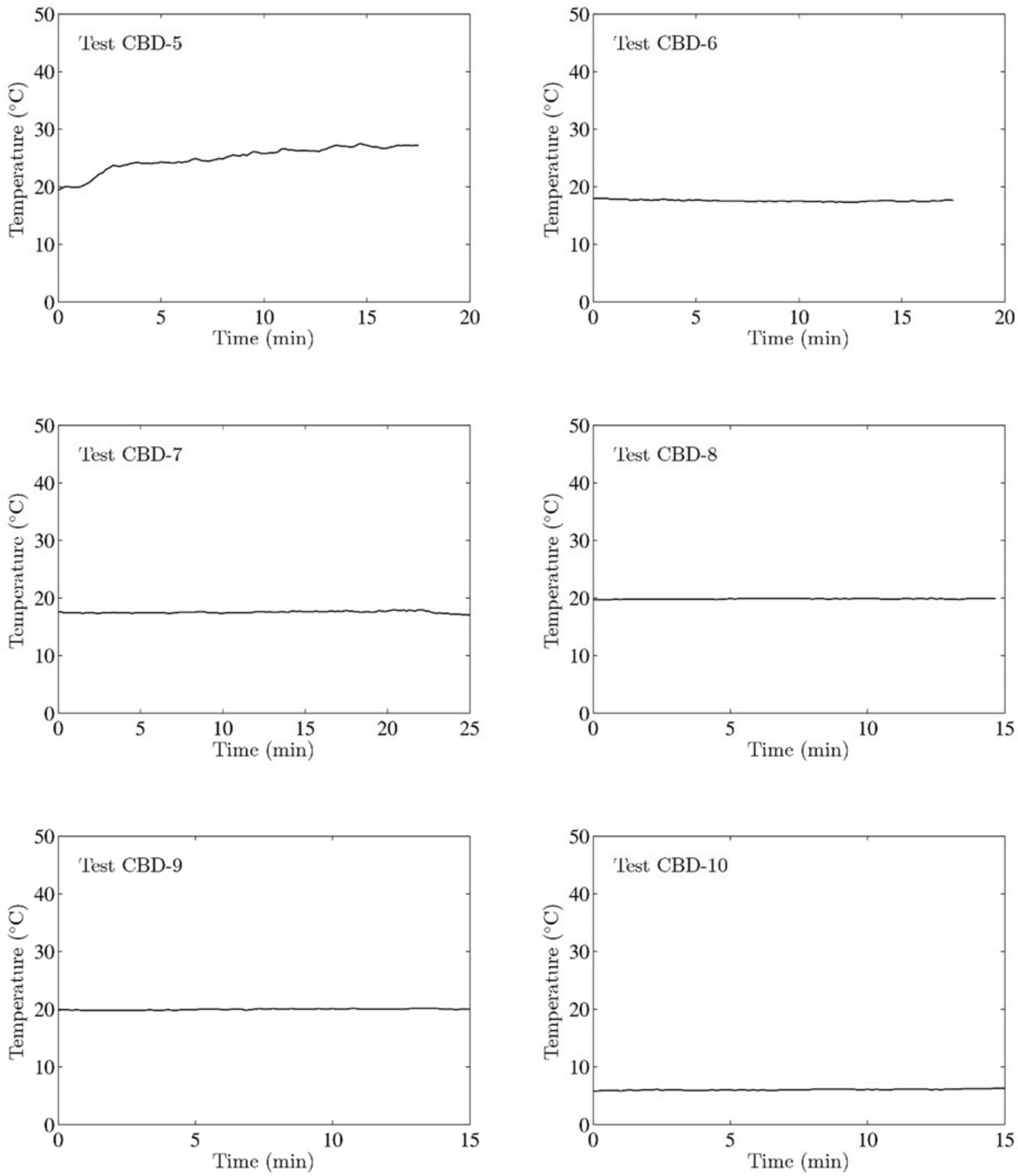


Figure A-2. Enclosure temperatures, Tests 5-10.

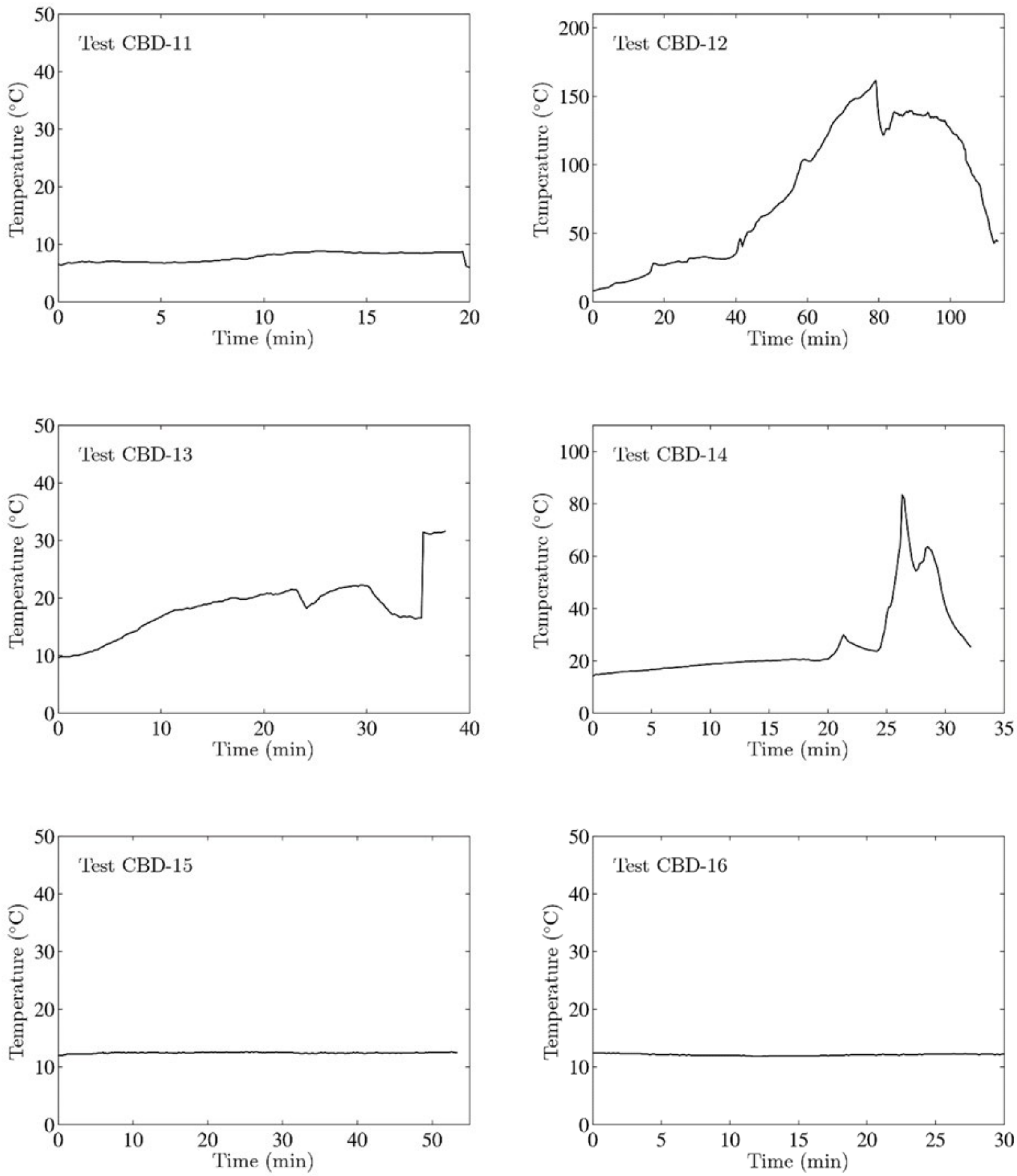


Figure A-3. Enclosure temperatures, Tests 11-16.

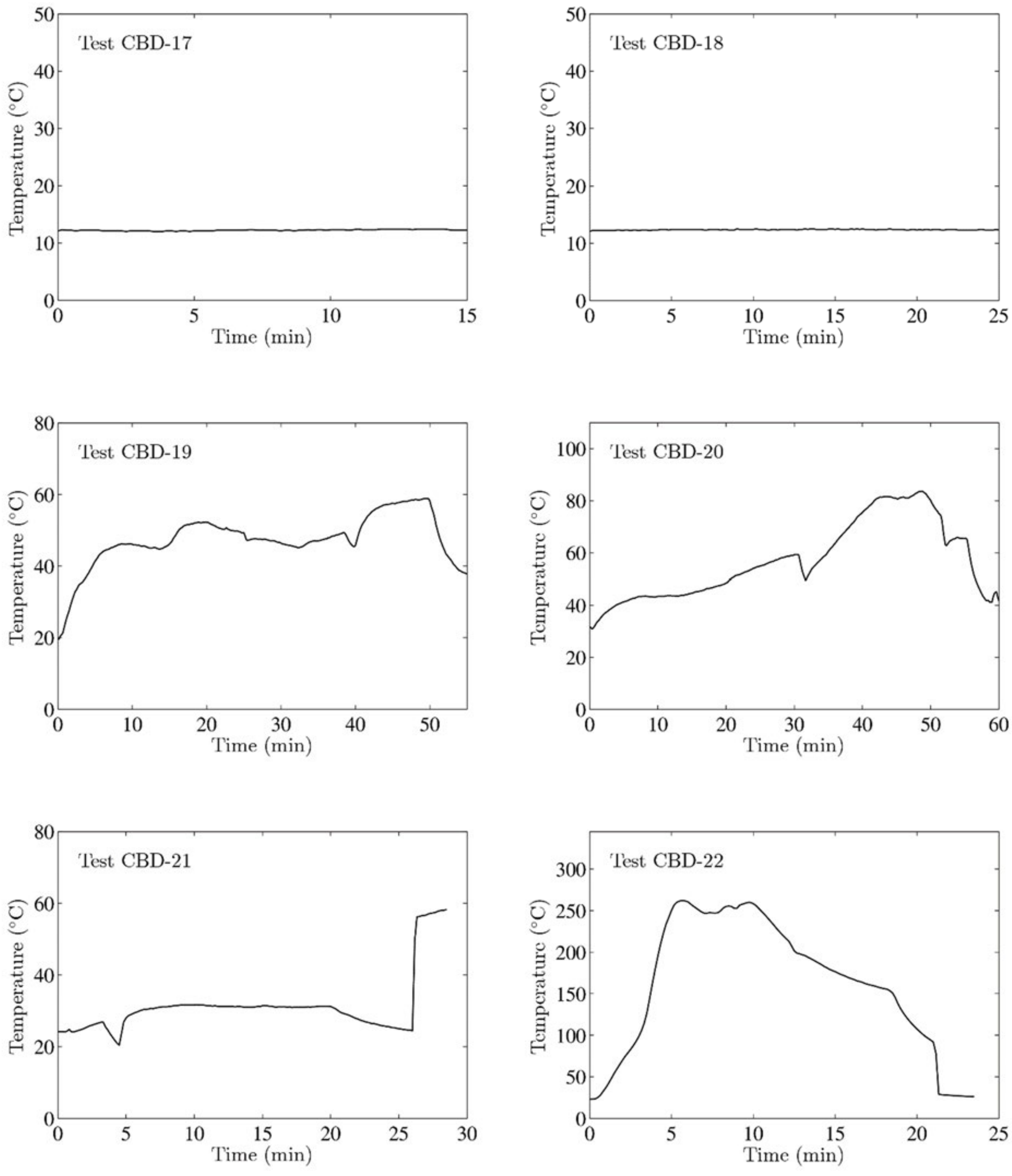


Figure A-4. Enclosure temperatures, Tests 17-22.

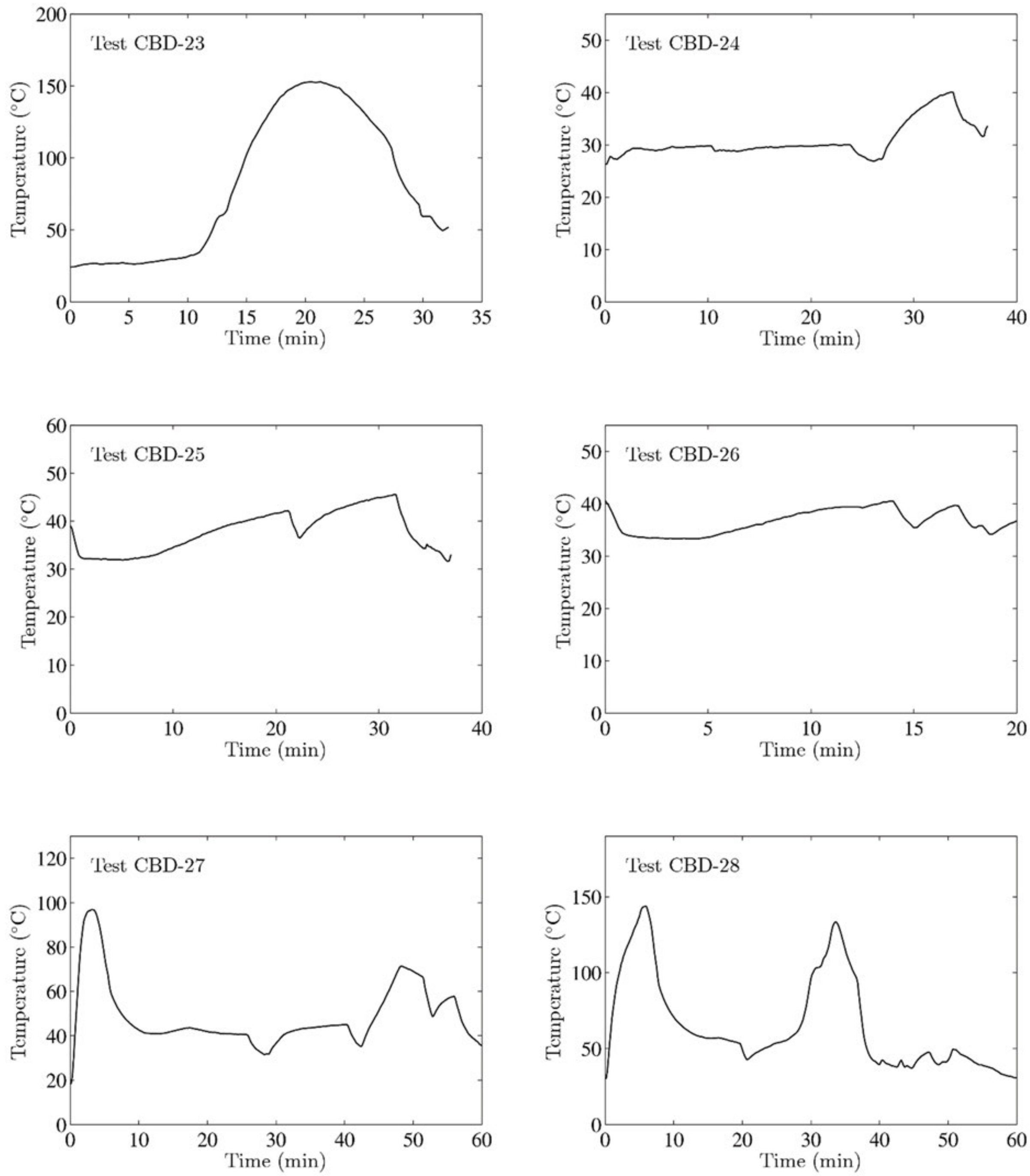


Figure A-5. Enclosure temperatures, Tests 23-28.

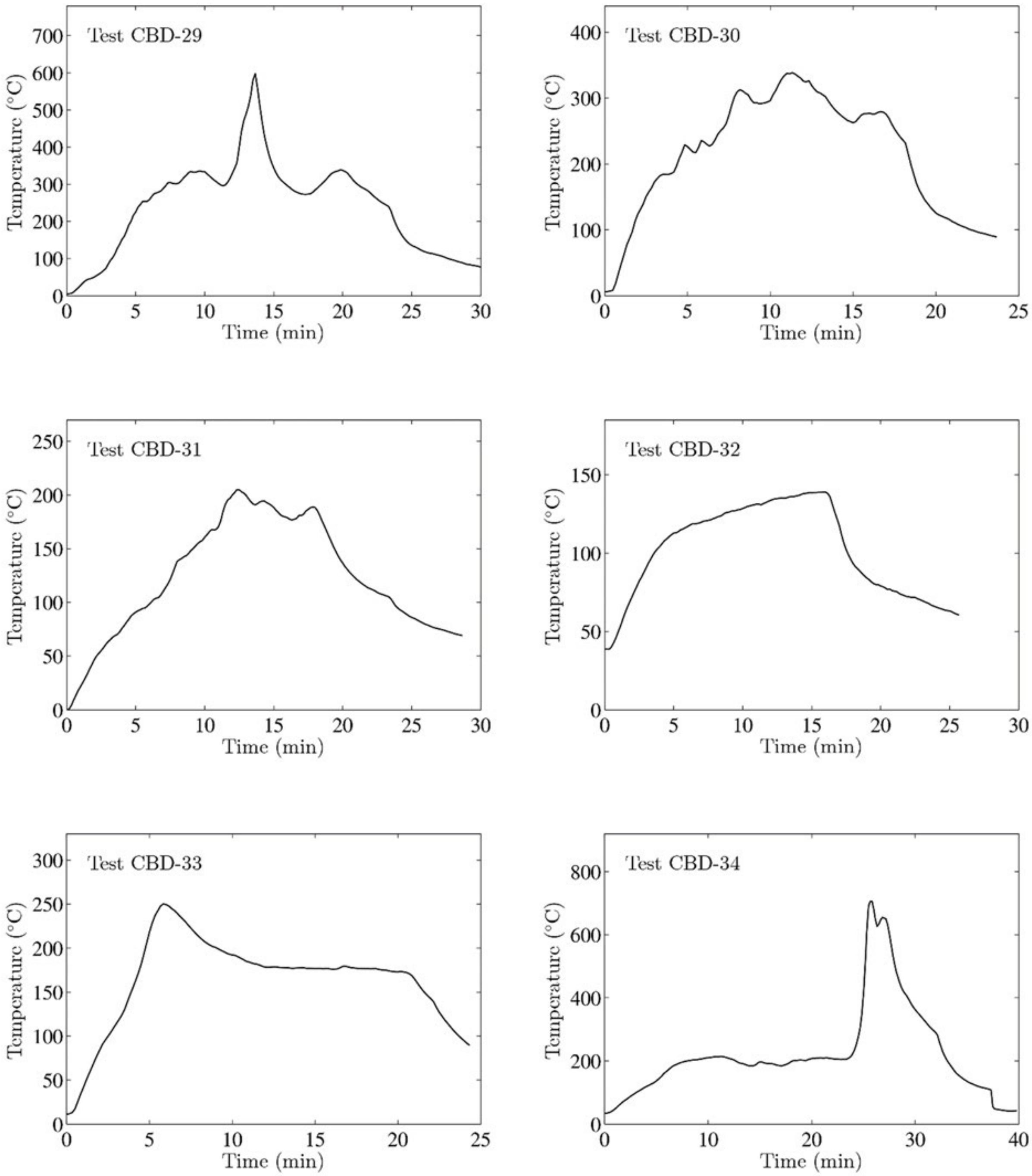


Figure A-6. Enclosure temperatures, Tests 29-34.

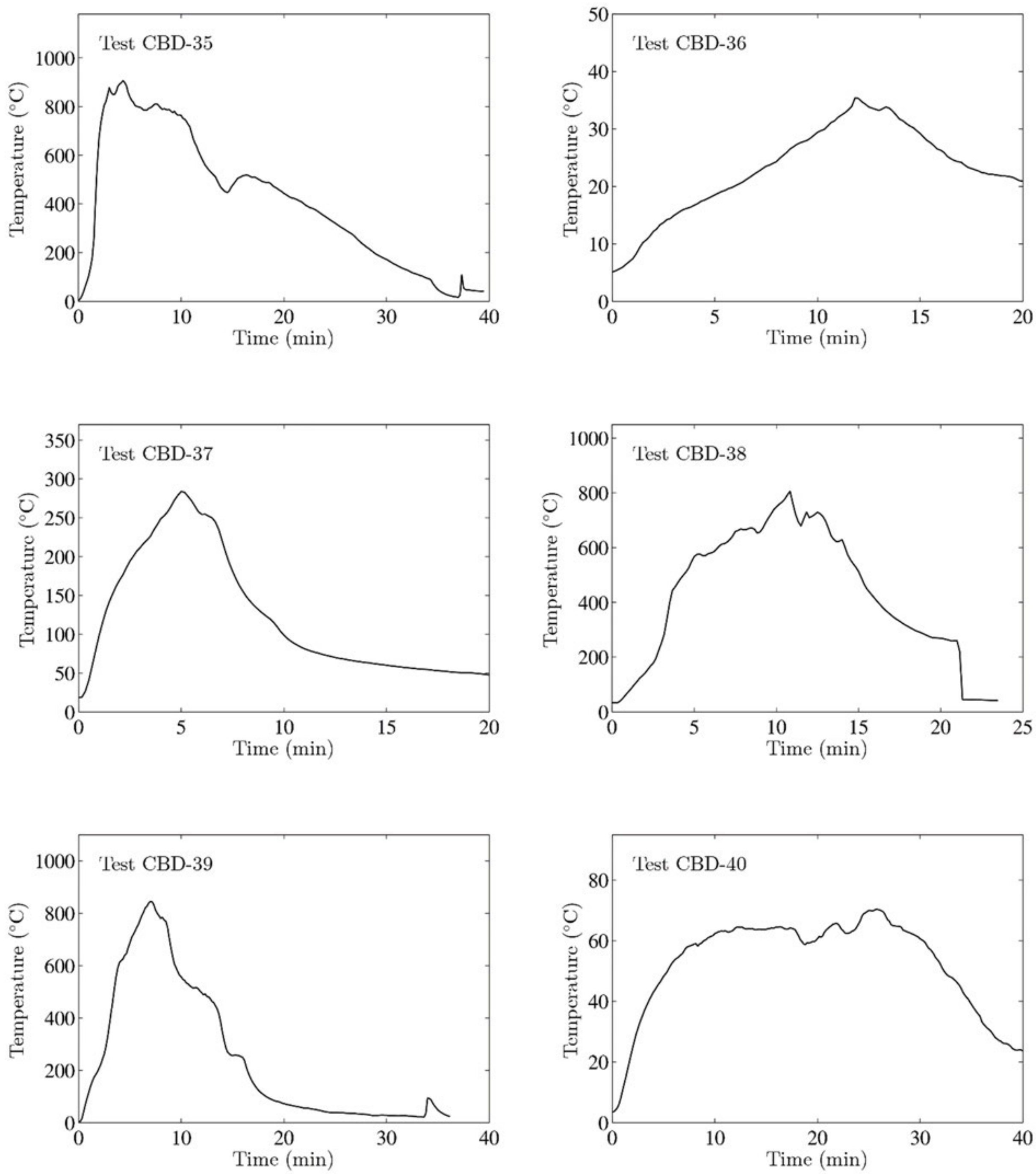
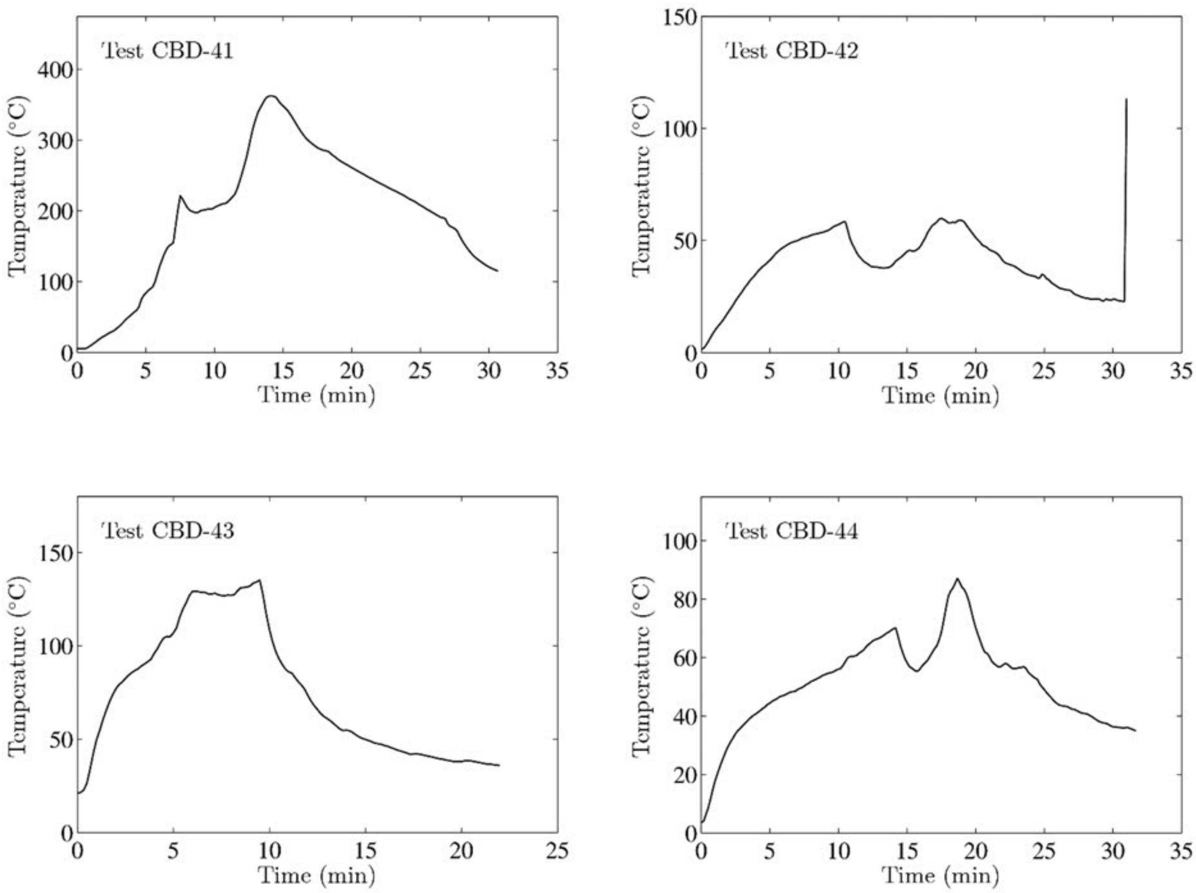
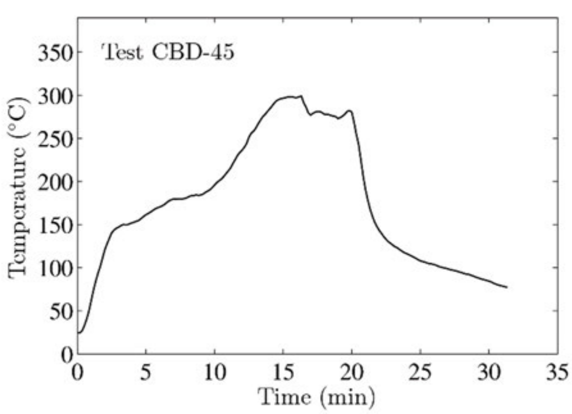


Figure A-7. Enclosure temperatures, Tests 35-40.





Enclosure temperatures were not measured for Test CBD-46.

Figure A-8. Enclosure temperatures, Tests 41-46.

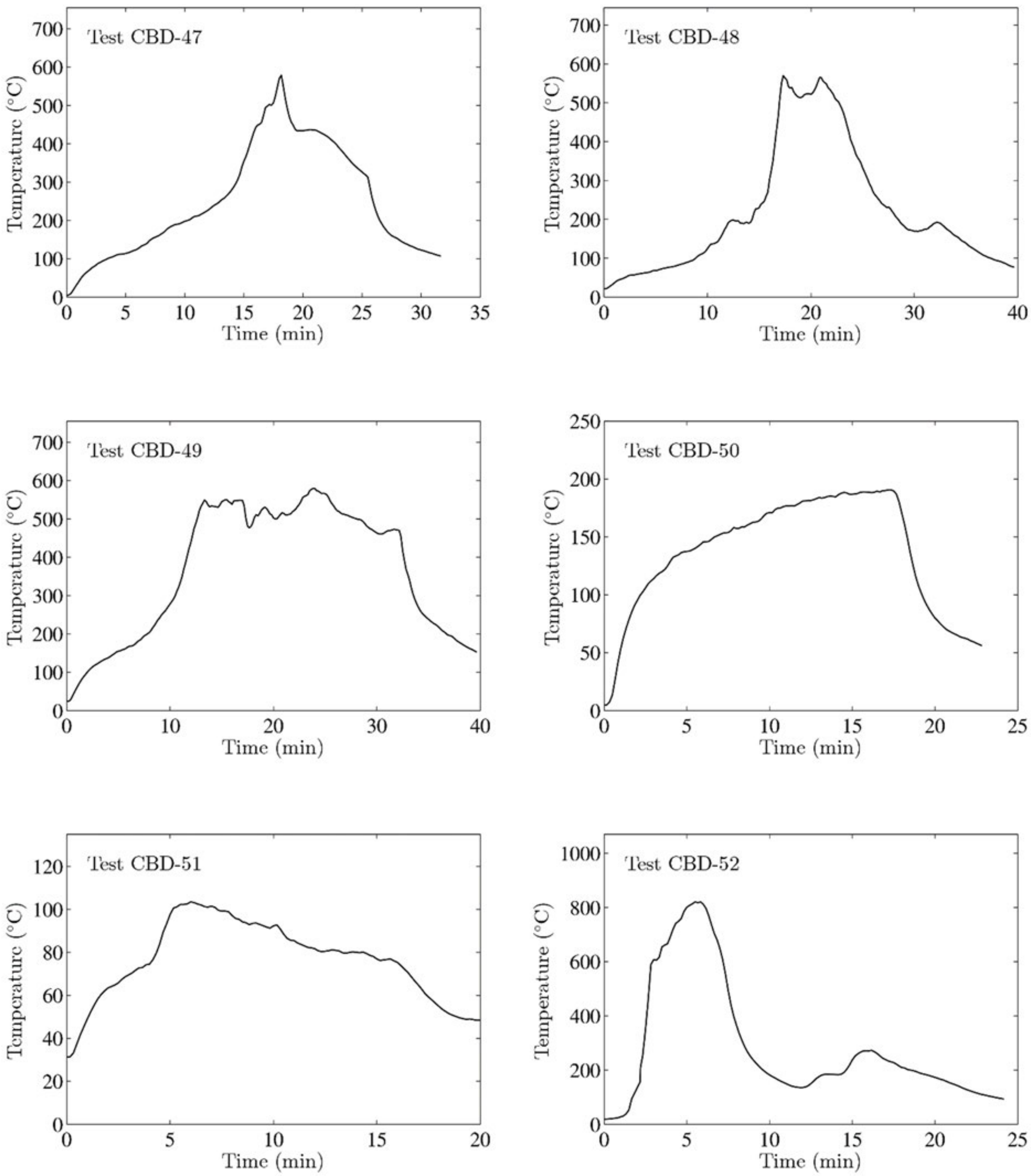


Figure A-9. Enclosure temperatures, Tests 47-52.

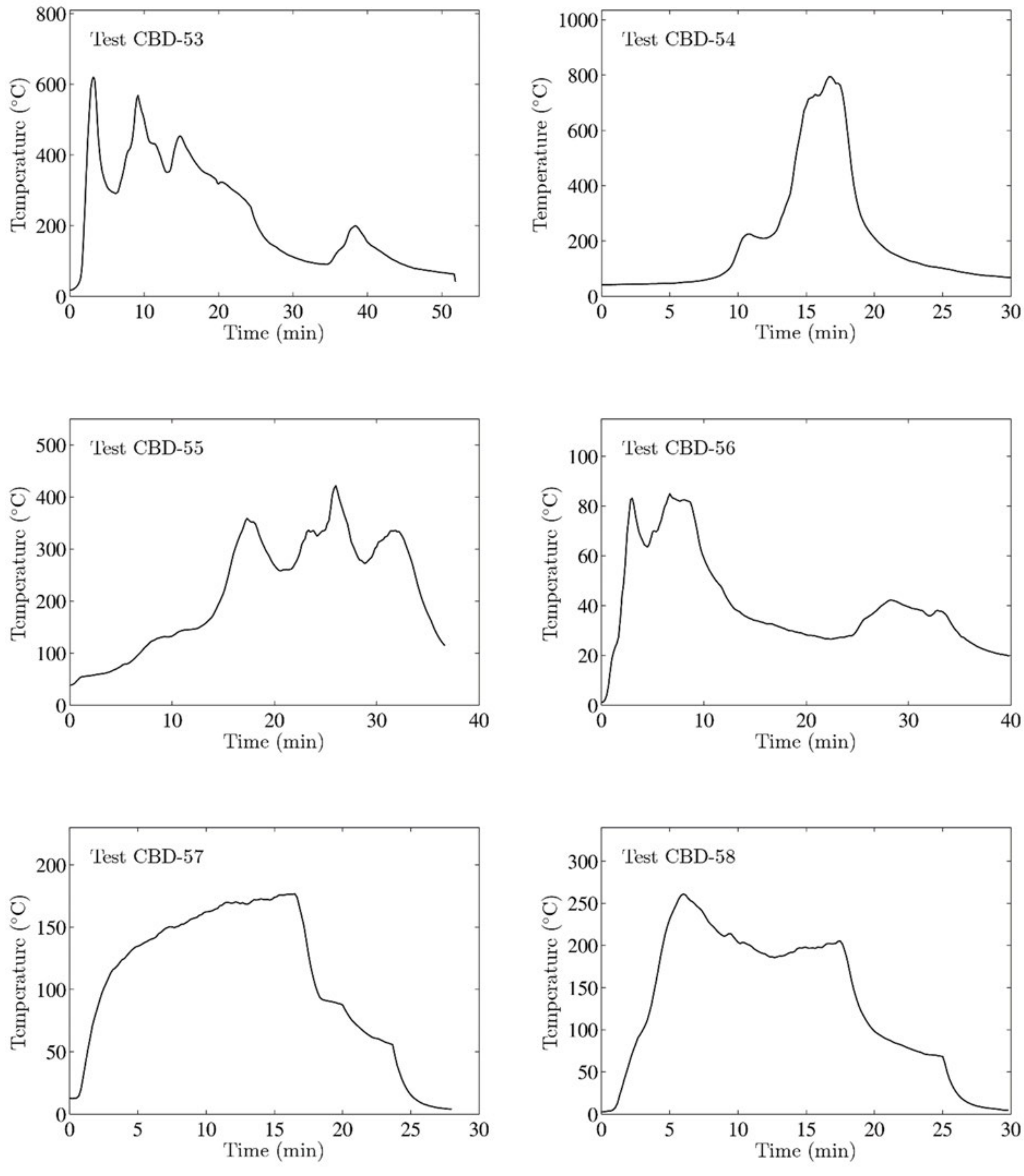


Figure A-10. Enclosure temperatures, Tests 53-58.

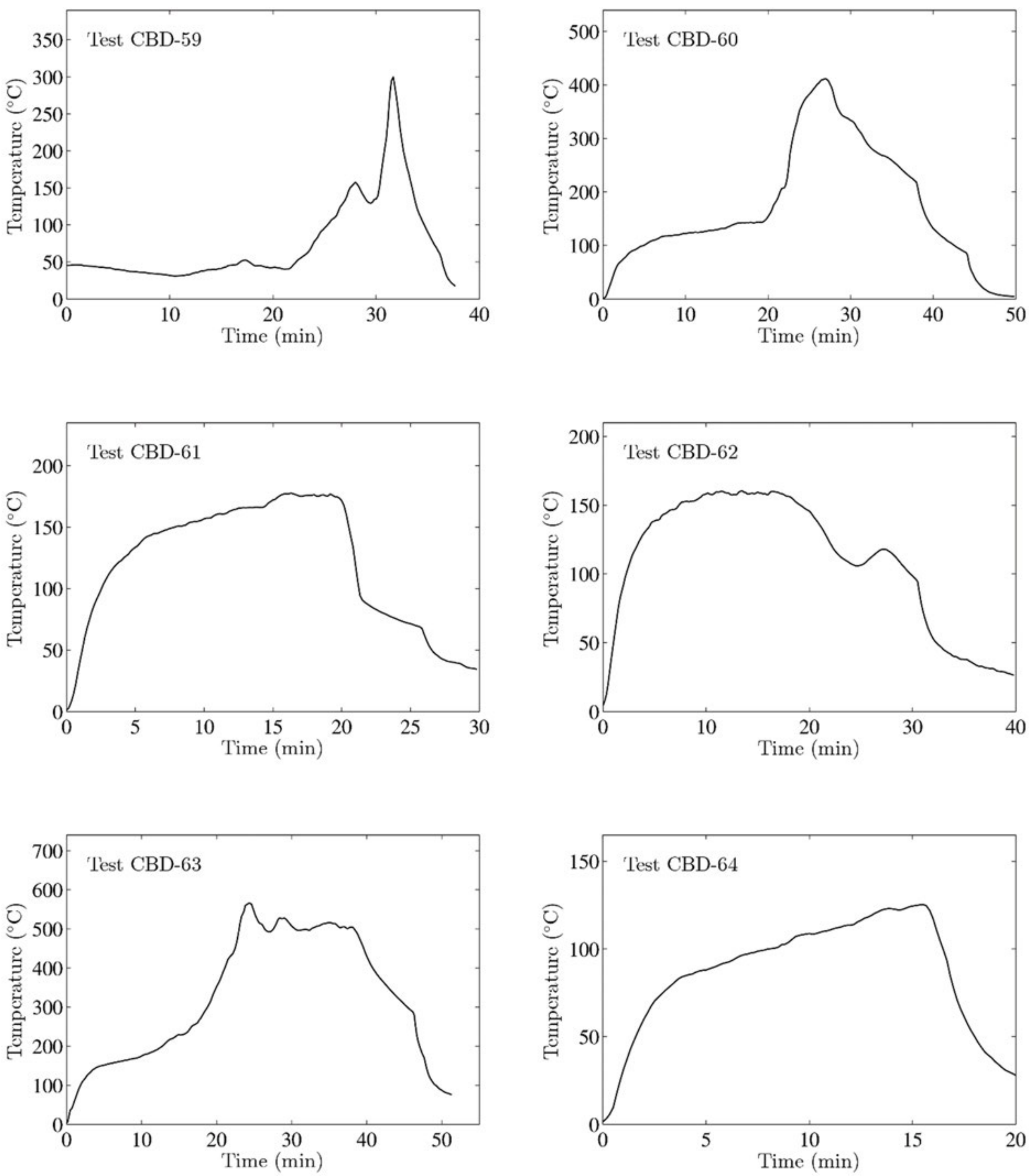


Figure A-11. Enclosure temperatures, Tests 59-64.

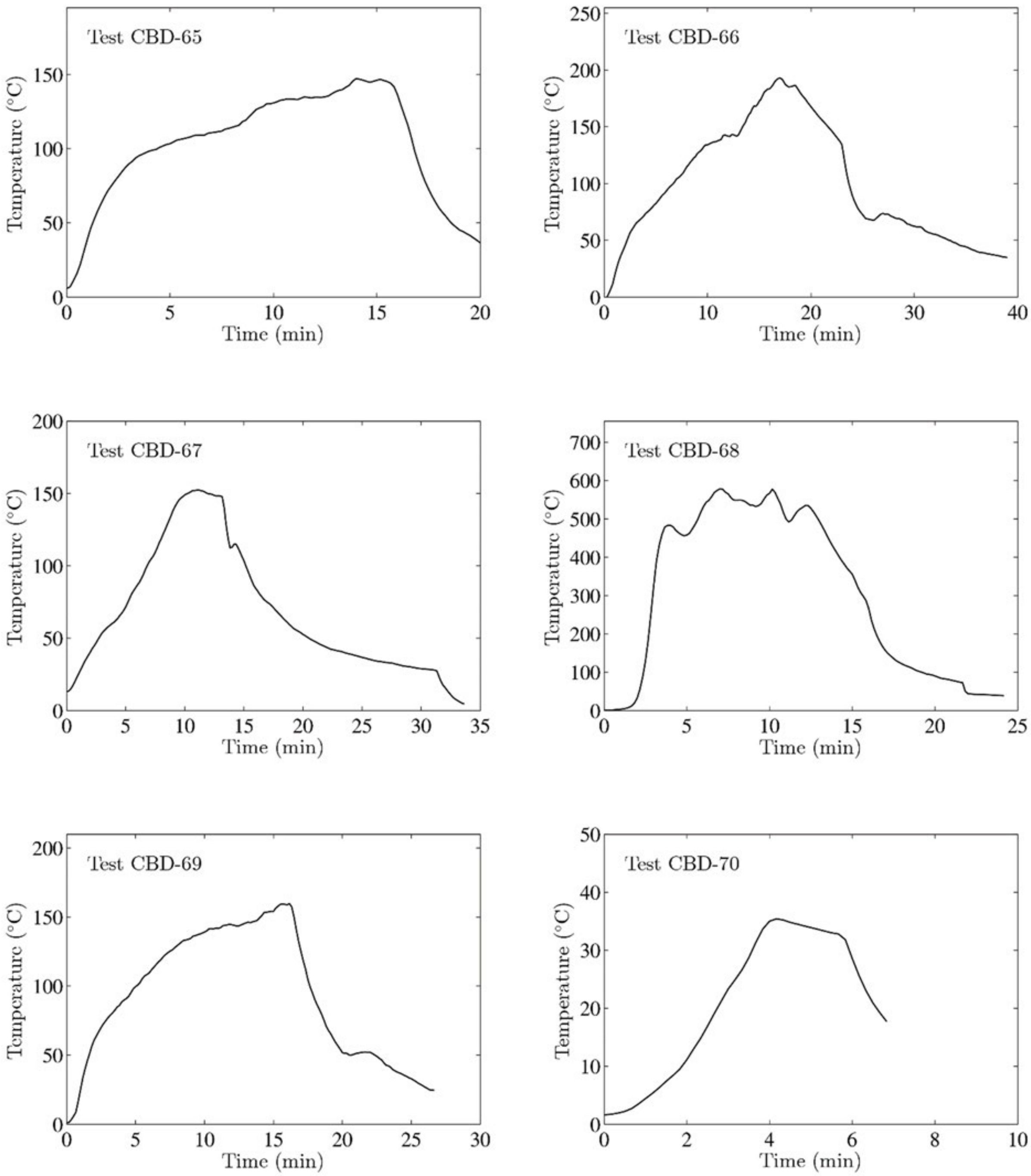


Figure A-12. Enclosure temperatures, Tests 65-70.

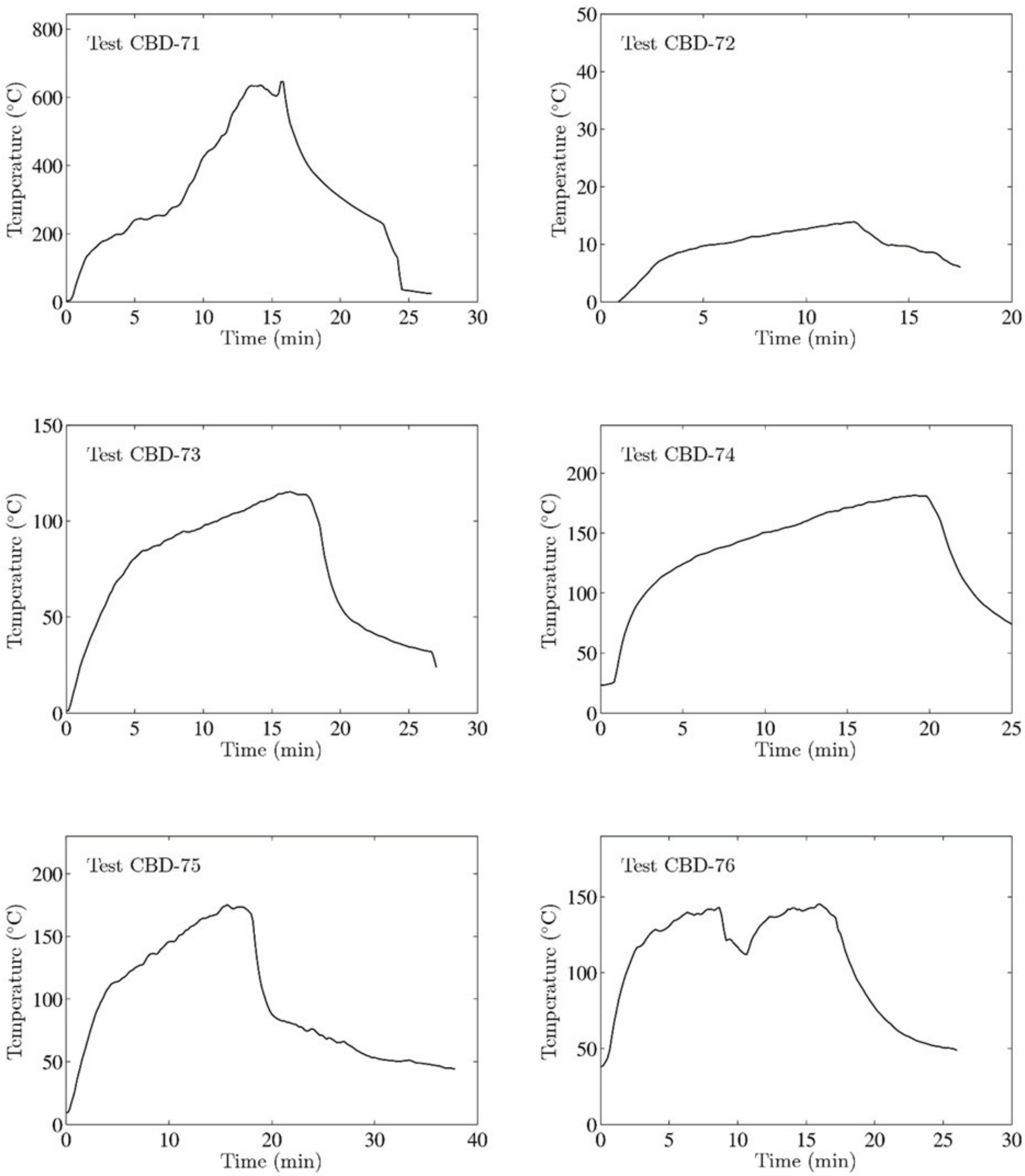


Figure A-13. Enclosure temperatures, Tests 71-76.

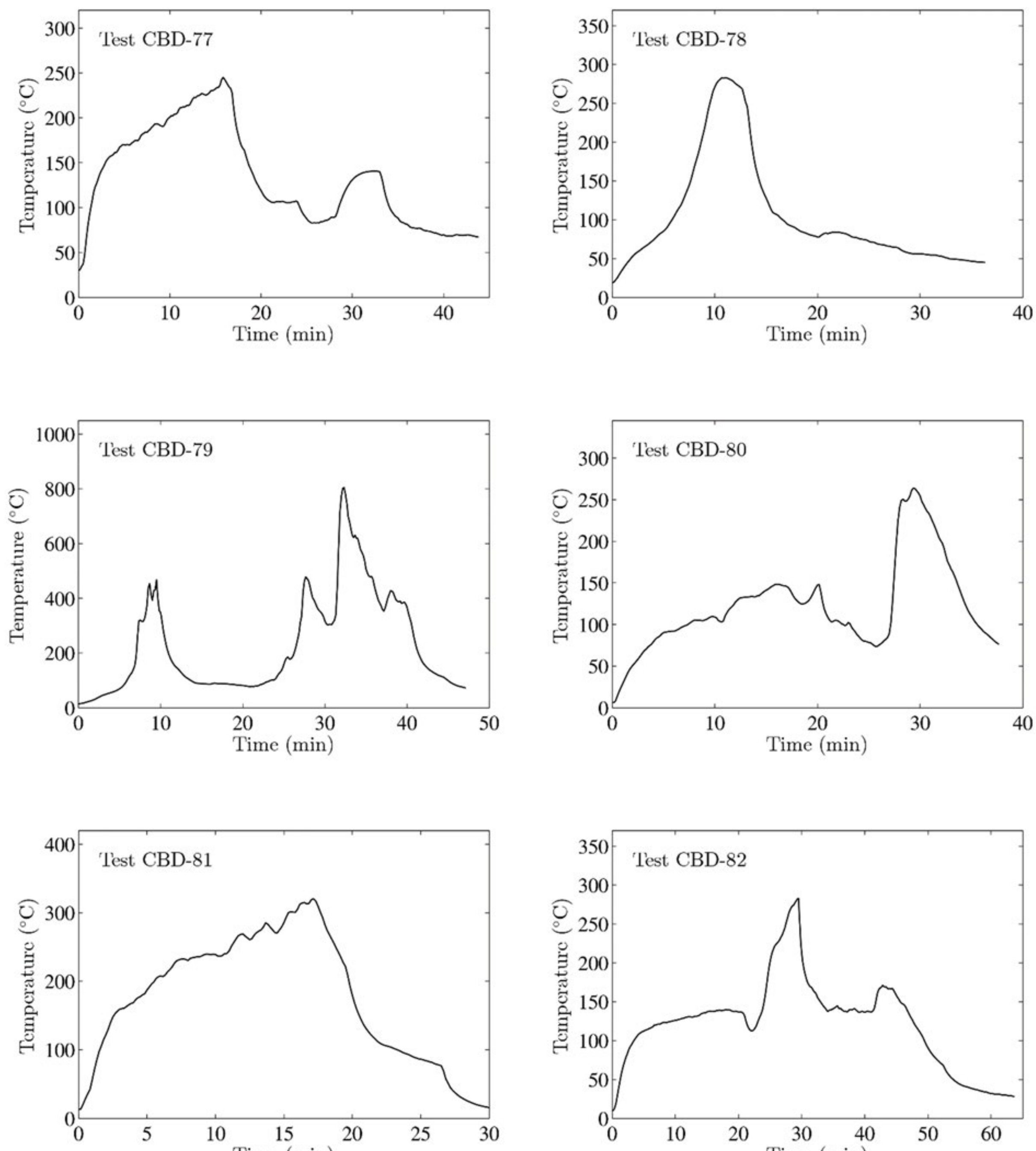


Figure A-14. Enclosure temperatures, Tests 77-82.

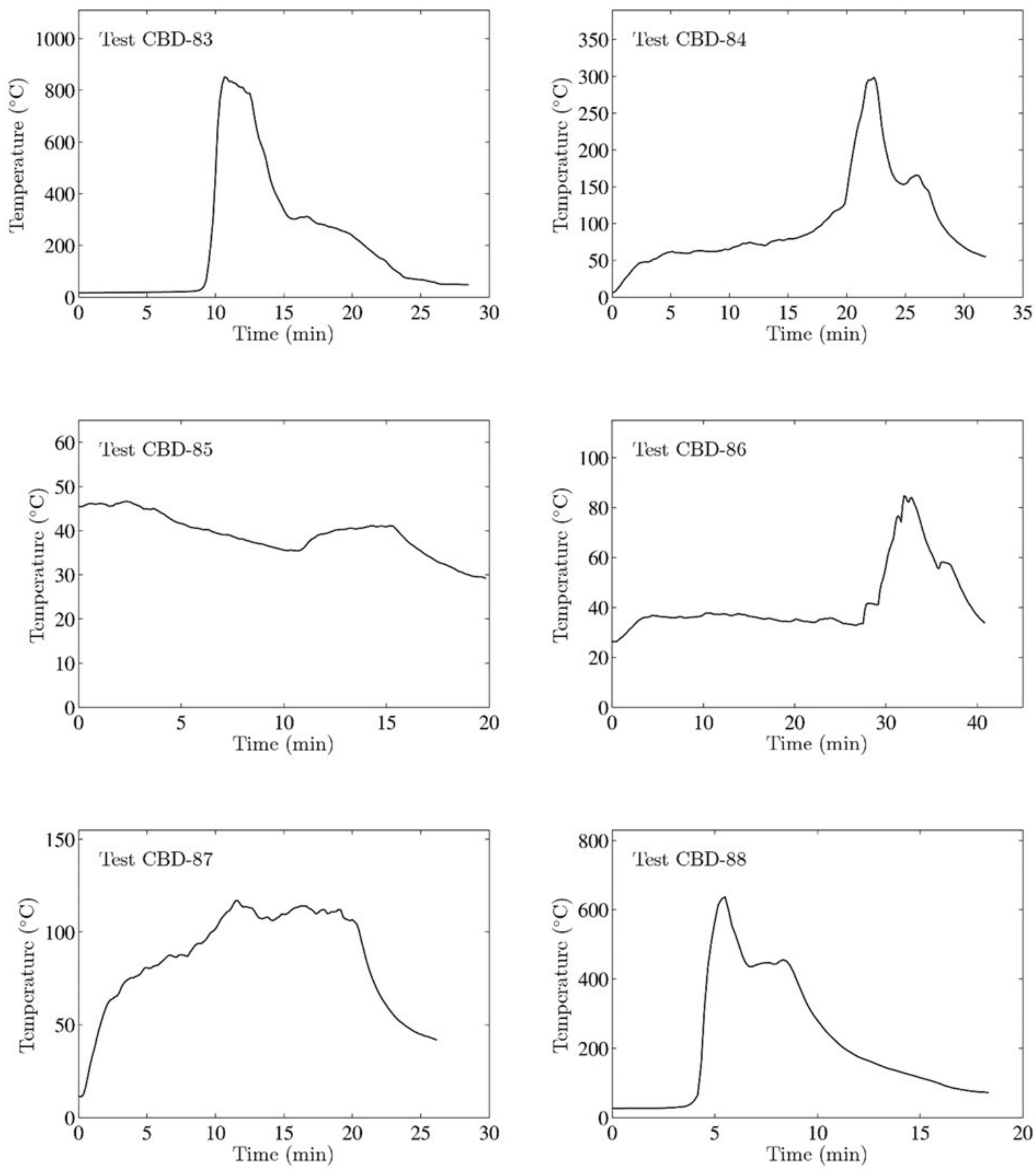


Figure A-15. Enclosure temperatures, Tests 83-88.

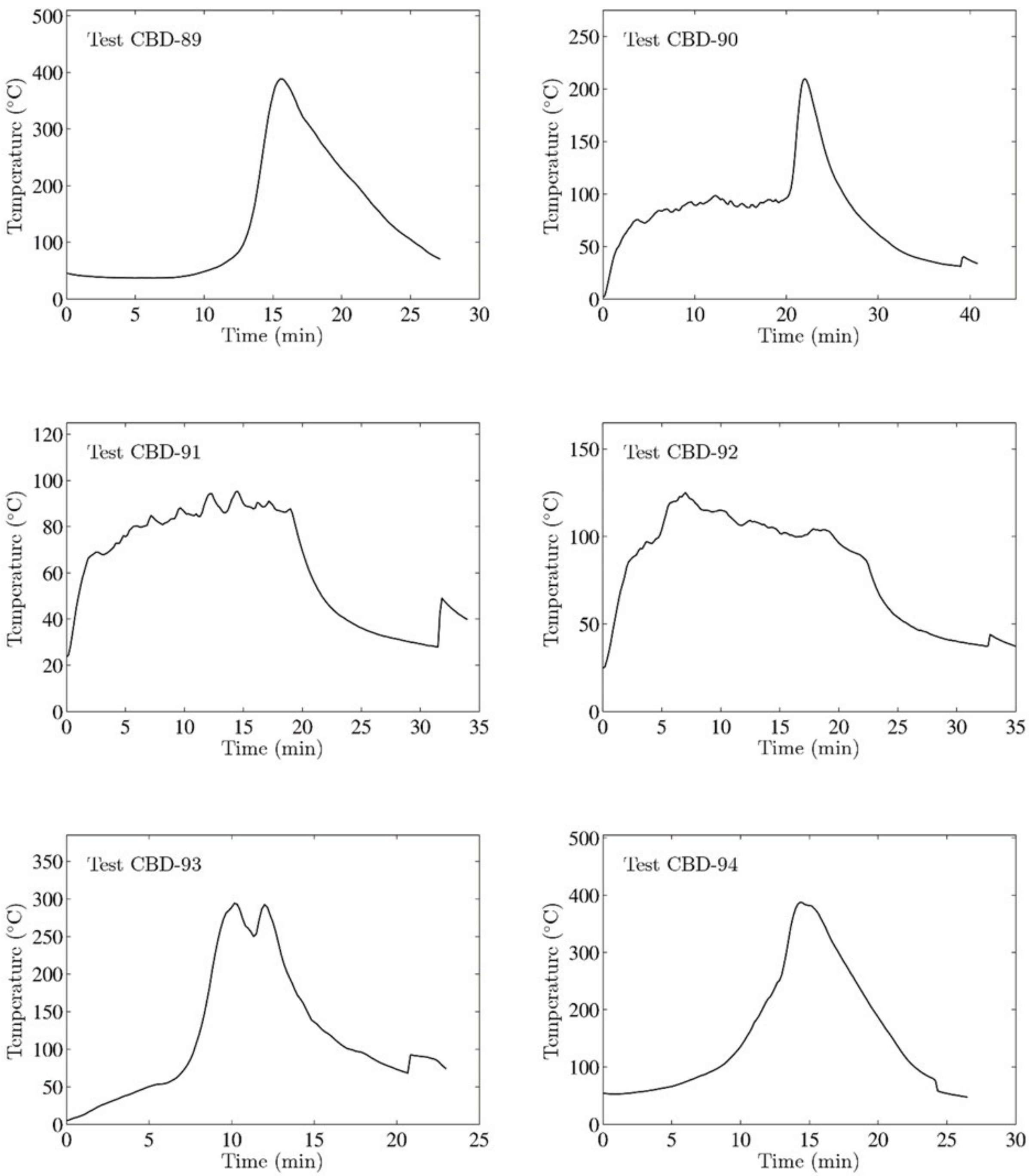


Figure A-16. Enclosure temperatures, Tests 89-94.

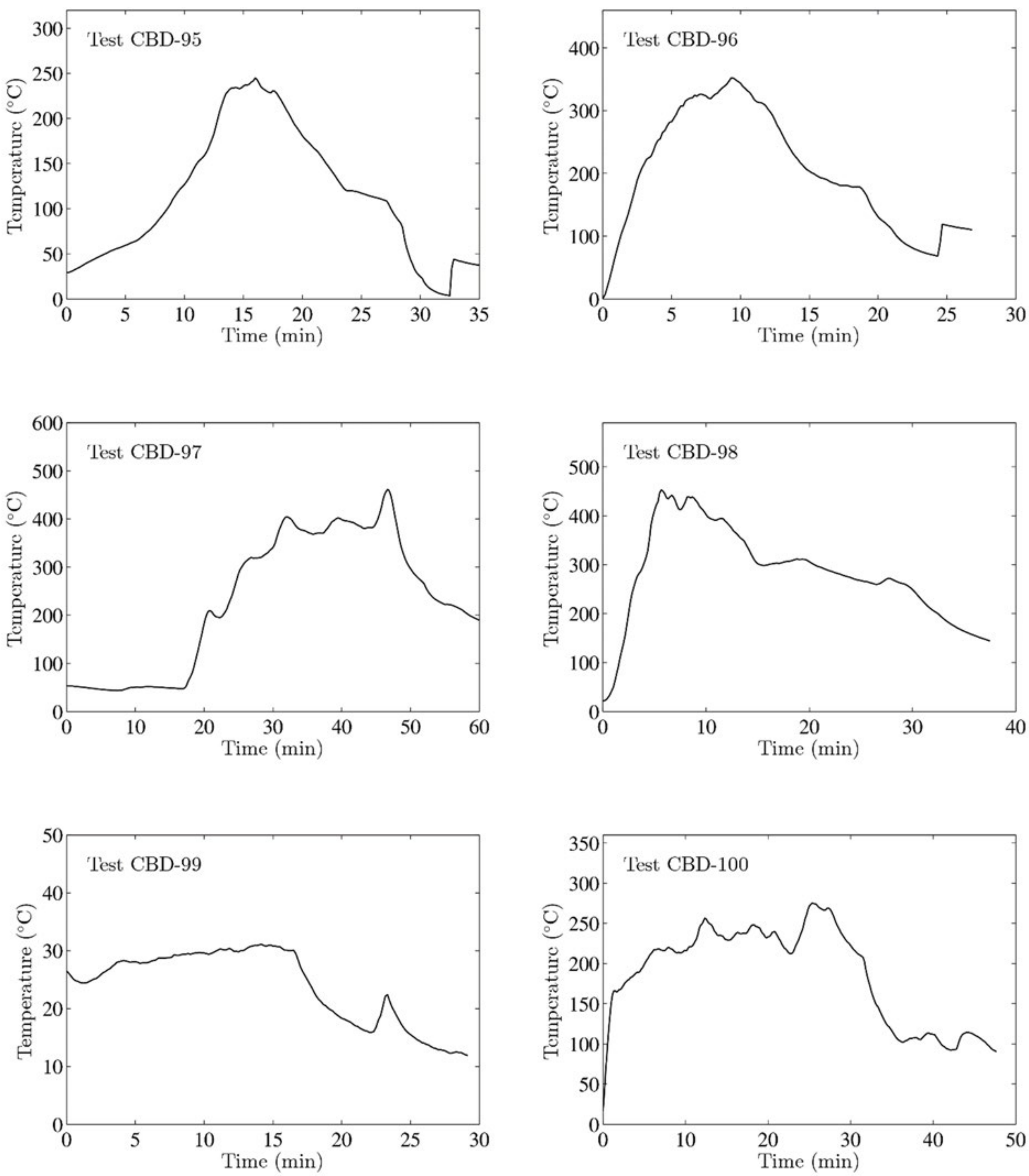


Figure A-17. Enclosure temperatures, Tests 95-100.

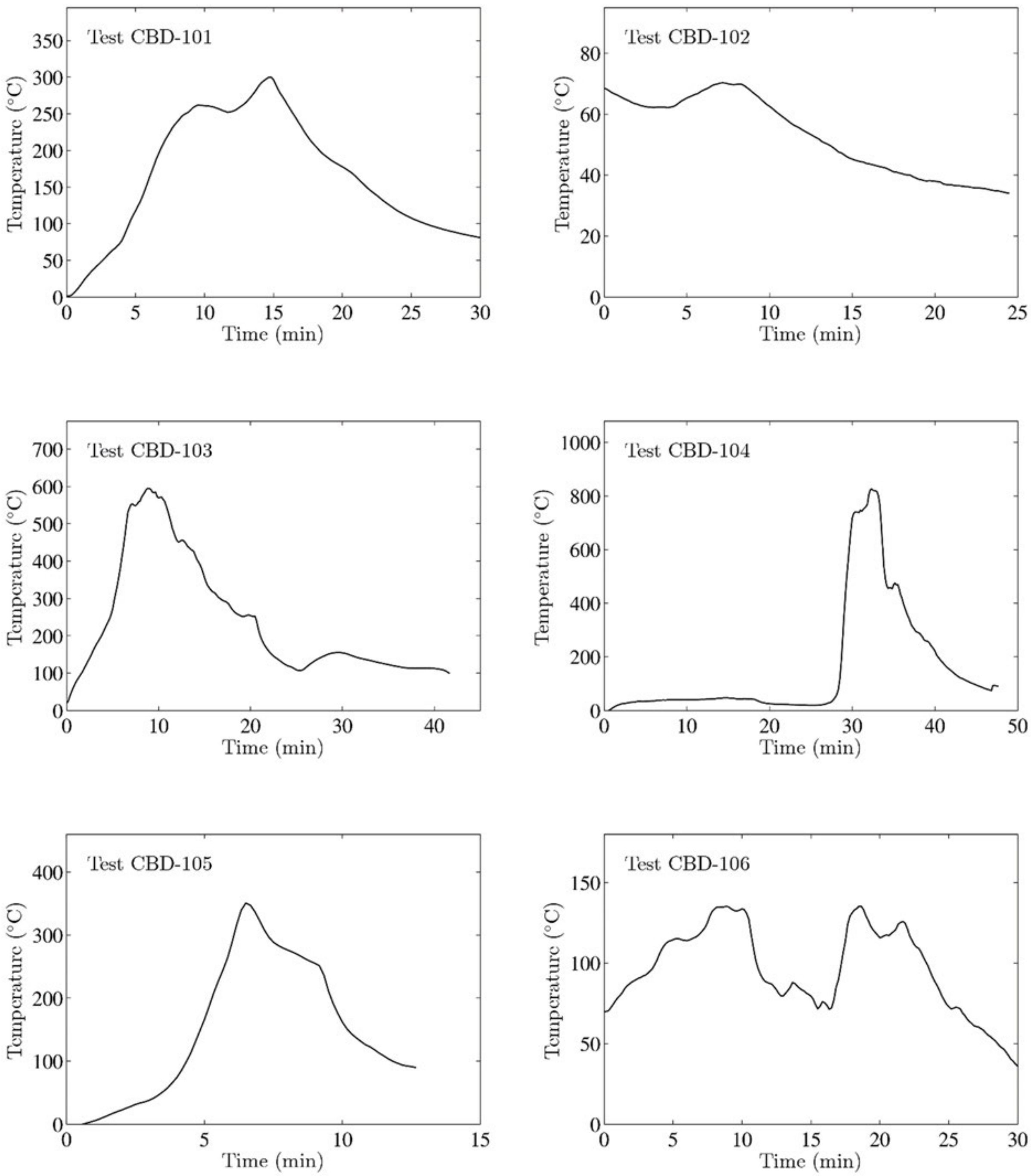


Figure A-18. Enclosure temperatures, Tests 101-106.

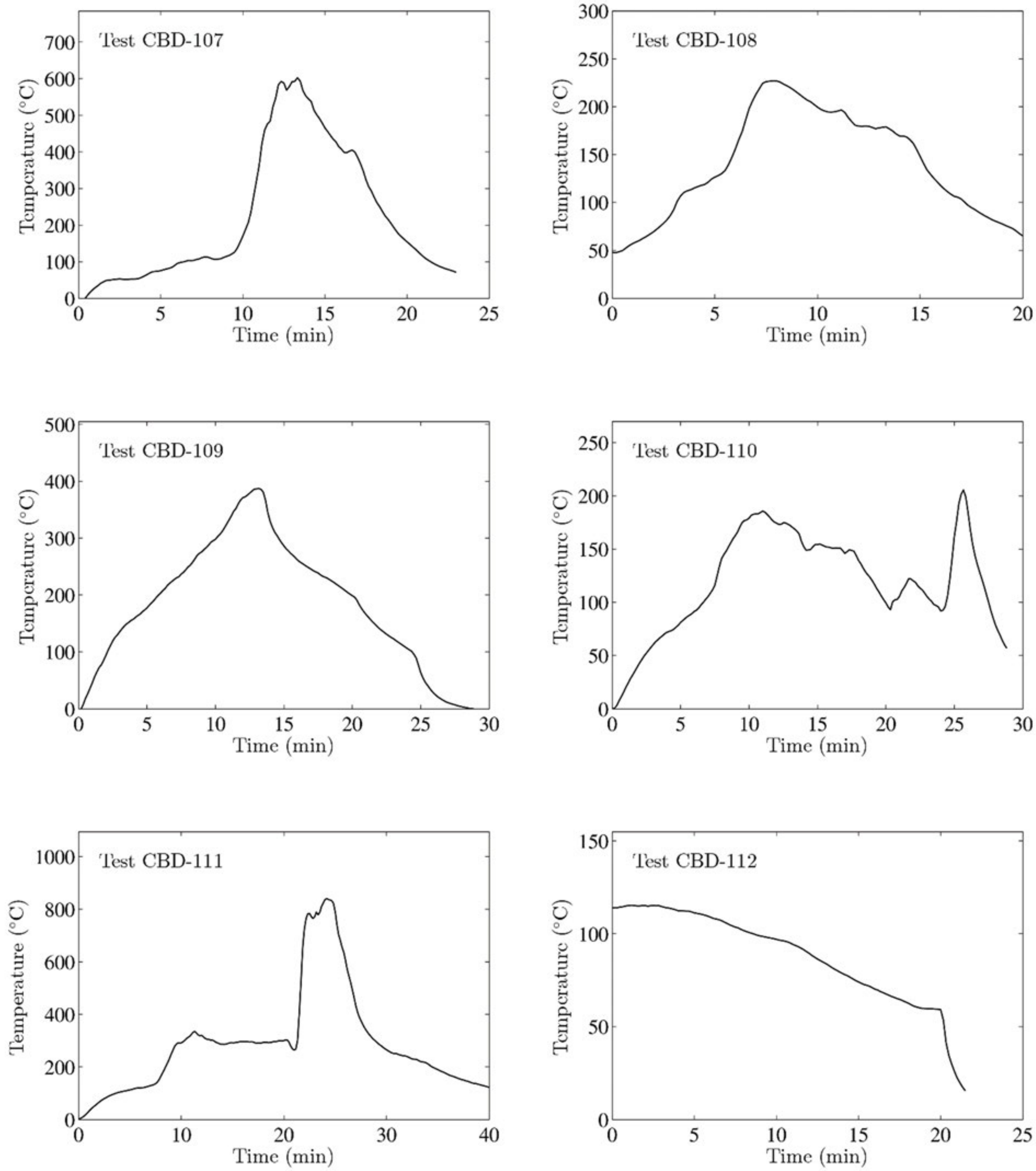


Figure A-19. Enclosure temperatures, Tests 107-112.

NRC FORM 335 (12-2010) NRCMD 3.7

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)

NUREG/CR-7197
Final

2. TITLE AND SUBTITLE

Heat Release Rates of Electrical Enclosure Fires (HELEN-FIRE)

3. DATE REPORT PUBLISHED

MONTH	YEAR
April	2016

4. FIN OR GRANT NUMBER

NRC-HQ-60-12-I-0007

5. AUTHOR(S)

Kevin McGrattan, Scott Bareham

6. TYPE OF REPORT

Technical

7. PERIOD COVERED (Inclusive Dates)

July 2012 - September 2014

8. PERFORMING ORGANIZATION - NAME AND ADDRESS (If NRC, provide Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)

National Institute of Standards and Technology
Engineering Laboratory; Fire Research Division
Gaithersburg, Maryland 20899

9. SPONSORING ORGANIZATION - NAME AND ADDRESS (If NRC, type "Same as above", if contractor, provide NRC Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address.)

Division of Risk Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES

D. Stroup, NRC Project Manager

11. ABSTRACT (200 words or less)

This report documents an experimental program to quantify the heat release rate and burning behavior of electrical enclosures commonly found in nuclear power plants. Electrical enclosures are a potential source of fire in nuclear power plants because they contain both combustible materials and live electrical circuits. These fires have the potential to disrupt power, instrumentation, and control in the plant. Key parameters affecting fire in an enclosure include its size, openings, electrical voltage, and combustible load.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

Fire experiments
Electrical enclosure fires

13. AVAILABILITY STATEMENT

unlimited

14. SECURITY CLASSIFICATION

(This Page) unclassified

(This Report) unclassified

15. NUMBER OF PAGES

16. PRICE

NRC FORM 335 (12-2010)

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, DC 20555-0001

OFFICIAL BUSINESS

@NRCgov

NUREG/CR-7197
Final

Heat Release Rates of Electrical Enclosure Fires (HELEN-FIRE)

April 2016