Draft Report for Comment

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)

Draft Report for Comment

Office of Nuclear Regulatory Research

Final Report Subject to Change Based on Review of Public Comments

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 Public Electronic Reading Room at http://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 Printing Office
   Mail Stop SSOP
   Washington, DC 20402-0001
   Internet: bookstore.gpo.gov
   Telephone: 202-512-1800
   Fax: 202-512-2250
2. The National Technical Information Service
   Springfield, VA 22161-0002
   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: Office of the Chief Information Officer, Reproduction and Distribution
Services Section
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
E-mail: DISTRIBUTION@nrc.gov
Facsimile: 301-415-2289

Some publications in the NUREG series that are posted at NRC's Web site address http://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, and 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 contractor-prepared 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).

.

 Draft Report for Comment

NUREG/CR-7197

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

Draft Report for Comment

Manuscript Completed: February 2015
Date Published: June 2015

Prepared by:
Kevin McGrattan
Scott Bareham

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

Draft Report for Comment

 Draft Report for Comment

ABSTRACT

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.

Draft Report for Comment

CONTENTS

 Draft Report for Comment

 Draft Report for Comment

LIST OF FIGURES

 Draft Report for Comment

LIST OF TABLES

 Draft Report for Comment

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. Key parameters affecting fire in an electrical enclosure include 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. 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.

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. 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.

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 varied from 0.3 kW to 576 kW. The mean was 43 kW; the median was 19 kW. Eleven fires peaked at greater than 100 kW. The mean time to peak was 16 min; the median was 13 min.

Draft Report for Comment

ACKNOWLEDGEMENTS

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.

DISCLAIMER

 Draft Report for Comment

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
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
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 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 electrical enclosure include its size, openings, electrical voltage, and combustible load.

1.2 Previous Studies

Heat release rate 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 heat release rates 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 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 heat release rates, 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 heat release rate 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.

1.3 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[1] 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 heat release rates of fires in electrical enclosures containing a wide variety of cable types, geometries, ventilation configurations, and ignition sources with the aim of producing a more realistic distribution of heat release rates than that of previous studies. The enclosures used in the experiments have been acquired from a nuclear power plant built in the late 1970s but never operated. These enclosures contain wiring typical of those built after the Brown's Ferry fire of 1975. In addition, these enclosures shall be refurbished after an initial set of experiments so that they resemble other types of enclosures found in other plants.

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

2 DESCRIPTION OF ENCLOSURES

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

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 show typical 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 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 2-4 displays photographs of motor control centers. These 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.

Draft Report for Comment

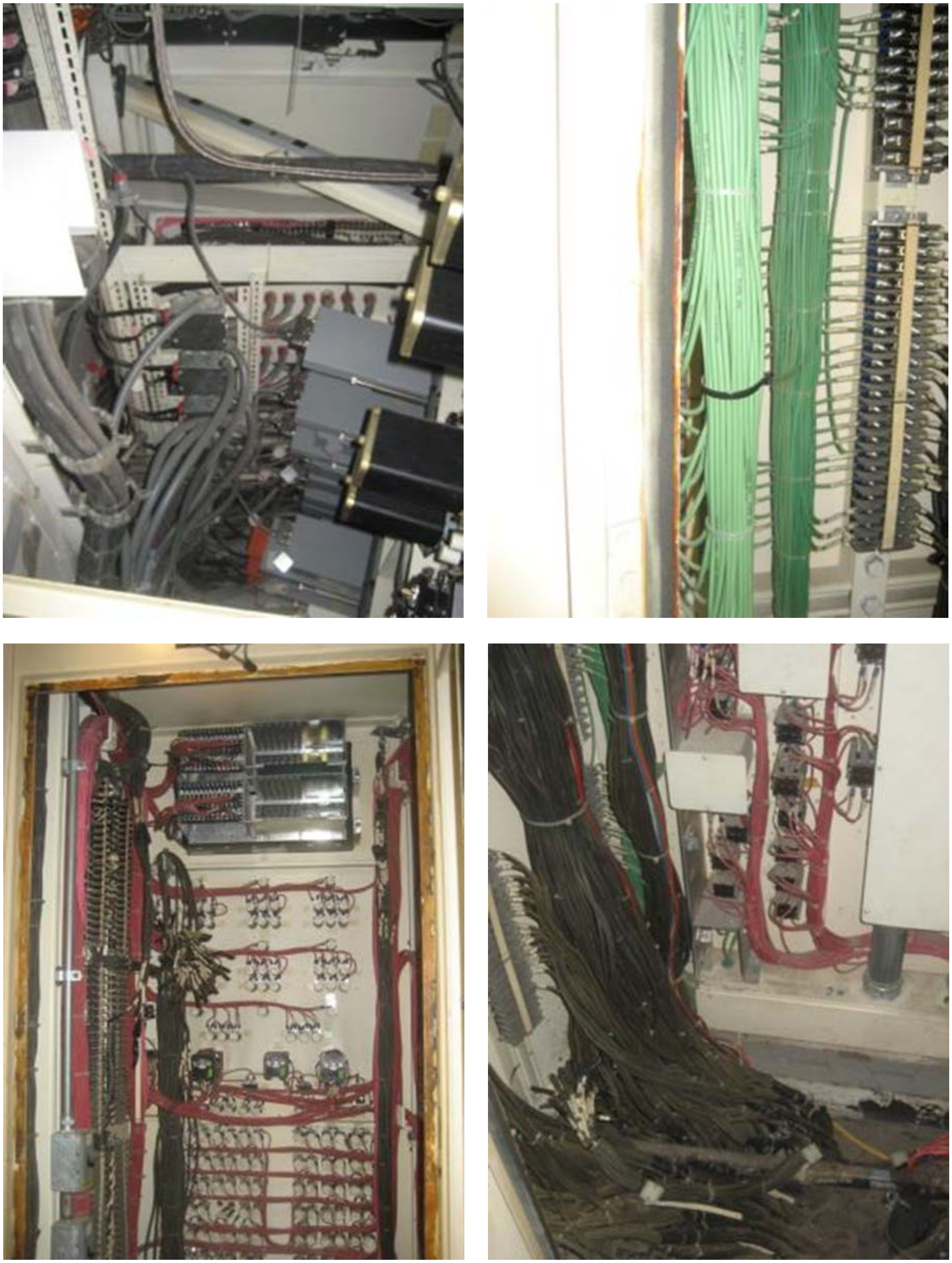


Figure 2-1. Photographs of enclosures typically found near the main control room.

 Draft Report for Comment

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.

 Draft Report for Comment

Figure 2-4. Photographs of the internal wiring of 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. 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.

The enclosures appear to have been manufactured in the late 1970s by one or two manufacturers. All were constructed of steel with a thickness of approximately 3 mm (1/8 in).

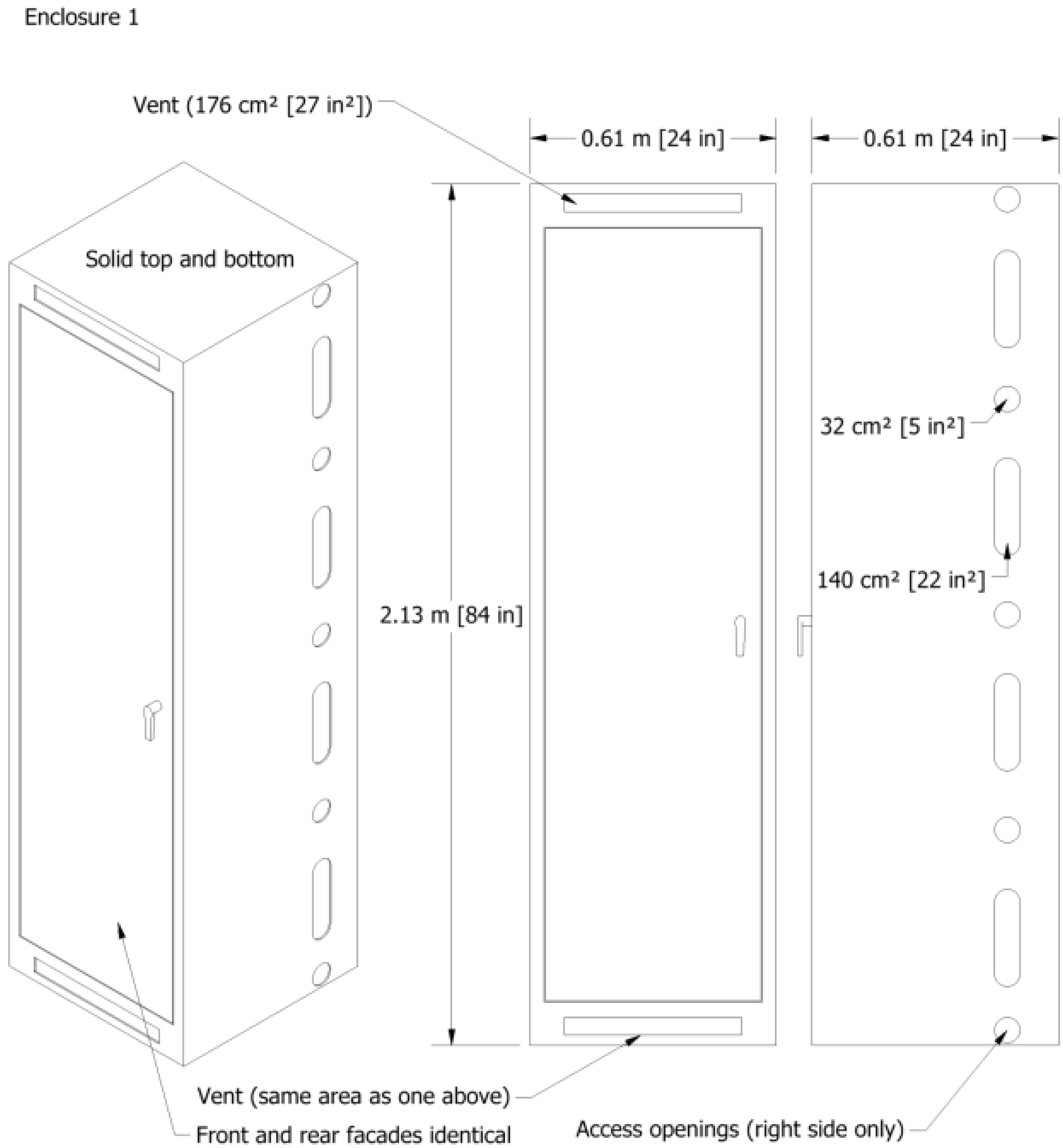
 Draft Report for Comment

 Draft Report for Comment

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 2-5. Photographs of Enclosure 1.



1
2 **Figure 2-6. 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 2-7. Photographs of Enclosure 2.

 Draft Report for Comment

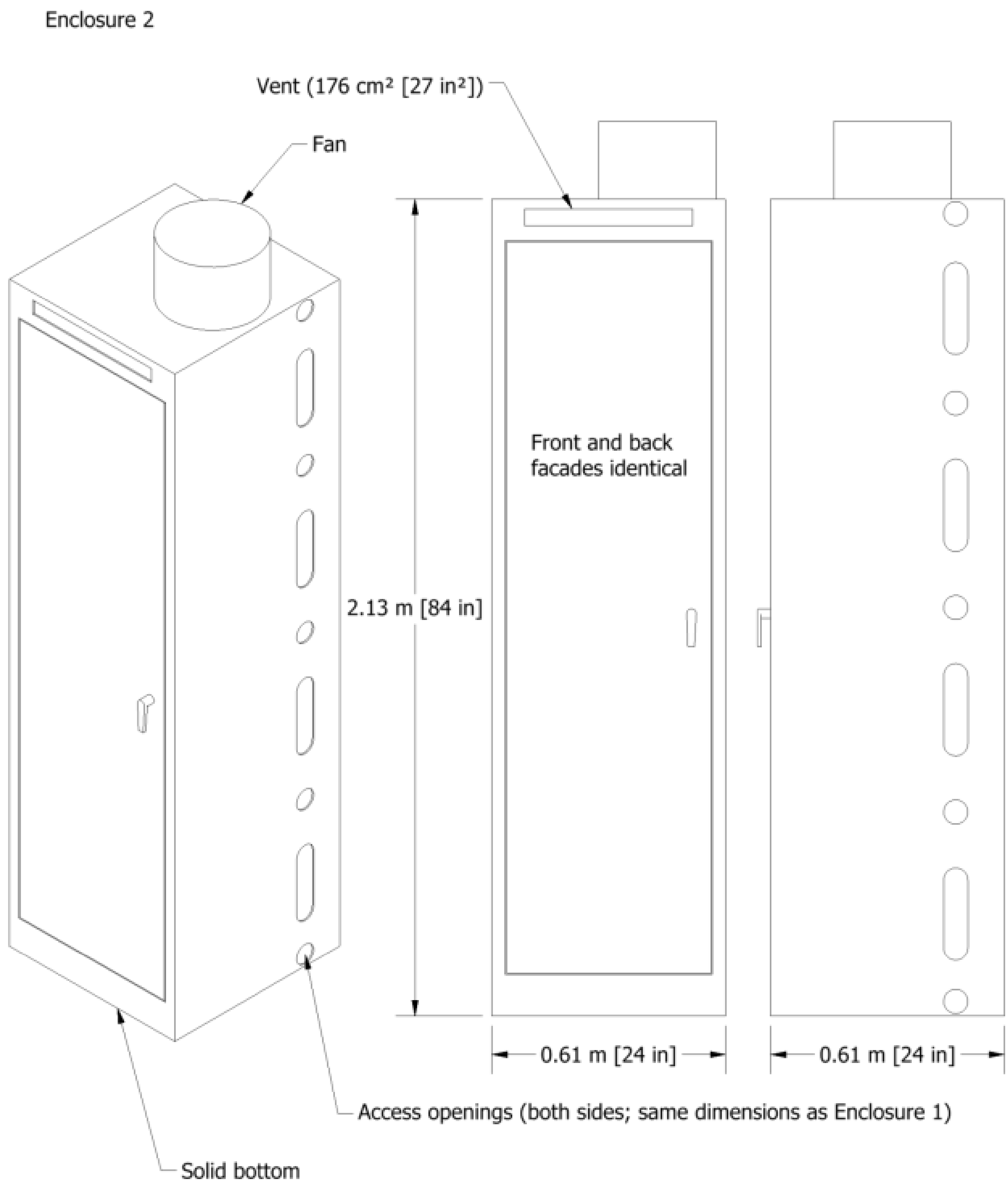


Figure 2-8. Sketch of Enclosure 2.

 Draft Report for Comment

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 plexi-glass window in Figure 2-9. 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 2-9. Photographs of Enclosure 3.

 Draft Report for Comment

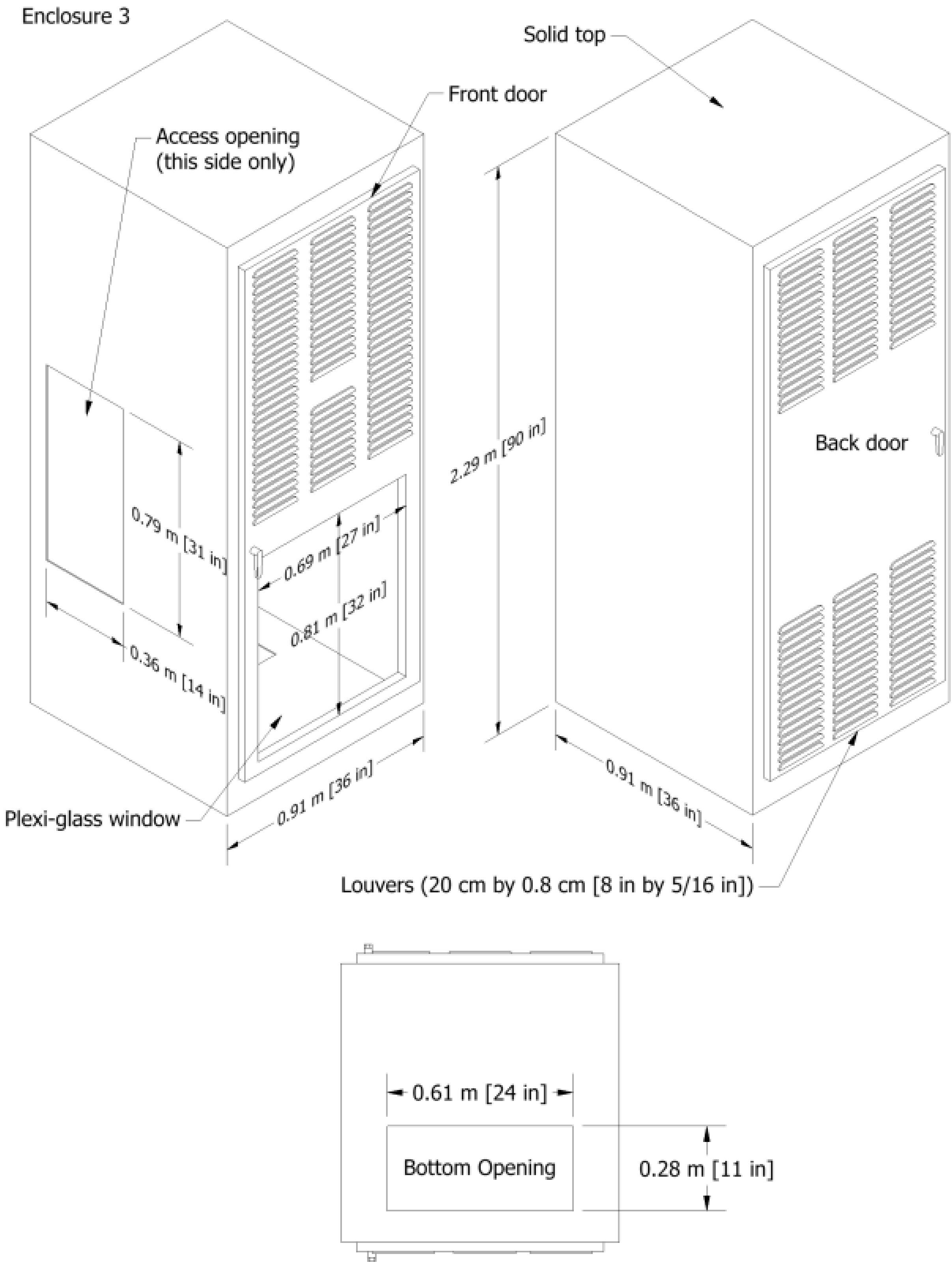


Figure 2-10. Sketch of Enclosure 3.

 Draft Report for Comment

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 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.

Figure 2-11. Photographs of Enclosures 4 and 5.

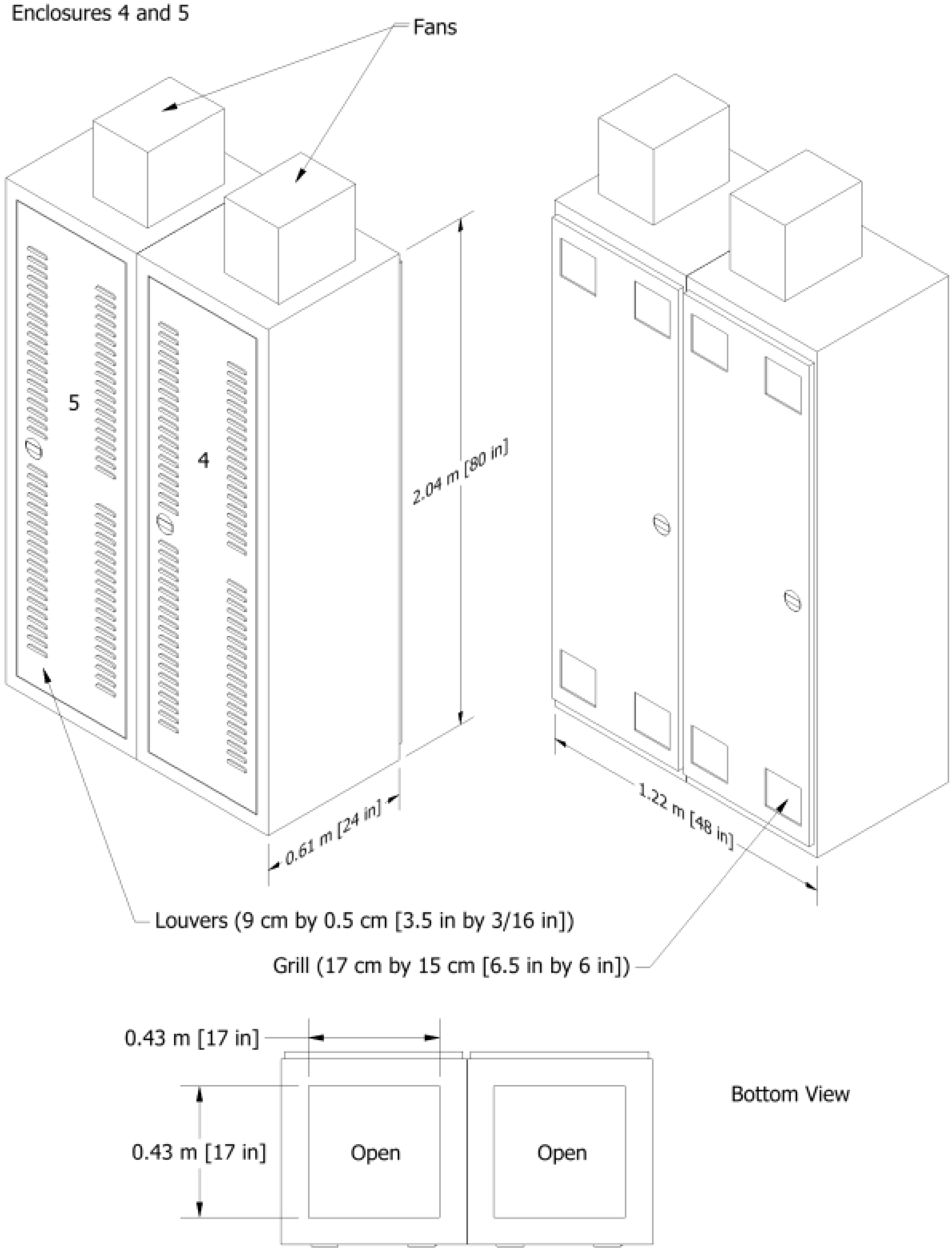


Figure 2-12. Sketch of Enclosures 4 and 5.

 Draft Report for Comment

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 2-13. Photographs of Enclosure 6.

 Draft Report for Comment

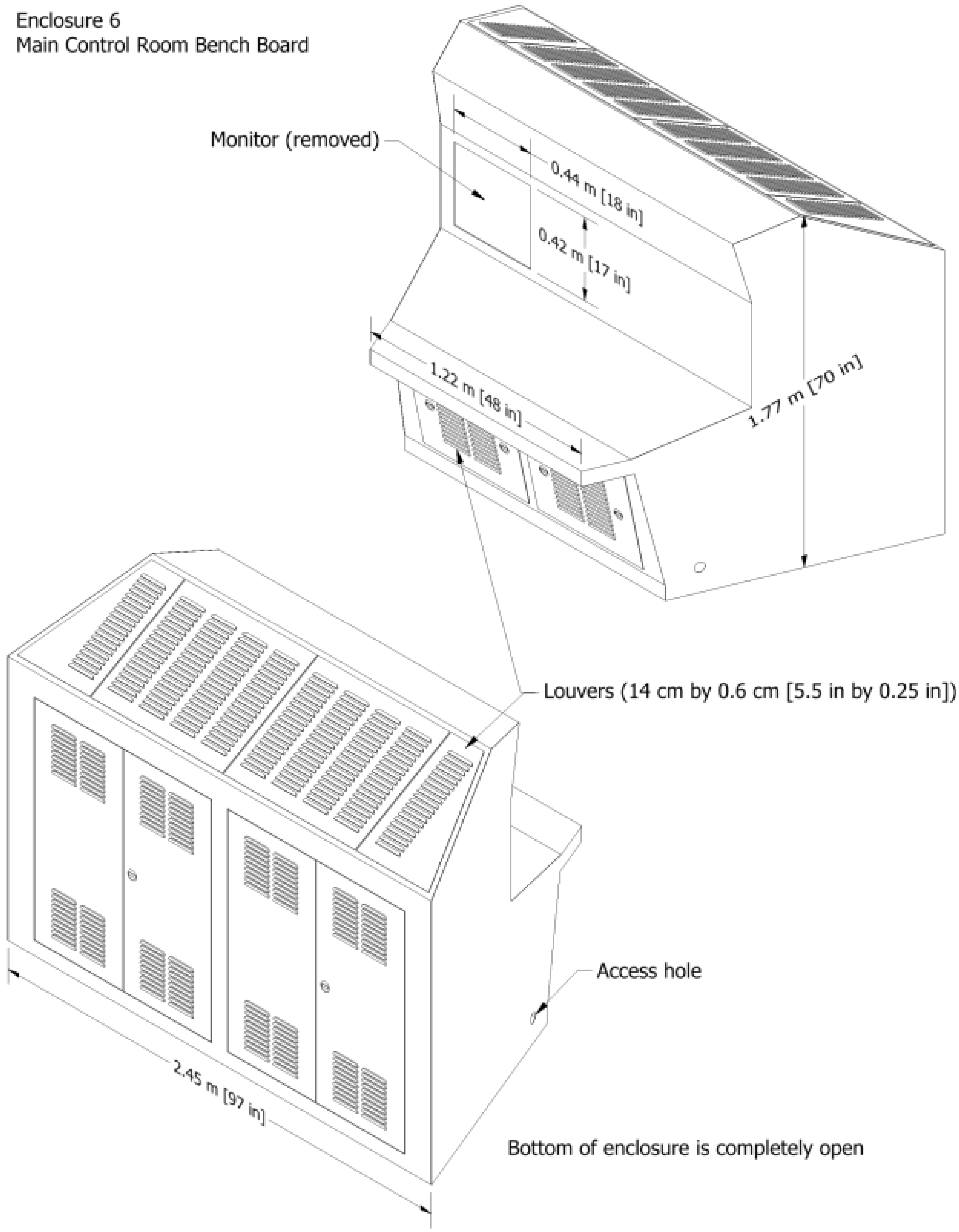


Figure 2-14. Sketch of Enclosure 6.

 Draft Report for Comment

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 2-15. Photographs of Enclosure 7.

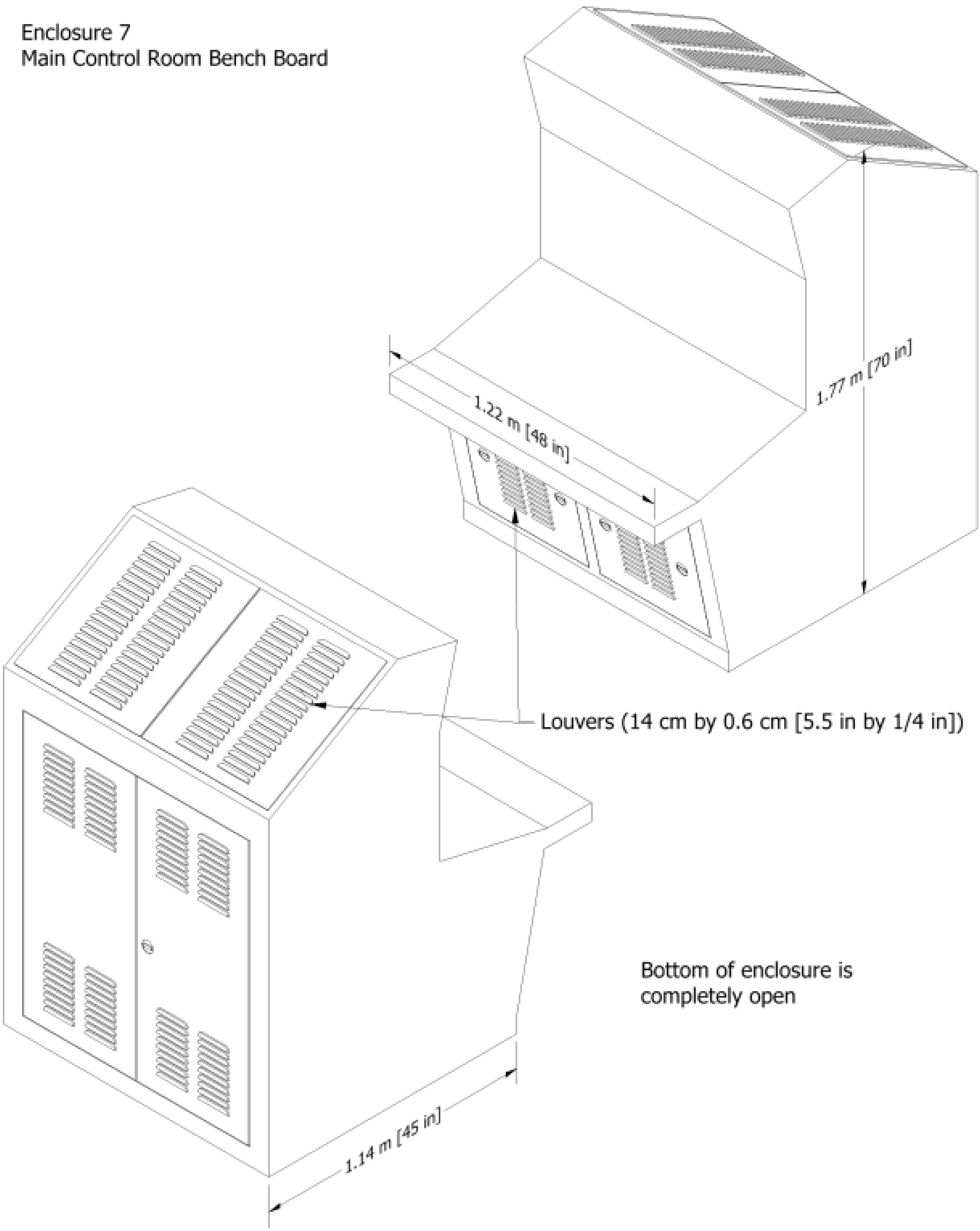


Figure 2-16. Sketch of Enclosure 7.

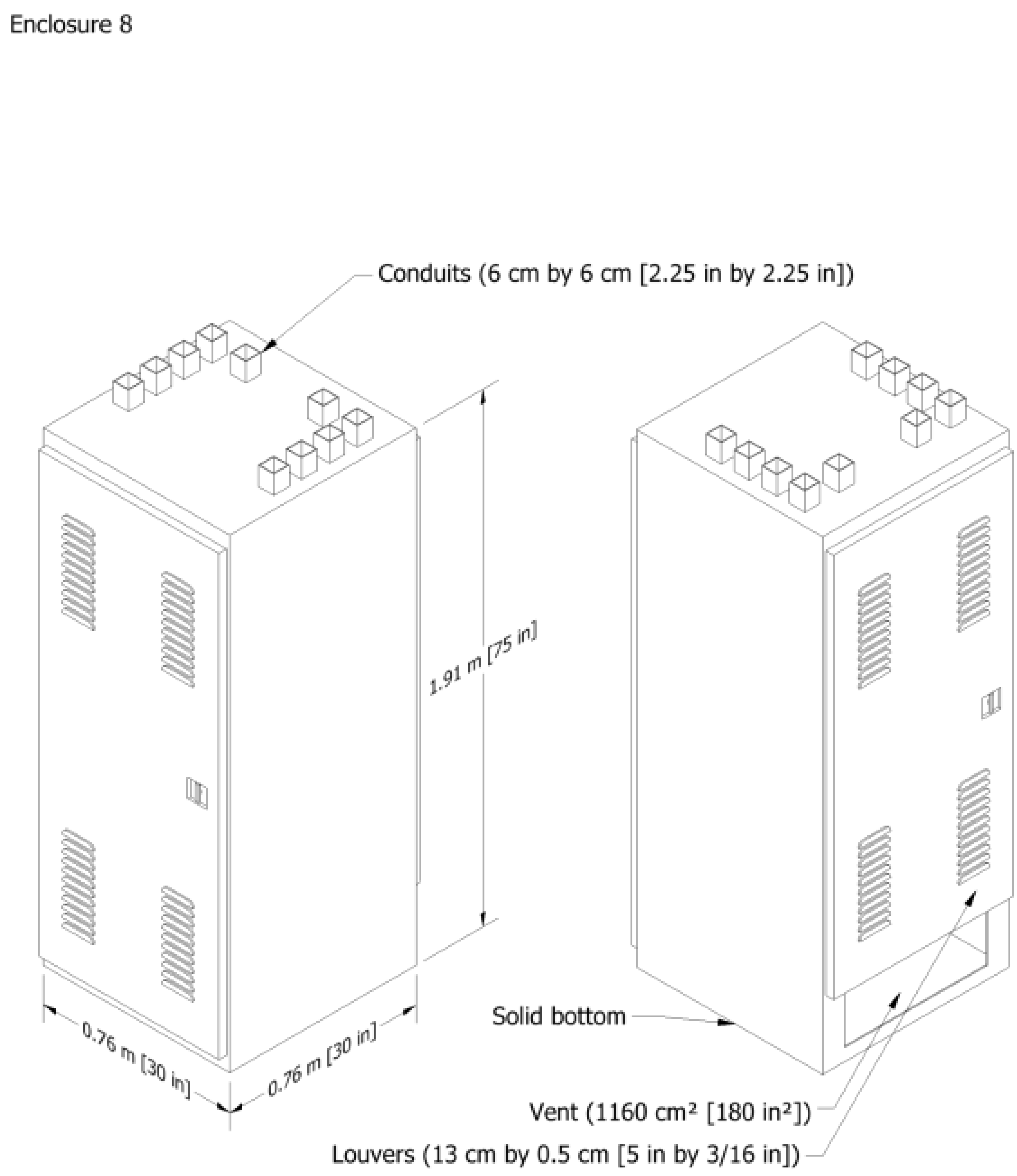
 Draft Report for Comment

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 2-17. Photographs of Enclosure 8.

 Draft Report for Comment



1
2 **Figure 2-18. Sketch of Enclosure 8.**

Draft Report for Comment

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.

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.

Draft Report for Comment

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
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

Cable No.	Source	Manufacturer*	Date	Cable 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	17.12	3.06	1.74	0.44	0.52	0.33	0.13	0.02
831	SIS	TS	TS	1	3.58	0.00	1.25	0.03	0.65	0.00	0.35	0.00
832	Unknown	Unknown	Unknown	1	6.78	0.98	2.34	0.08	0.15	0.37	0.21	0.01
833	Unknown	Unknown	Unknown	1	4.70	N/A	1.74	0.05	0.63	0.00	0.37	0.00
834	XLPE	No Jacket	TS	1	3.97	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	TVA Type MXPSJ	TVA Type MXPSJ	TS	2	8.57	2.60	1.48	0.11	0.24	0.46	0.13	0.10
837	TVA Type MXPSJ	TVA Type MXPSJ	TS	4	16.9	2.86	1.48	0.38	0.13	0.53	0.07	0.20
838	TVA Type MXPSJ	TVA Type MXPSJ	TS	6	18.4	2.86	1.48	0.46	0.17	0.55	0.09	0.12

 Draft Report for Comment

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
839	TVA Type MXPSJ	TVA Type MXPSJ	TS	8	19.8	2.86	1.48	0.55	0.20	0.16	0.13	0.06
840	TVA Type MXPSJ	TVA Type MXPSJ	TS	10	23.4	3.65	1.48	0.77	0.25	0.31	0.17	0.04
841	TPE	TPE	TP	3	13.46	2.08	1.19	0.12	0.29	0.50	0.15	0.06
842	Unknown	Unknown		40	1.2	Unknown	Unknown	0.08	Unknown	Unknown	Unknown	Unknown
843	Unknown	Unknown	Unknown	352	36.1	N/A	Unknown	2.86	Unknown	Unknown	Unknown	Unknown
844	PVC	PVC	TP	3	10.2	01.80	0.76	0.17	0.06	0.06	0.04	0.01
845	EP	TS	TS	1	5.9	0	2.10	0.08	0.5	0	0.3	0

 Draft Report for Comment

4 EXPERIMENTAL PROCEDURE

4.1 Oxygen Consumption Calorimeter

The measurements of the heat release rate of the enclosure fires were performed at the Chesapeake Bay Detachment of the Naval Research Laboratory[2]. This facility has a 6.1 m by 6.1 m (20 ft by 20 ft) large-scale calorimeter that is designed to measure the heat release rate 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 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 45 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.

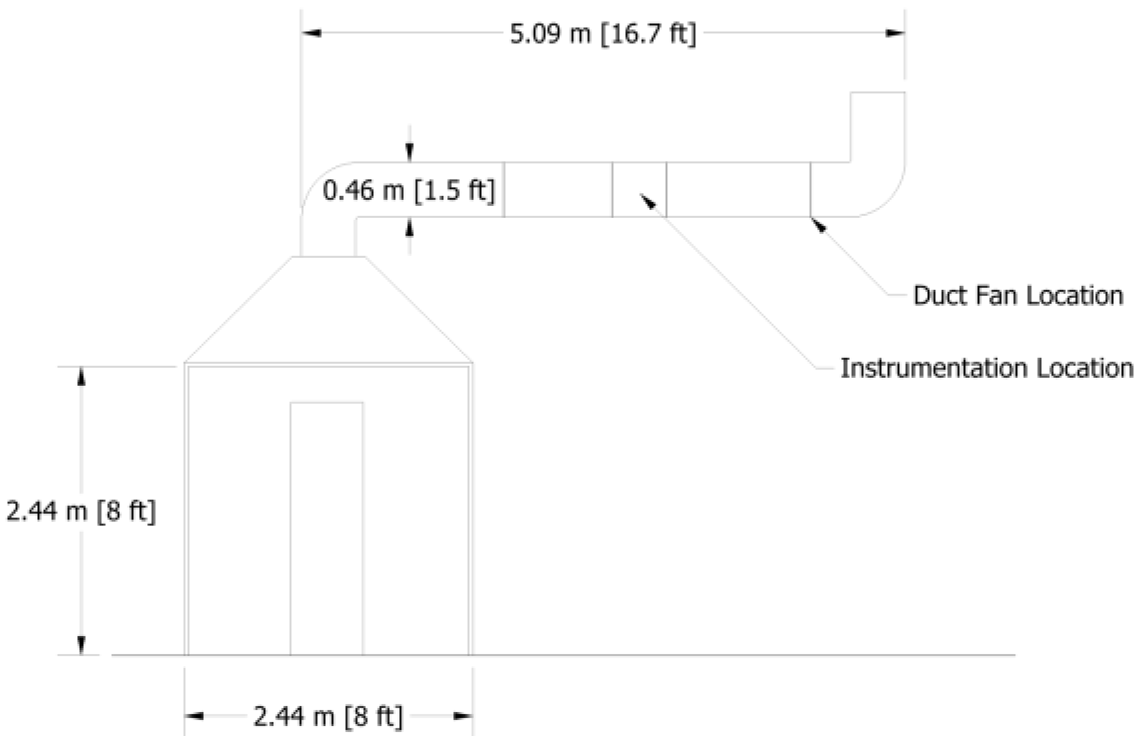


Figure 4-1. Schematic diagram of the small calorimeter.

[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.

 Draft Report for Comment

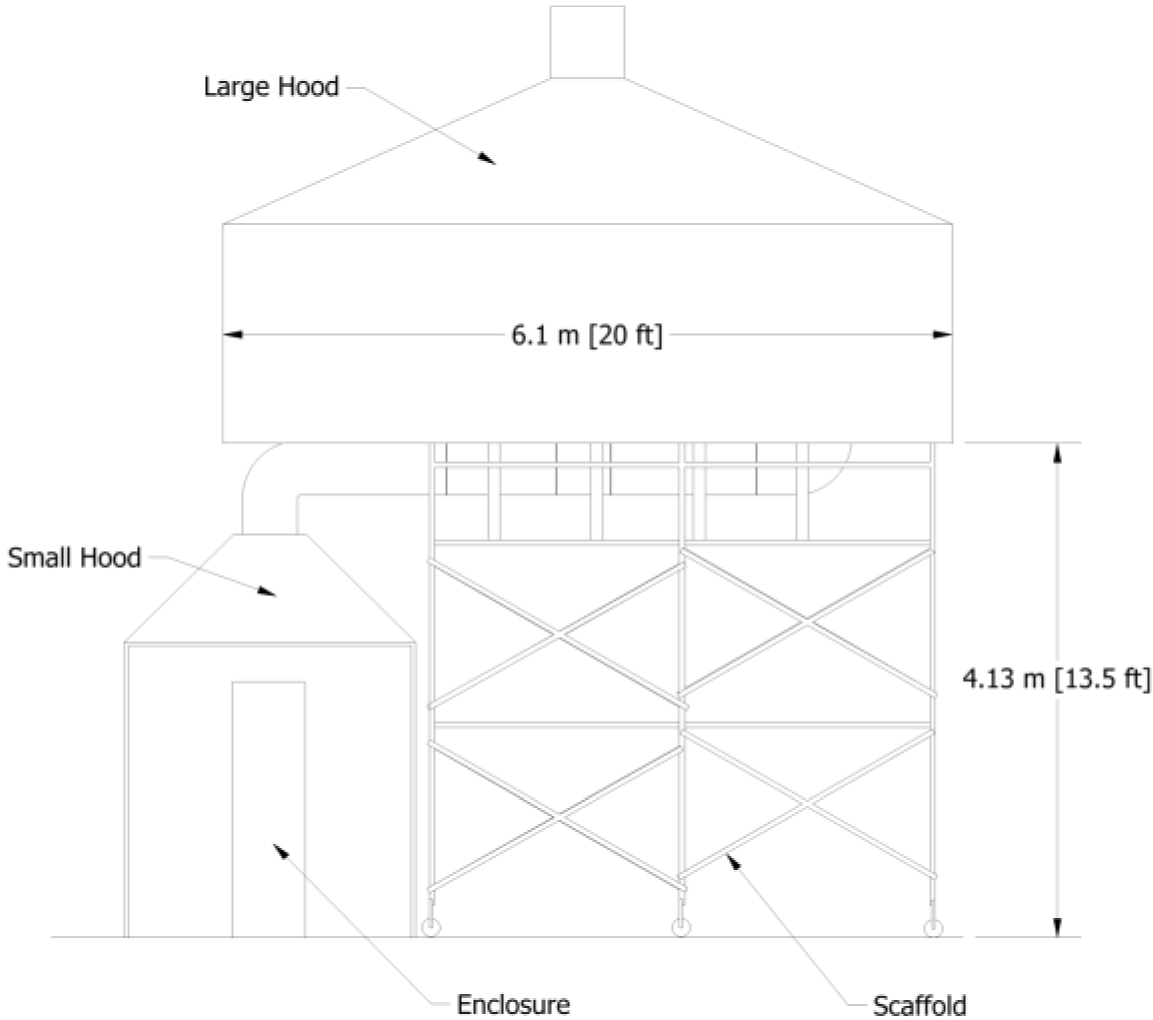


Figure 4-2. Schematic diagram of the small calorimeter underneath the large hood at the CBD test facility.

The heat release rate 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):

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

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 $\dot{Q}$ Heat release rate (kW)
E Heat release per unit mass of oxygen consumed (12800 kJ/kg)
φ Oxygen depletion factor

 Draft Report for Comment

α	Volumetric expansion factor (1.105)
$\dot{m}_{\mathrm{e}}$	Mass flow rate in the exhaust duct (kg/s)
$M_{\mathrm{O_2}}$	Molecular mass of oxygen (32 g/mol)
M_{a}	Molecular mass of the ambient air (29 g/mol)
$X_{\mathrm{H_2O}}^{\mathrm{a}}$	Volume fraction of water vapor in the ambient air
$X_{\mathrm{CO_2}}^{\mathrm{a}}$	Volume fraction of carbon dioxide in the ambient air
$X_{\mathrm{O_2}}^{\mathrm{a}}$	Volume fraction of oxygen in the ambient air
$X_{\mathrm{CO_2}}^{\mathrm{e}}$	Volume fraction of carbon dioxide in the exhaust duct
$X_{\mathrm{O_2}}^{\mathrm{e}}$	Volume fraction of oxygen in the exhaust duct

The mass flow rate of the exhaust gases, $\dot{m}_{\mathrm{e}}$, is the product of their density, ρ, and their 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 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:

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

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 to the extent recommended by the manufacturer of the Annubar®.

The uncertainty in the heat release rate measurement is primarily due to the value of the heat of combustion based on oxygen consumption, E, the mass flow rate in the duct, $\dot{m}_{\mathrm{e}}$, and the oxygen depletion, $X_{\mathrm{O_2}}^{\mathrm{a}} - X_{\mathrm{O_2}}^{\mathrm{e}}$. Tewarson (*SFPE Handbook*, 2008) estimates that E equals 12800 kJ/kg with a relative standard uncertainty of 7 %. 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 heat release rate 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 relative standard deviation in the heat release rate is thus estimated to be approximately 10 %.

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 arcing 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 (0.5 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.

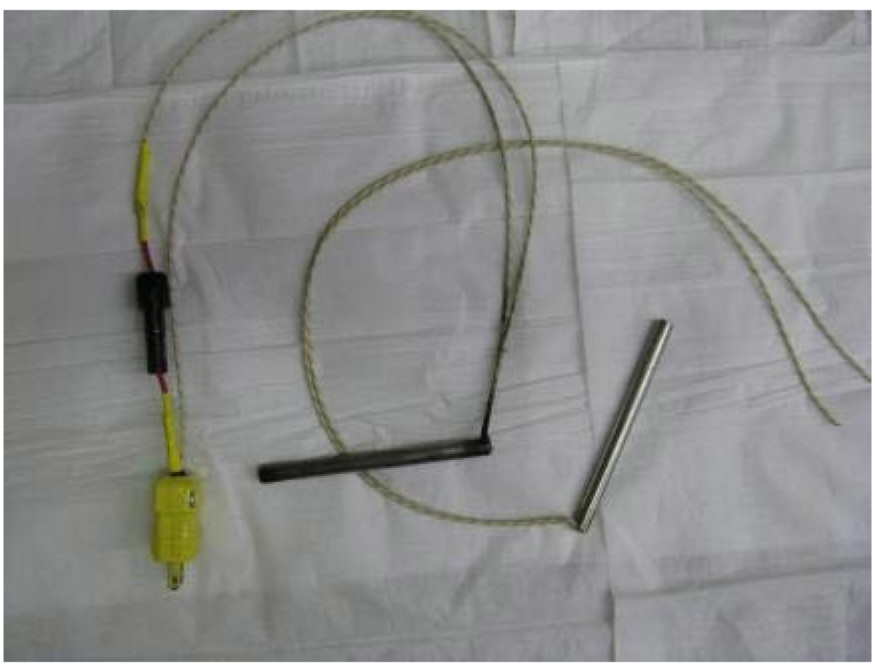


Figure 4-3. Two 300 W cartridge heaters. One has an in-line circuit breaker.

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 3/8 in[3] (0.95 cm) 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. The smaller burner produced flames with heat release rates 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 heat release rate 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.

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

[3] The copper tubing is listed specifically in inches.

Draft Report for Comment

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.

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. Instead, a variety of heaters were used to pre-heat the interior of the enclosures prior to or at the beginning of each experiment. The most effective way to do this was to place a pan of ethanol or acetone at the base of the enclosure away from the combustibles. 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."

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 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 heat release rates, even though bundling was necessary to accumulate enough combustible mass in the vicinity of the igniter to facilitate fire spread.

 Draft Report for Comment

Table 5-1. Summary of enclosure fire measurements

Test	Encl.	Ignition HRR (kW)	Preheat HRR (kW)	Fuel Mass (kg)	Cable Class.	Door Position	Peak HRR (kW) Note 2	Time to Peak HRR (min)	Total Energy Release (MJ)
1	1	0.3	0	Note 1	Q	Open	2	40	2
2	2	0.5	0	Note 1	Q	Open	2	1	1
3	2	0.5	0	Note 1	Q	Open	2	15	2
4	2	0.7	0	Note 1	Q	Open	2	14	1
5	2	0.7	0	Note 1	Q	Open	1	15	1
6	4	0.7	0	Note 1	Q	Open	2	13	1
7	5	0.7	0	Note 1	Q	Open	9	8	6
8	3	0.7	0	Note 1	Q	Open	0	1	1
9	3	0.7	0	Note 1	Q	Open	1	2	1
10	3	0.7	0	Note 1	Q	Open	1	1	1
11	1	0.7	0	11.2	Q	Open	1	13	1
12	1	0.7	0	11.2	Q	Closed	52	85	120
13	8	0.7	0	Note 1	Q	Closed	2	36	4
14	8	0.7	0	Note 1	Q	Closed	4	27	2
15	5	0.7	0	3.4	Q	Open	3	34	7
16	5	0.7	0	1.9	Q	Open	2	23	2
17	4	0.7	0	2.7	Q	Open	0	6	0
18	4	0.7	0	1.8	UQ	Open	3	15	3
19	5	0.7	0	3.4	Q	Closed	3	51	7
20	5	0.7	0	1.9	Q	Closed	5	52	9
21	4	0.7	0	1.9	Q	Closed	4	22	3
22	4	0.7	0	1.8	Q	Closed	4	22	4
23	5	0.7	0	1.6	UQ	Open	18	13	12
24	5	0.7	0	0.7	Q	Closed	4	35	4
25	1	0.7	0	3.1	Q	Closed	4	22	5

 Draft Report for Comment

Test	Encl.	Ignition HRR (kW)	Preheat HRR (kW)	Fuel Mass (kg)	Cable Class.	Door Position	Peak HRR (kW) Note 2	Time to Peak HRR (min)	Total Energy Release (MJ)
26	1	0.7	0	3.1	Q	Closed	1	1	0
27	1	0.7	14	3.1	Q	Closed	1	2	9
28	1	0.7	16	3.1	Q	Closed	3	6	17
29	1	18	0	3.1	Q	Closed	82	13	76
30	1	18	0	3.1	Q	Closed	72	8	59
31	4	5.5	22	0.7	Q	Closed	28	13	45
32	4	5.5	25	0.7	Q	Closed	6	4	35
33	5	25	0	1.5	Q	Closed	50	6	40
34	5	35	0	1.5	Q	Closed	6	7	46
35	8	27	0	11.7	Q	Closed	146	8	153
36	2	4	0	2.8	Q	Closed	4	13	4
37	2	54	0	5.5	Q	Closed	35	6	27
38	2	20	0	5.5	Q	Closed	169	9	95
39	8	25	0	5.8	Q	Closed	60	13	65
40	3	12	0	0.1	Q	Closed	2	25	19
41	3	20	0	5.0	Q	Closed	232	15	141
42	4	5.5	0	2.9	Q	Closed	34	18	35
43	4	16	0	2.9	Q	Closed	18	10	21
44	5	5.5	0	2.9	Q	Closed	31	19	32
45	5	5.5	22	2.9	Q	Closed	5	16	34
46	4	19	0	2.8	Q	Closed	45	19	68
47	4	19	0	1.4	Q	Closed	40	17	49
48	4	19	0	2.8	Q	Open	87	18	89
49	4	19	0	2.8	Q	Closed	50	15	76
50	4	22	0	1.4	Q	Closed	1	13	21
51	4	30	0	1.4	Q	Open	31	6	34

Test	Encl.	Ignition HRR (kW)	Preheat HRR (kW)	Fuel Mass (kg)	Cable Class.	Door Position	Peak HRR (kW) Note 2	Time to Peak HRR (min)	Total Energy Release (MJ)
52	4	5.5	0	2.8	Q	Open	122	4	61
53	4	5.5	0	2.8	Q	Closed	79	39	60
54	4	2.2	0	1.6	UQ	Open	94	17	41
55	4	10	0	3.1	UQ	Closed	21	17	26
56	5	0.8	22	1.7	UQ	Closed	8	6	16
57	5	0.8	24	1.7	UQ	Closed	5	13	26
58	5	0.8	21	3.4	UQ	Closed	26	6	36
59	5	0.8	0	3.4	UQ	Open	22	28	14
60	1	0.8	19	7.4	UQ	Closed	88	28	96
61	1	0.8	19	12.1	Q	Closed	5	17	29
62	1	1.6	19	12.1	Q	Closed	3	18	33
63	1	5.5	19	12.1	Q	Closed	92	25	156
64	8	0.8	11	6.0	Q	Closed	6	14	13
65	8	0.8	11	6.0	Q	Closed	7	16	15
66	4	5.5	24	3.4	UQ	Closed	26	17	57
67	4	5.5	0	3.4	UQ	Closed	25	9	21
68	1	0.8	0	4.5	UQ	Closed	216	11	121
69	8	1.6	13	3.5	UQ	Closed	10	13	22
70	1	1.6	0	3.1	Q	Closed	2	4	1
71	1	5.5	0	3.1	Q	Closed	138	14	99
72	4	0.8	0	2.9	Q	Closed	10	13	7
73	4	1.6	22	2.9	Q	Closed	4	5	26
74	5	1.6	20	2.4	Q	Closed	5	13	28
75	5	5.5	26	2.9	Q	Closed	15	12	57
76	5	22	0	2.9	Q	Closed	9	9	25
77	5	5.5	24	2.4	Q	Closed	13	17	53

Test	Encl.	Ignition HRR (kW)	Preheat HRR (kW)	Fuel Mass (kg)	Cable Class.	Door Position	Peak HRR (kW) Note 2	Time to Peak HRR (min)	Total Energy Release (MJ)
78	5	5.5	0	2.4	Q	Closed	54	13	27
79	4	5.5	0	6.1	Q	Closed	65	28	63
80	4	5.5	19	2.8	Q	Closed	79	29	92
81	5	30	0	2.9	Q	Closed	24	18	48
82	1	1.6	19	7.4	UQ	Closed	43	30	112
83	1	0.8	0	4.5	UQ	Open	577	13	152
84	7	0.8	20	3.3	Q	Open	37	19	51
85	7	0.8	0	2.0	Q	Closed	2	13	2
86	7	5	0	2.0	Q	Open	19	37	15
87	7	0.8	21	3.3	Q	Closed	29	12	35
88	7	0.8	0	1.1	UQ	Closed	147	6	18
89	7	0.8	0	1.1	UQ	Closed	25	16	10
90	7	0.8	16	23.4	Q	Closed	12	20	33
91	7	1.6	20	2.1	Q	Closed	3	15	26
92	7	5.5	20	2.1	Q	Closed	15	6	37
93	7	5.5	0	3.1	UQ	Closed	59	10	27
94	7	5.5	0	4.9	Q	Closed	37	13	23
95	7	5.5	0	5.4	UQ	Closed	30	16	27
96	6	5.5	21	5.4	UQ	Closed	33	9	47
97	6	5.5	0	4.6	UQ	Closed	89	20	120
98	6	20	0	7.7	Q	Closed	121	8	126
99	6	5.5	0	3.3	UQ	Open	3	9	7
100	6	5.5	0	6.2	UQ	Closed	34	27	42
101	6	20	0	6.2	UQ	Closed	66	10	70
102	6	23	0	3.6	Q	Open	10	6	17
103	6	5.5	0	1.1	UQ	Closed	42	13	50

 Draft Report for Comment

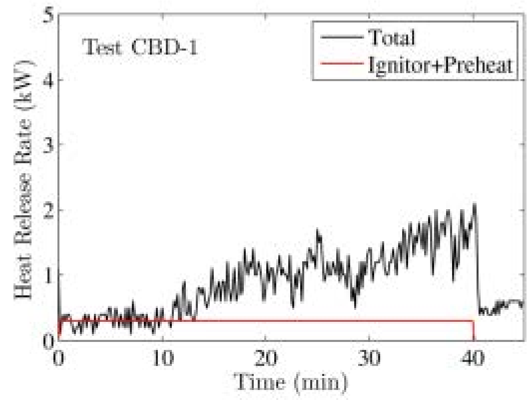
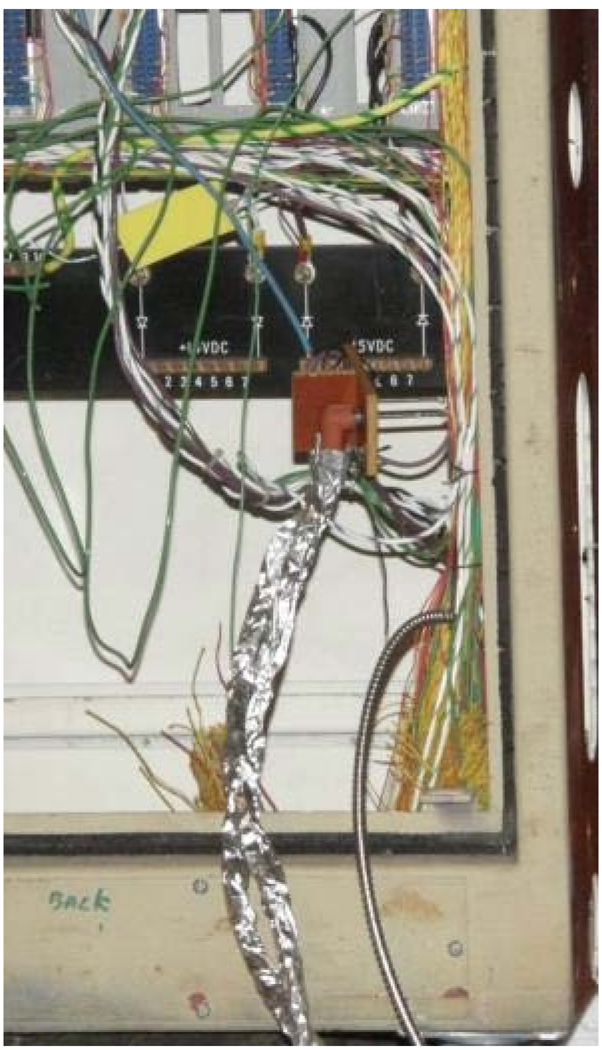
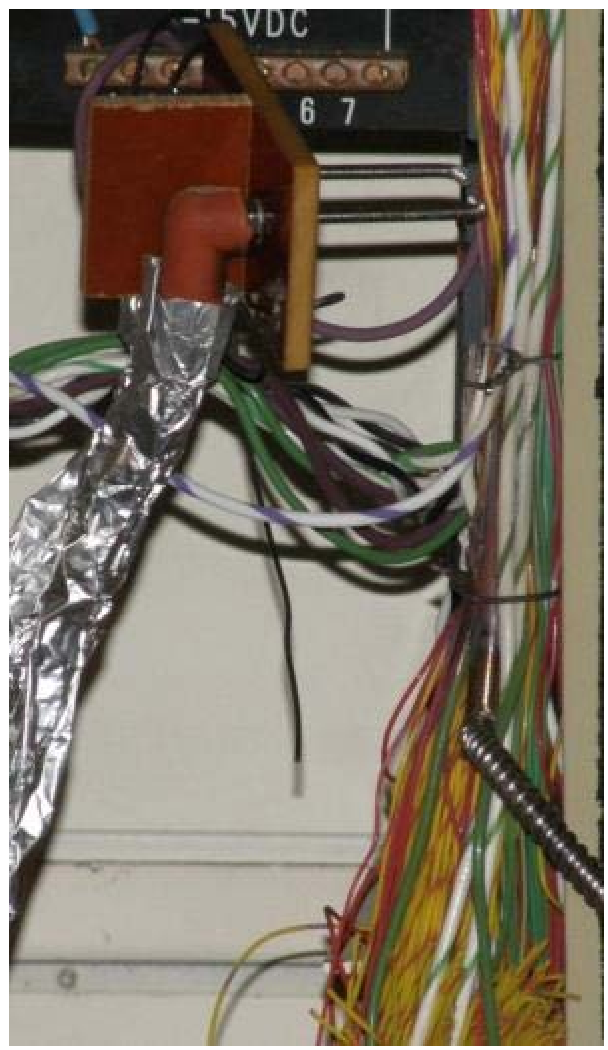
Test	Encl.	Ignition HRR (kW)	Preheat HRR (kW)	Fuel Mass (kg)	Cable Class.	Door Position	Peak HRR (kW) Note 2	Time to Peak HRR (min)	Total Energy Release (MJ)
104	1	0.8	24	4.5	UQ	Open	220	33	141
105	1	5.5	0	6.1	UQ	Closed	80	7	25
106	1	5.5	0	6.1	UQ	Closed	33	14	25
107	1	5.5	19	0.6	Q	Open	55	13	51
108	1	5.5	0	5.5	Q	Closed	32	7	15
109	8	5.5	19	6.1	Q	Closed	64	14	61
110	4	5.5	24	2.2	UQ	Closed	7	15	32
111	5	5.5	20	3.1	UQ	Closed	268	23	120
112	4	5.5	0	2.2	UQ	Open	17	11	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.

Table 5-2. Summary of Test 1

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.	
	

 Draft Report for Comment

Table 5-3. Summary of Test 2

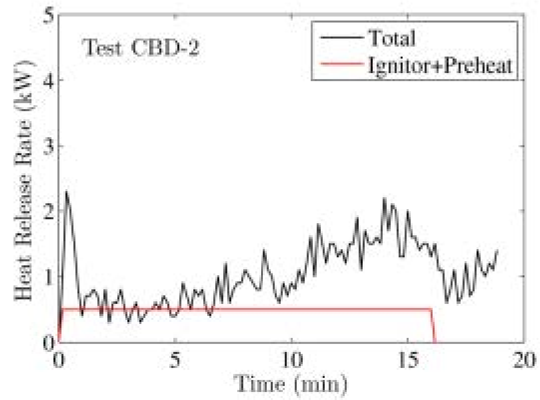
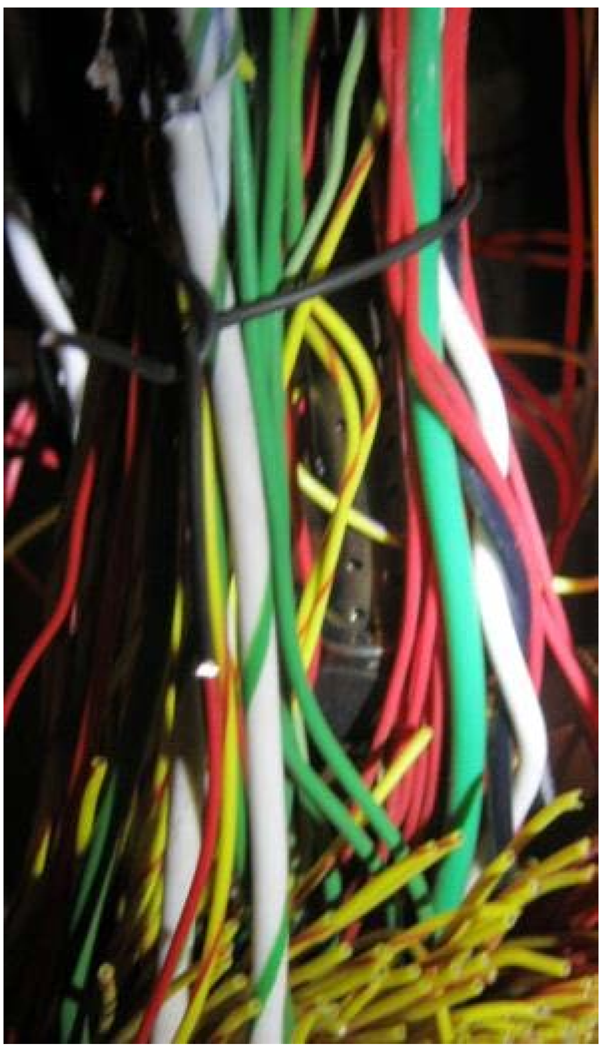
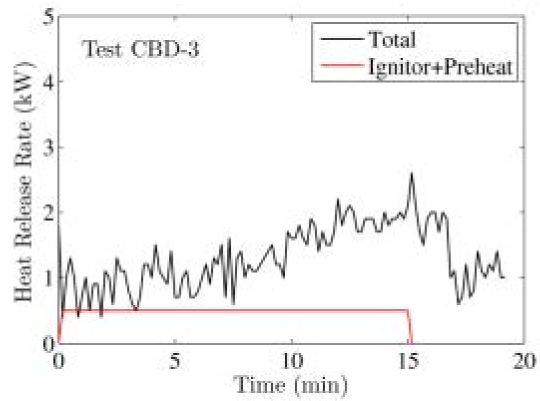
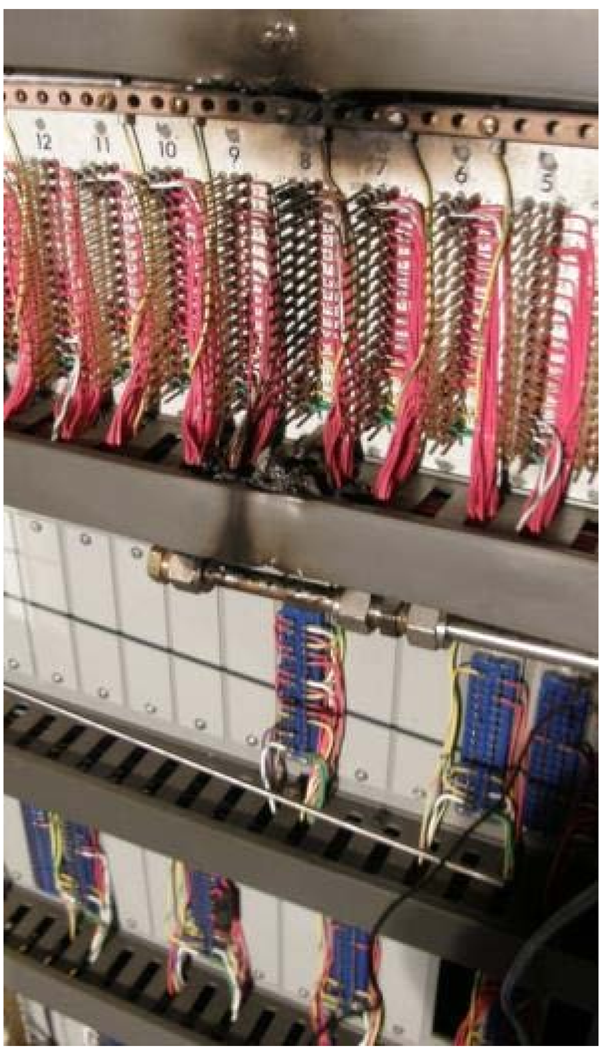
Test: 2 **Enclosure:** 2 **Fuel Load:** Vertical bundle of SIS wire **Ignition Source:** 0.5 kW propane burner **Ventilation:** Door open **Notes:** The fire did not spread beyond its point of origin. The burner was turned off after approximately 16 min.	
	

Table 5-4. Summary of Test 3

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


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

</td>
<td>

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

 Draft Report for Comment

Table 5-5. Summary of Test 4

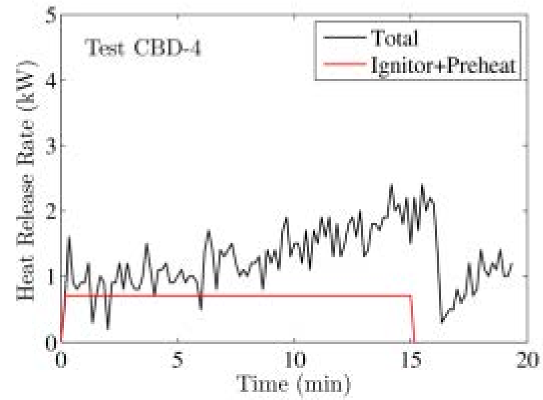
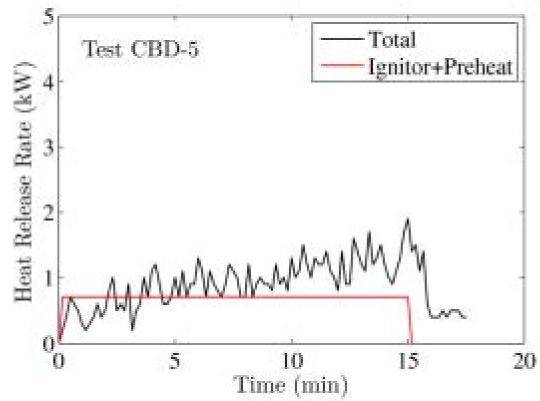
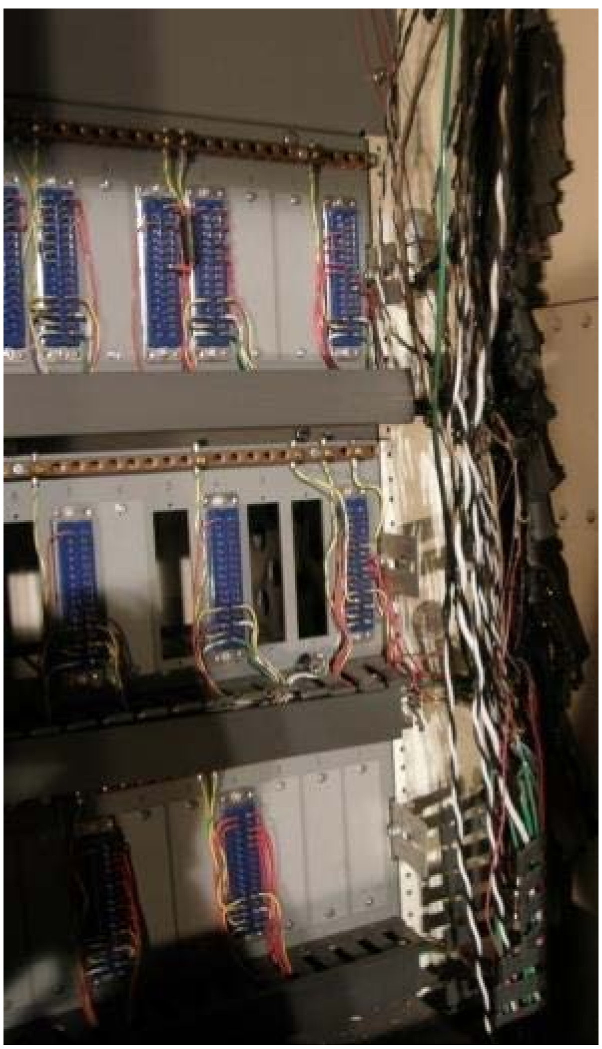
Test: 4 **Enclosure:** 4 **Fuel Load:** Vertical bundle of SIS wire enclosed by plastic conduit **Ignition Source:** 0.7 kW propane burner **Ventilation:** Door open **Notes:** The fire did not spread beyond point of origin. The burner was turned off at approximately 15 min.	
	

Table 5-6. Summary of Test 5

Test: 5 **Enclosure:** 2 **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.	
	

 Draft Report for Comment

Table 5-7. Summary of Test 6

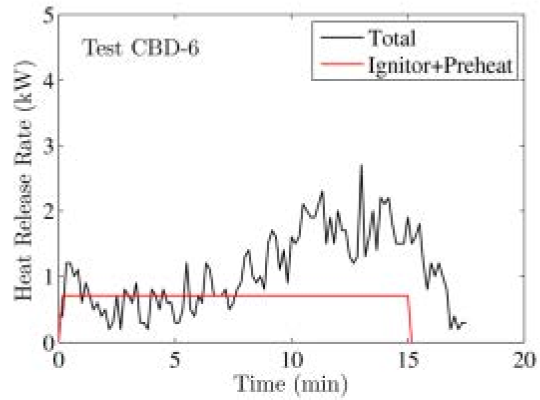
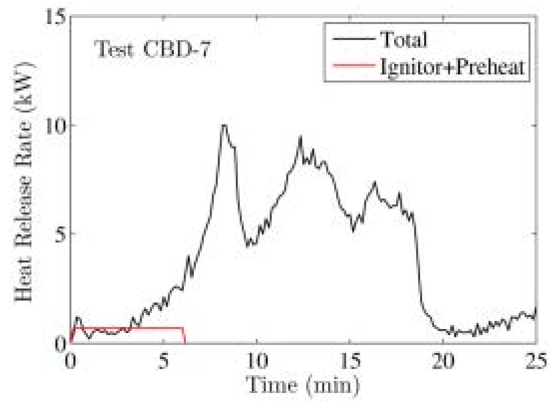
Test: 6 **Enclosure:** 4 **Fuel Load:** Vertical bundle of SIS wire enclosed by plastic conduit **Ignition Source:** 0.7 kW propane burner **Ventilation:** Door open **Notes:** The fire did not spread beyond point of origin. The plastic melted near the burner but did not appear to add much to the HRR.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

Table 5-8. 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

 Draft Report for Comment

Table 5-9. 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.

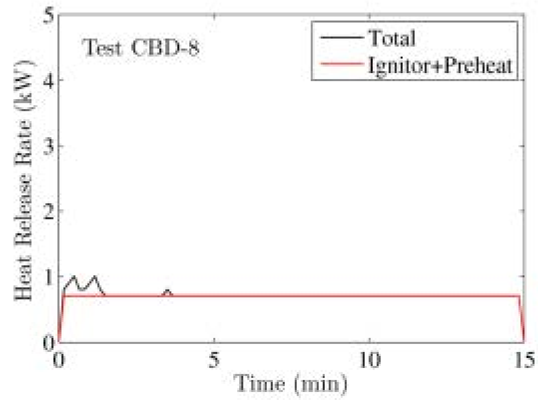
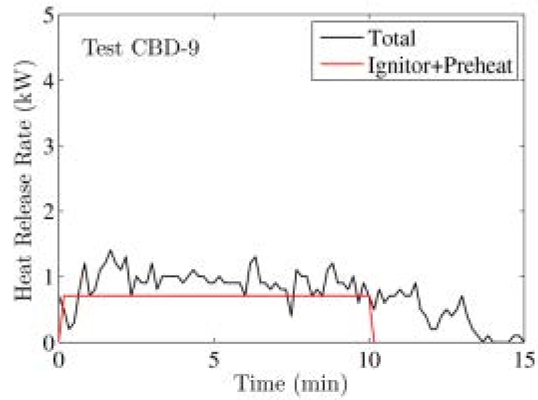


Table 5-10. Summary of Test 9

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

 Draft Report for Comment

Table 5-11. Summary of Test 10

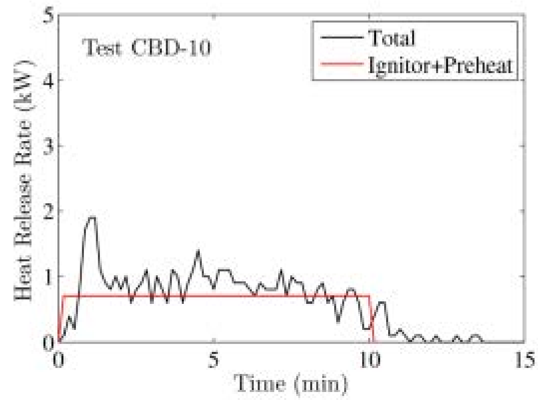
Test: 10 **Enclosure:** 3 **Fuel Load:** Vertical bundle of relay wire bound by a rubber harness **Ignition Source:** 0.7 kW propane burner **Ventilation:** Door open **Notes:** The rubber harness material burned, but there was no measureable heat release or significant spread. The burner was turned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

Table 5-12. Summary of Test 11

<table>
<tr>
<td>

Test: 11

Enclosure: 1

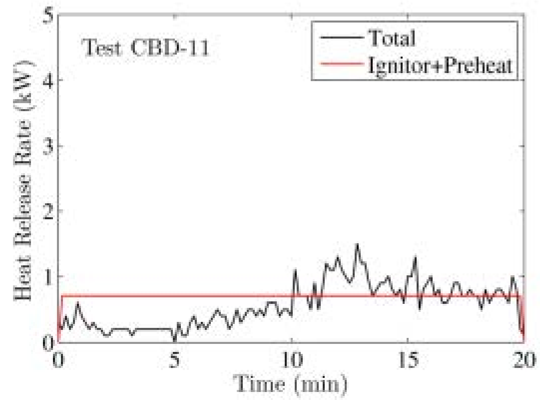
Fuel Load: Loose collection of control cables that were originally installed in the enclosure

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.

</td>
<td>



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

</td>
<td>

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

Table 5-13. Summary of Test 12

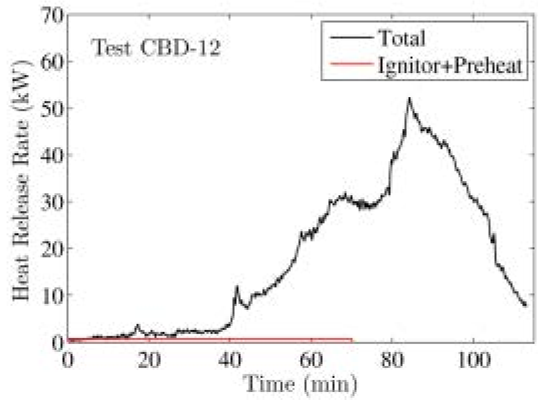
Test: 12 **Enclosure:** 1 **Fuel Load:** Same cables from Test 11 **Ignition Source:** 0.7 kW propane burner **Ventilation:** Door closed **Notes:** The door of the enclosure was initially closed, but it was opened at approximately 40 min to check on progress. The fire flared up due, presumably, to the introduction of fresh air. The door was closed at about 41 min. The cables burned or smoldered for about an hour. All that remained was glowing char.	
	

Table 5-14. Summary of Test 13

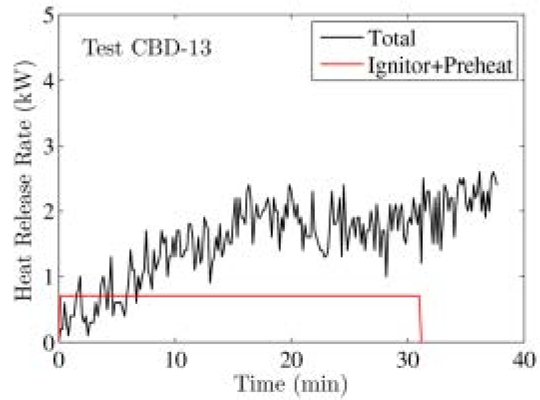
Test: 13 **Enclosure:** 8 **Fuel Load:** Control cables originating at interior connection panel and directed through conduits at the top of the enclosure into a cable tray **Ignition Source:** 0.7 kW propane burner **Ventilation:** Door closed **Notes:** The door was opened at 23 min and then closed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

Table 5-15. Summary of Test 14

Test: 14

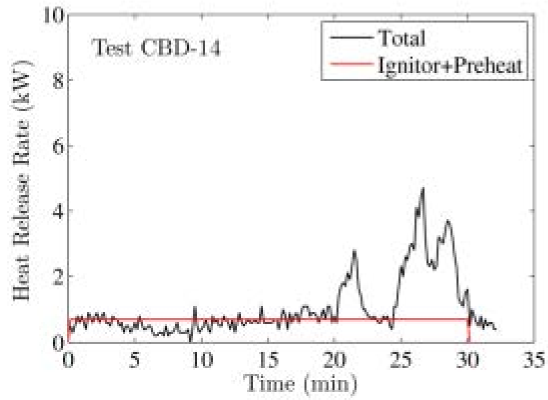
Enclosure: 8

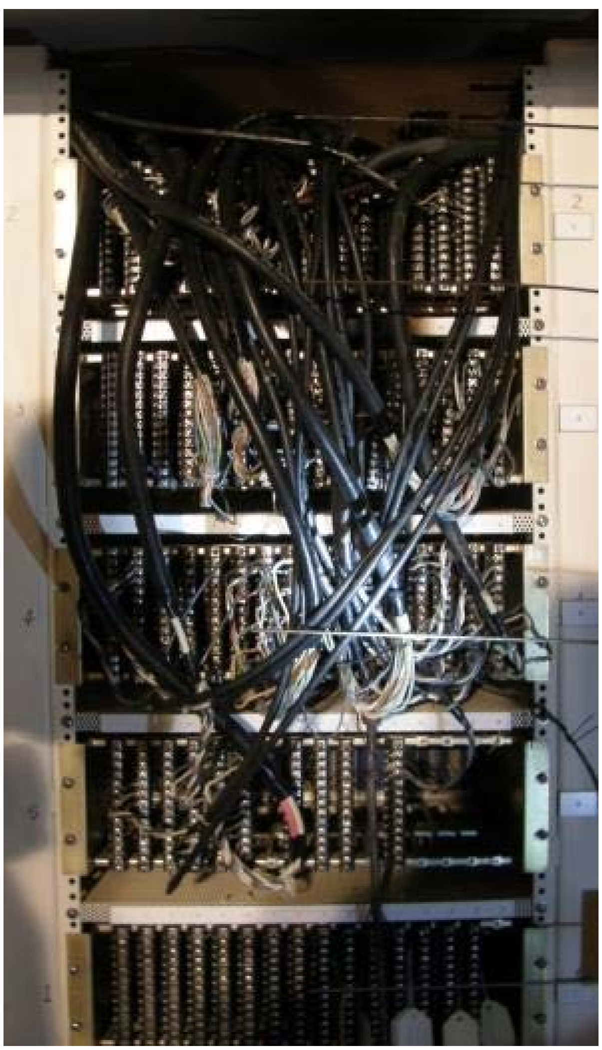
Fuel Load: Same as Test 13

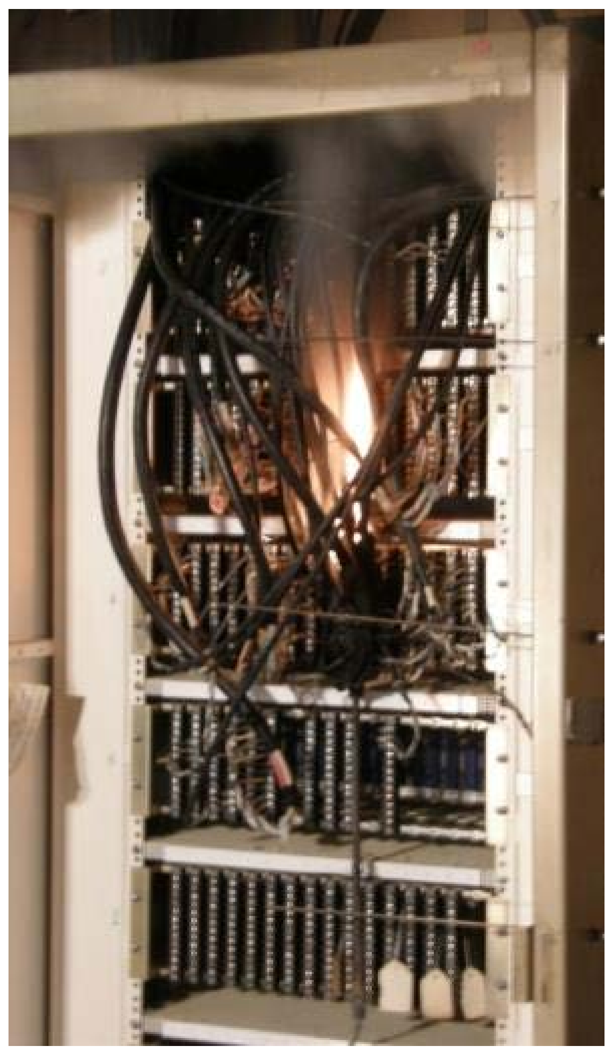
Ignition Source: 0.7 kW propane burner

Ventilation: Door closed

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







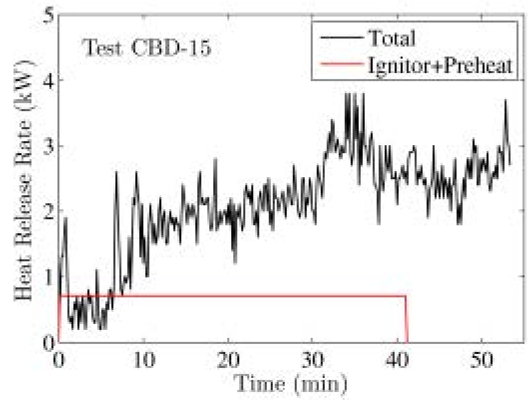
Draft Report for Comment

Table 5-16. Summary of Test 15

<table>
<tr>
<td>

Test: 15
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
Notes: The fire did not spread or grow appreciably in 30 min. At approximately 35 min, 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.

</td>
<td>



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

</td>
<td>

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

Table 5-17. Summary of Test 16

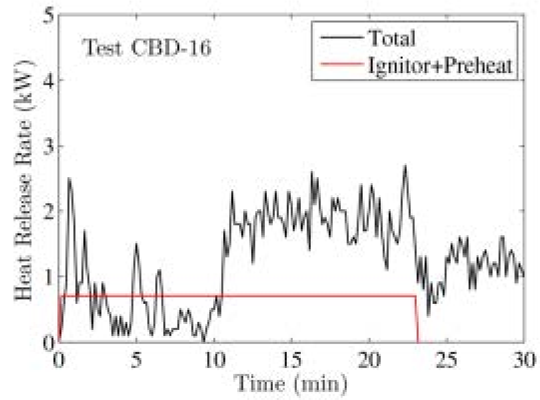
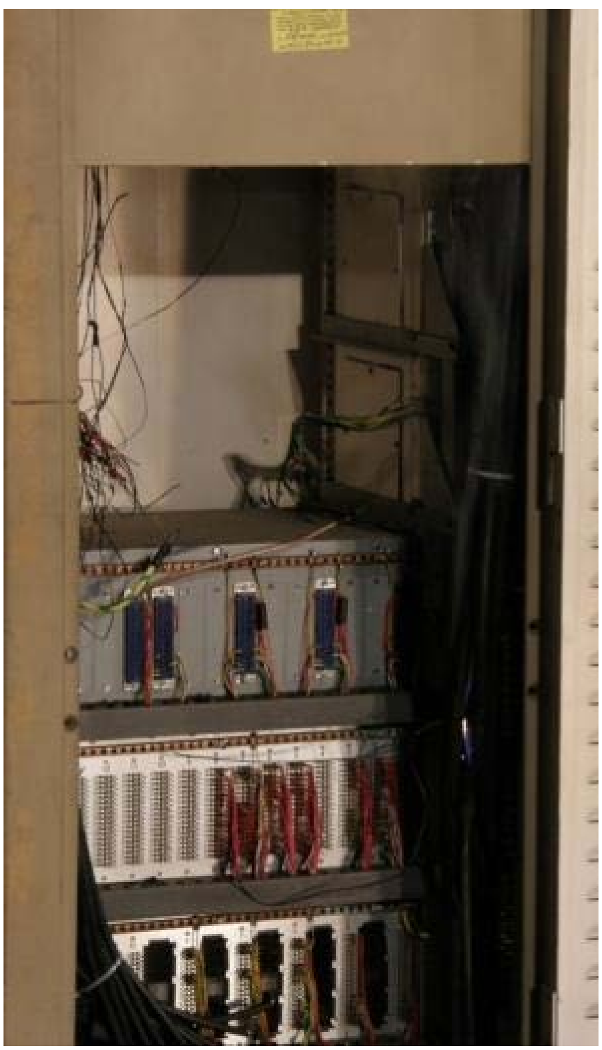
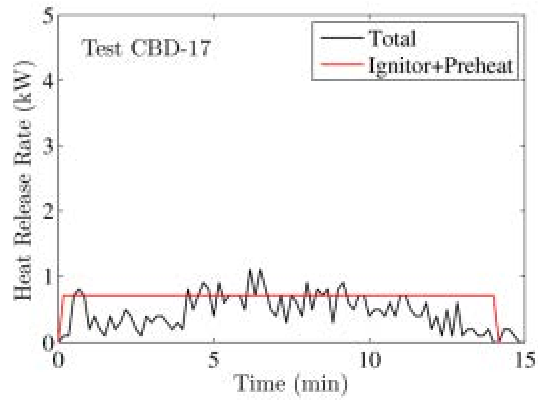
Test: 16 **Enclosure:** 5 **Fuel Load:** 7 cables (#807), 1.8 m (6 ft) long, routed up right side of enclosure **Ignition Source:** 0.7 kW propane burner **Ventilation:** Door open **Notes:** The holes of the propane burner became clogged, and the burner was cleaned at approximately 10 min. The fire did not spread beyond its point of origin. The burner was turned off at 23 min.	
	

Table 5-18. 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.	
	

 Draft Report for Comment

Table 5-19. Summary of Test 18

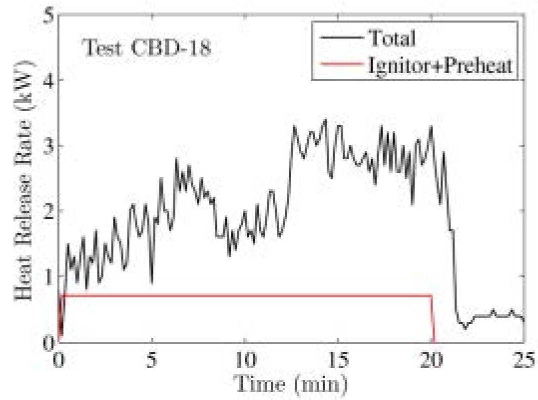
Test: 18 **Enclosure:** 4 **Fuel Load:** 30 cables (#845), 1.8 m (6 ft) long, routed up right side of enclosure **Ignition Source:** 0.7 kW propane burner **Ventilation:** Door open **Notes:** The fire spread upwards approximately 60 cm (2 ft) above the propane burner. The burner was turned off at 20 min.	
	

Table 5-20. Summary of Test 19

<table>
<tr>
<td>

Test: 19

Enclosure: 5

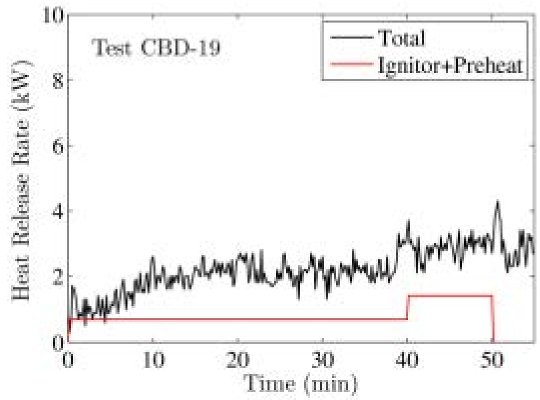
Fuel Load: 22 cables (#817), 1.8 m (6 ft) long, routed up left side of enclosure

Ignition Source: 0.7 kW propane burner

Ventilation: Door closed

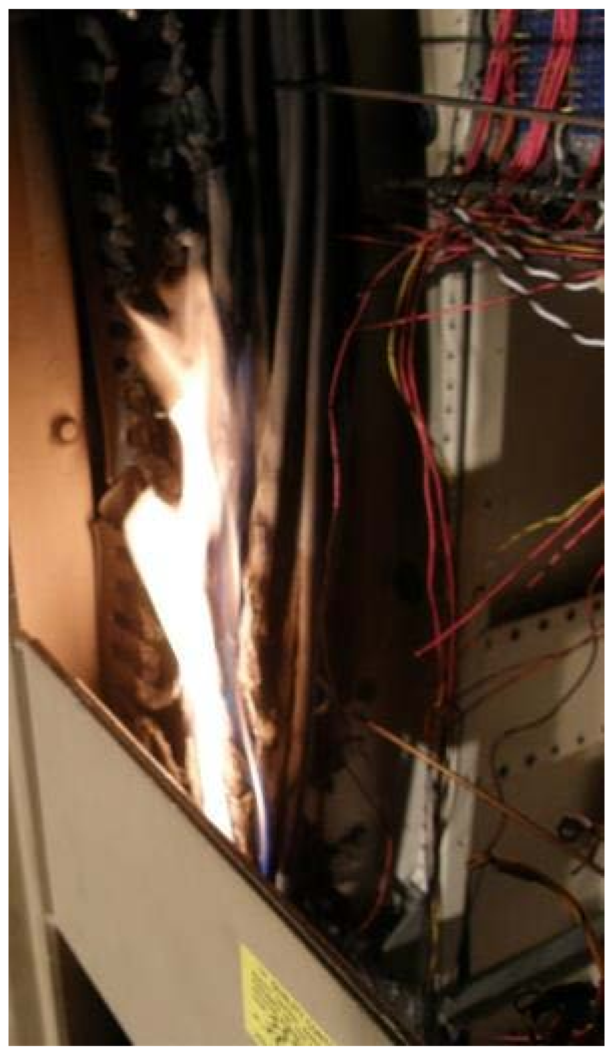
Notes: The fire did not spread beyond its point of origin. The door was opened at 24 min and at 40 min. At 40 min, the propane burner was increased to 1.7 kW, but the fire still did not spread.

</td>
<td>



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

</td>
<td>



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

 Draft Report for Comment

Table 5-21. Summary of Test 20

Test: 20

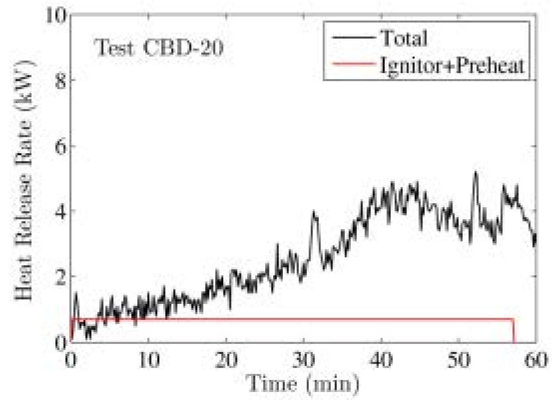
Enclosure: 5

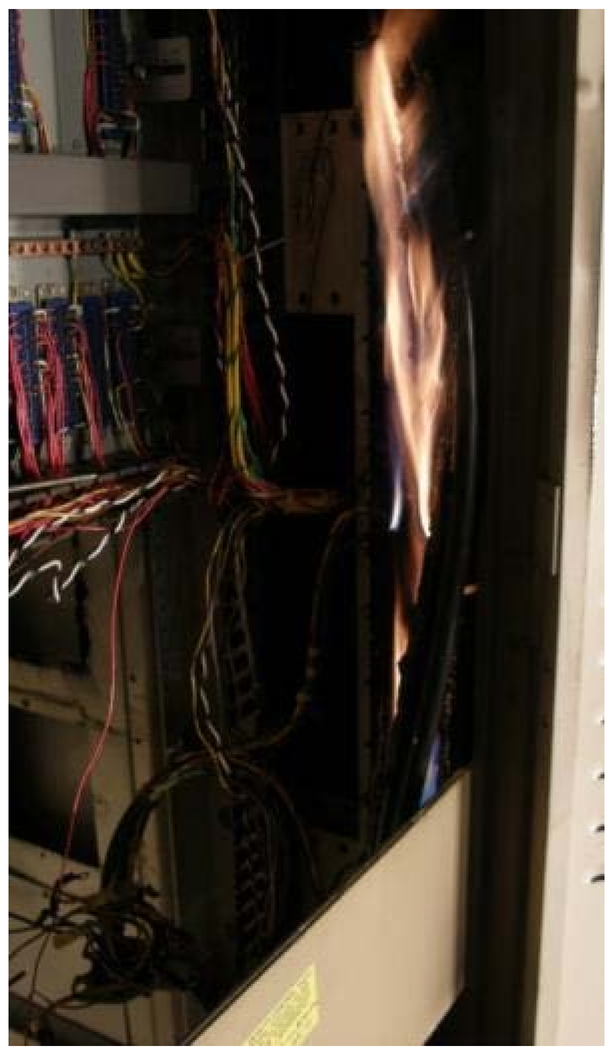
Fuel Load: 7 cables (#807), 1.8 m (6 ft) long, routed up right side of enclosure

Ignition Source: 0.7 kW propane burner

Ventilation: Door closed

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. The fire did not spread beyond 60 cm (2 ft). The burner was turned off just short of an hour.





 Draft Report for Comment

Table 5-22. 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.

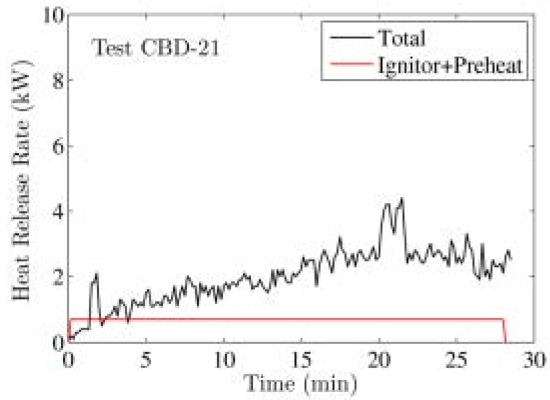


Table 5-23. Summary of Test 22

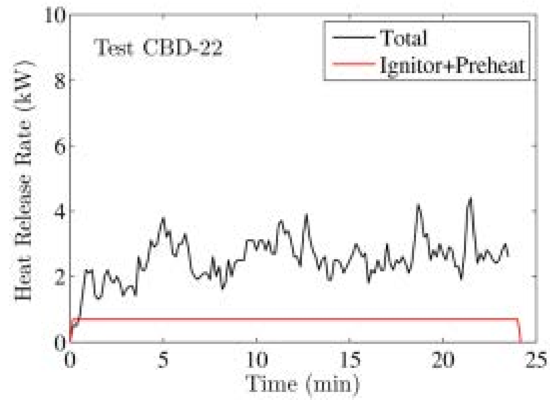
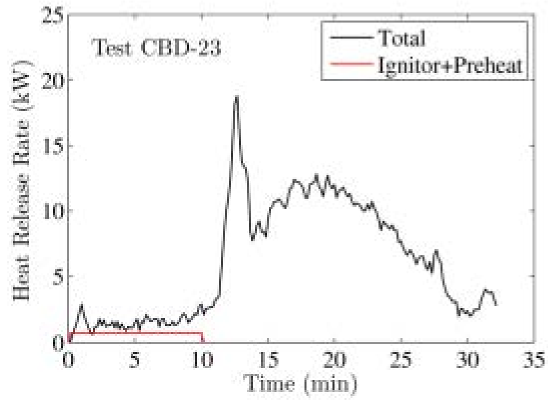
Test: 22 **Enclosure:** 4 **Fuel Load:** 30 cables (#845), 1.8 m (6 ft) long, routed up right side of enclosure **Ignition Source:** 0.7 kW propane burner **Ventilation:** Door closed **Notes:** The fire did not spread beyond the point of origin.	
	

Table 5-24. 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 at piled onto the floor of the enclosure where it burned for approximately 20 min.	
	

 Draft Report for Comment

Table 5-25. Summary of Test 24

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.

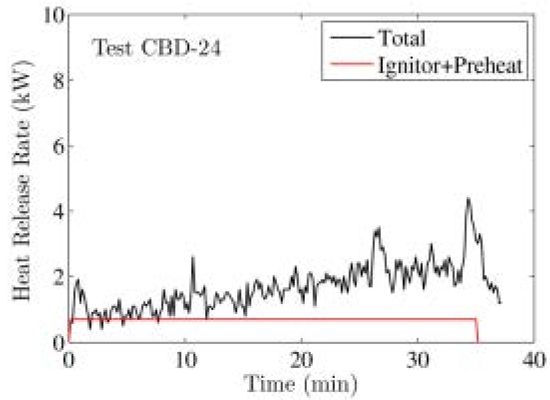


Table 5-26. Summary of Test 25

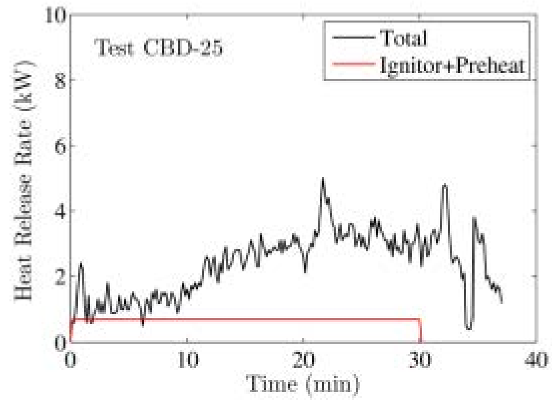
Test: 25 **Enclosure:** 1 **Fuel Load:** 768 m (2520 ft) insulated conductors (#834) connected to center board and running down both sides of enclosure **Ignition Source:** 0.7 kW propane burner **Ventilation:** Door closed **Notes:** The fire spread approximately 20 cm (8 in) above the burner. The door was opened at approximately 20 min to check progress. The fire did not spread beyond the vicinity of the burner.	
	

Table 5-27. Summary of Test 26

Test: 26

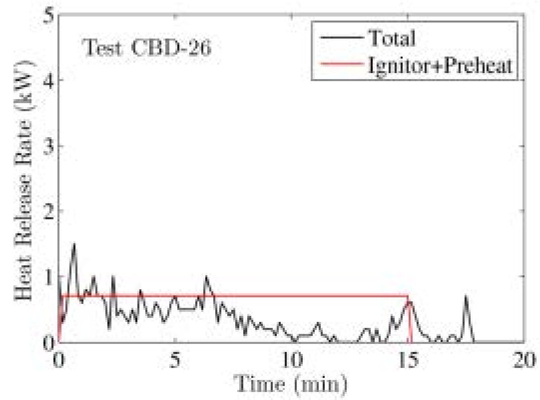
Enclosure: 1

Fuel Load: Same as Test 25

Ignition Source: 0.7 kW propane burner

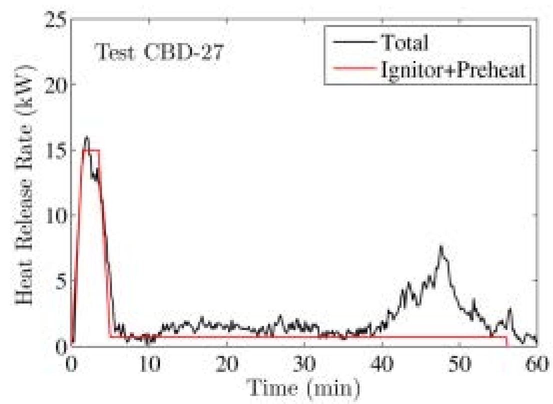
Ventilation: Door closed

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.



 Draft Report for Comment

Table 5-28. Summary of Test 27

Test: 27 **Enclosure:** 1 **Fuel Load:** Same as Test 25 **Ignition Source:** 0.7 kW propane burner **Preheating Source:** 150 mL ethanol pan fire **Ventilation:** Door closed **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. Each time the door was opened, the cables were jostled with a crowbar. The burner was turned off at 56 min.	
	

 Draft Report for Comment

Table 5-29. Summary of Test 28

Test: 28

Enclosure: 1

Fuel Load: Same as Test 25

Ignition Source: 0.7 kW propane burner

Preheating Source: 300 mL ethanol pan fire

Ventilation: Door closed

Notes: The ethanol fire was exhausted at approximately 9 min after which the propane burner was ignited. At 19 min, the door was opened and the wires in the vicinity of the burner were jostled with a crowbar. The fire then spread upwards, approximately 0.6 m (2 ft) above the burner. The process was repeated at 40 min.

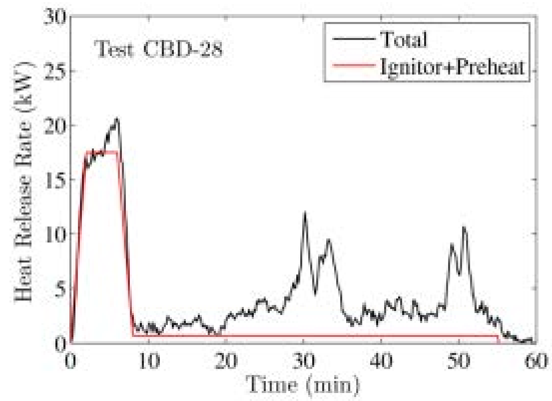


Table 5-30. Summary of Test 29

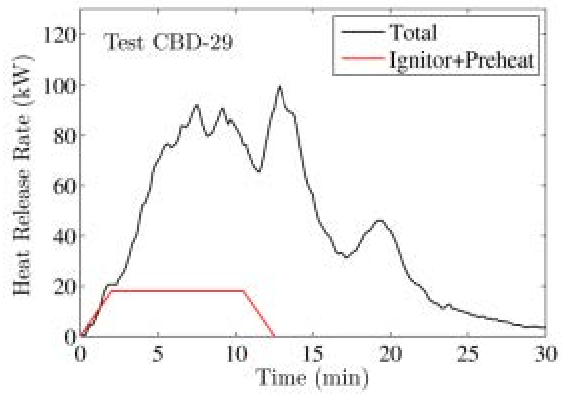
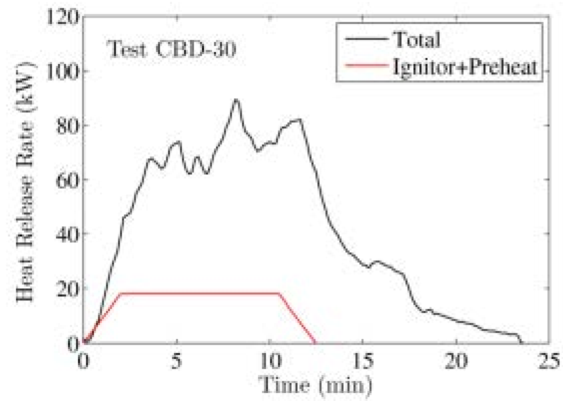
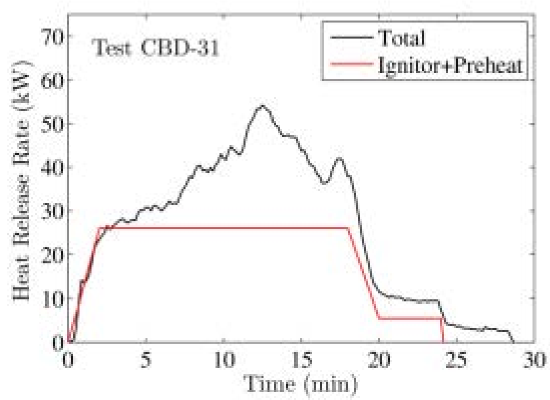
Test: 29 **Enclosure:** 1 **Fuel Load:** Same as Test 25 **Ignition Source:** 500 mL acetone pan fire **Ventilation:** Door closed **Notes:** The bottom ends of 3 bundles, each consisting of 37 insulated conductors, were placed into the 15 cm by 23 cm (6 in by 9 in) steel baking pan at the lower left side of the enclosure. The acetone burned for approximately 12 min, 30 s. The fire spread up one side of the enclosure.	
	

Table 5-31. Summary of Test 30

Test: 30 **Enclosure:** 1 **Fuel Load:** Same as Test 25 **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.	
	

 Draft Report for Comment

Table 5-32. Summary of Test 31

Test: 31 **Enclosure:** 4 **Fuel Load:** 72 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.	
	

 Draft Report for Comment

Table 5-33. Summary of Test 32

Test: 32

Enclosure: 4

Fuel Load: 72 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

Notes: The acetone was exhausted at approximately 16 min, and the propane burner was turned off at 22 min. The fire did not spread beyond the vicinity of the propane burner.

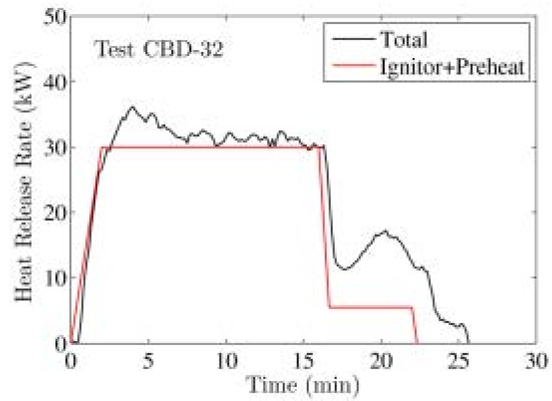


Table 5-34. Summary of Test 33

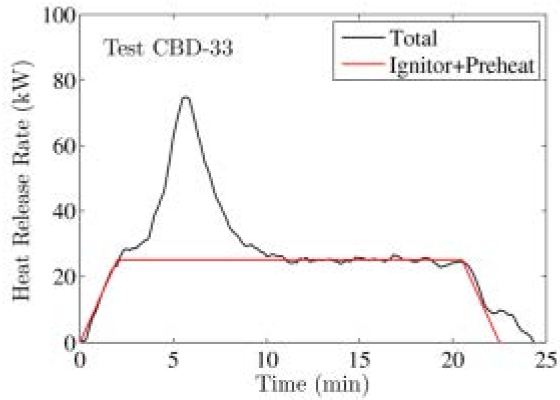
Test: 33 **Enclosure:** 5 **Fuel Load:** Remnants of Test 31 and 32 **Ignition Source:** 5.5 kW propane burner and 1 L acetone pan fire at the overlap region of left and right side bundles **Ventilation:** Door closed **Notes:** This was an attempt to burn the wiring on both sides of the enclosure. The 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.	
	

Table 5-35. Summary of Test 34

Test: 34
Enclosure: 5
Fuel Load: Remnants of Test 33
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.

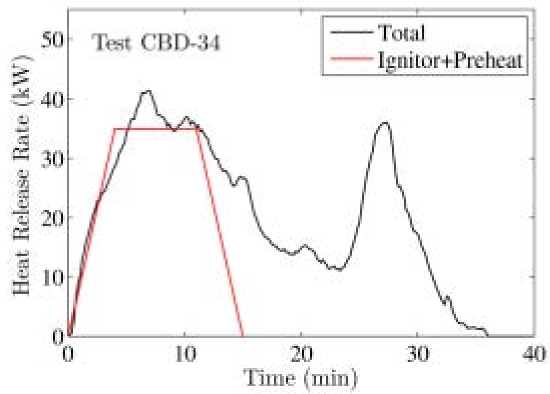
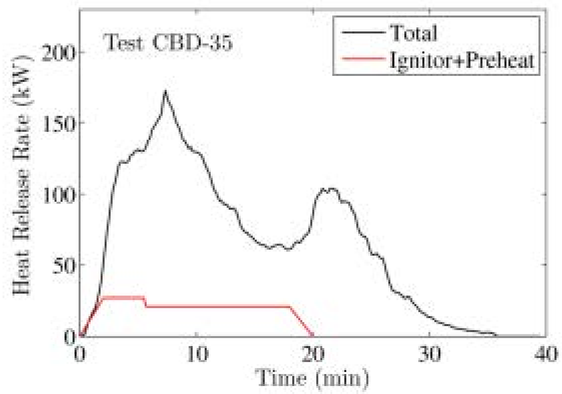
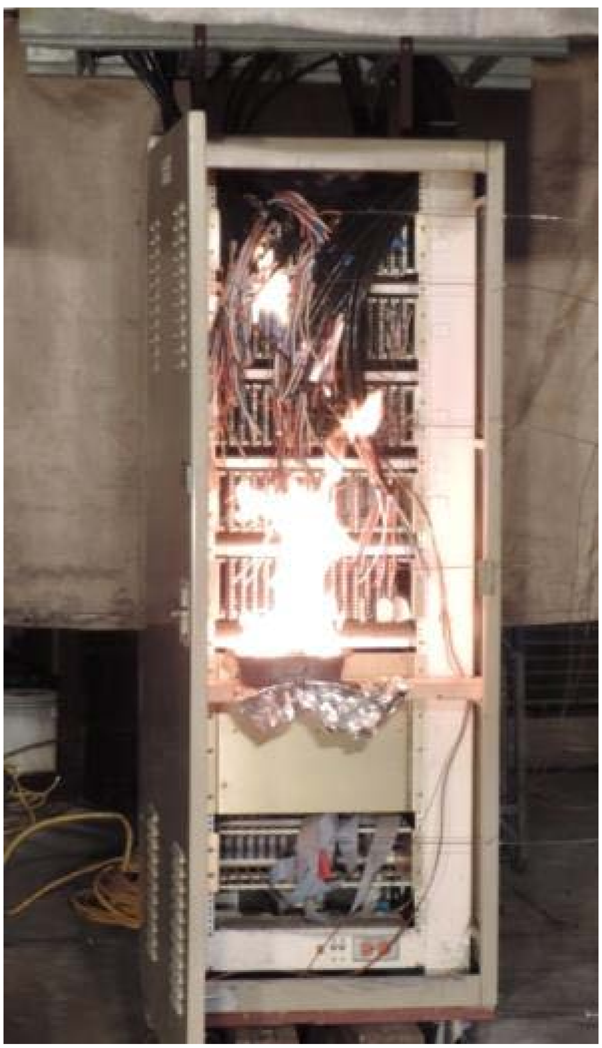
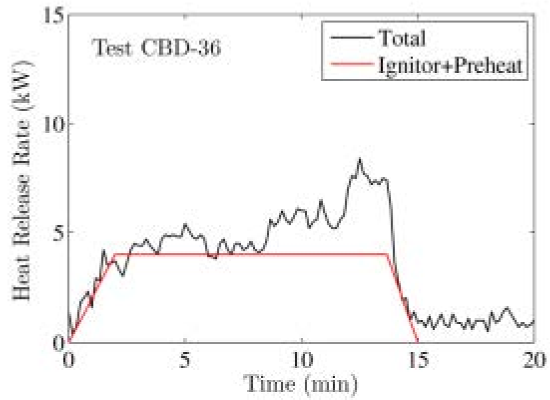
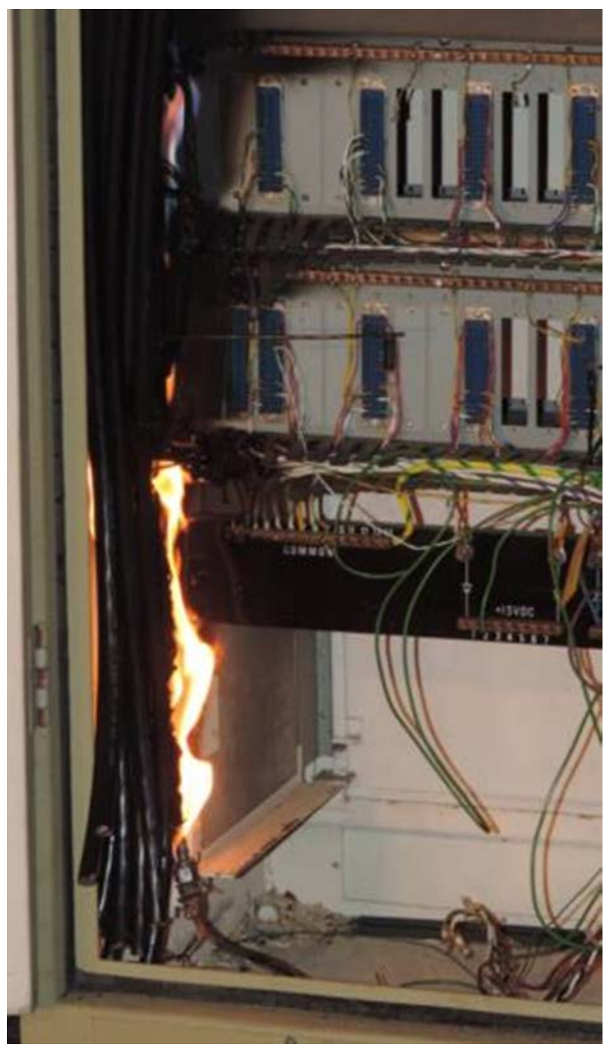


Table 5-36. Summary of Test 35

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 **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.	
	

 Draft Report for Comment

Table 5-37. Summary of Test 36

Test: 36 **Enclosure:** 2 **Fuel Load:** Bundle of 10 control cables (#807) **Ignition Source:** 4 kW propane burner **Ventilation:** Door closed **Notes:** The fire did not spread beyond its point of origin near the base of the bundle. The burner was turned off at approximately 14 min.	
	

 Draft Report for Comment

Table 5-38. Summary of Test 37

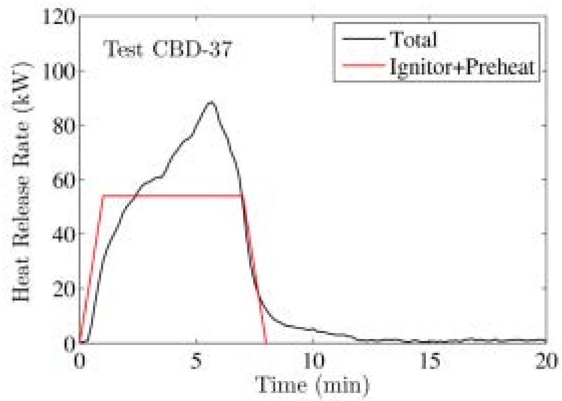
Test: 37 **Enclosure:** 2 **Fuel Load:** Two bundles of 10 control cables (#807); one on each side of enclosure **Ignition Source:** Two pans of acetone, each containing 500 mL **Ventilation:** Door closed **Notes:** The fire spread upwards on the left side bundle, but did not spread upwards on the right.	
	

Table 5-39. Summary of Test 38

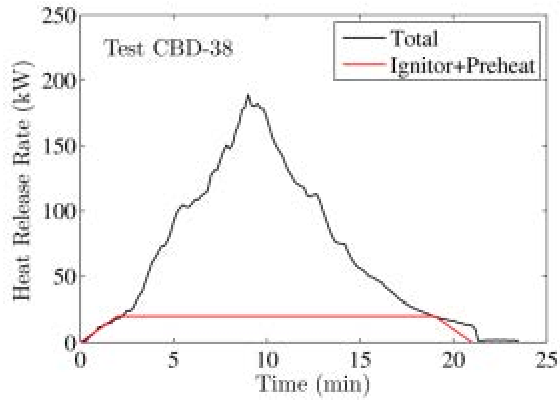
Test: 38 **Enclosure:** 2 **Fuel Load:** Same cables from Test 37, with both left and right bundles gathered together in front of central partition with the ends terminating in the fuel pan **Ignition Source:** 1 L acetone pan fire **Ventilation:** Door closed **Notes:** The fire consumed all of the 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 5-40. Summary of Test 39

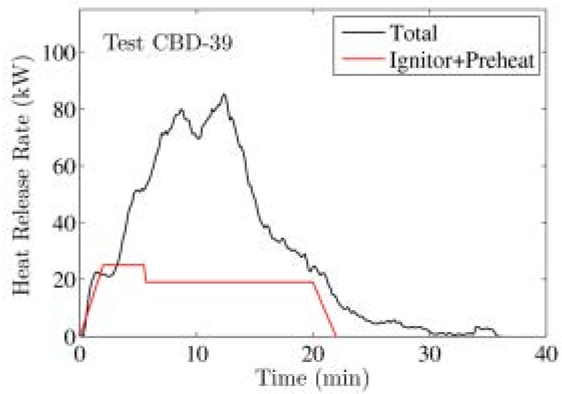
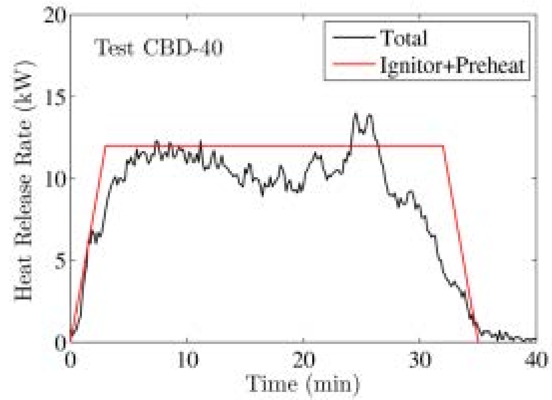
Test: 39 **Enclosure:** 8 **Fuel Load:** Similar to Test 35, using 21 instead of 42 control cables (#807) **Ignition Source:** 5.5 kW propane burner within the bundled cable and 1 L acetone pan fire 60 cm (2 ft) below base of cable bundle **Ventilation:** Door closed **Notes:** The fire spread upwards through the 10 conduits in the top of the enclosure and consumed the cables in the tray directly above.	
	

Table 5-41. Summary of Test 40

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.	
	

 Draft Report for Comment

Table 5-42. Summary of Test 41

Test: 41

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, and the fire grew rapidly afterwards. The coated relay wiring on the back side of the partition between the front and middle sections burned.

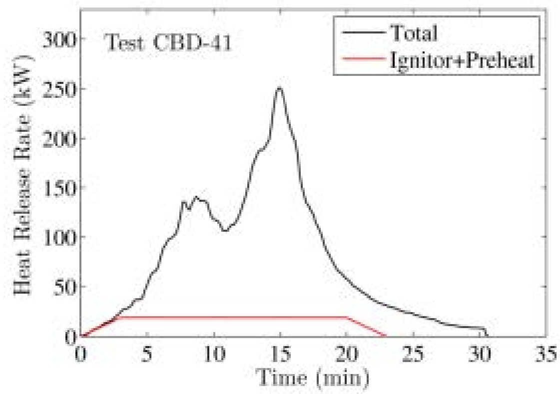


Table 5-43. Summary of Test 42

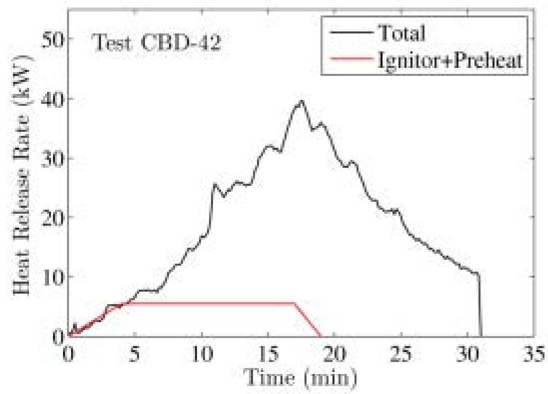
Test: 42 **Enclosure:** 4 **Fuel Load:** 10 cables (#813), 1.8 m (6 ft) long, routed up right side of enclosure **Ignition Source:** 5.5 kW propane burner **Ventilation:** Door closed then opened at 10 min **Notes:** The fire spread upwards along the cables in the right side of the enclosure. The door 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 5-44. 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

Notes: Even though the cables were immersed in the acetone, the fire did not spread upwards. The acetone was exhausted at approximately 14 min.

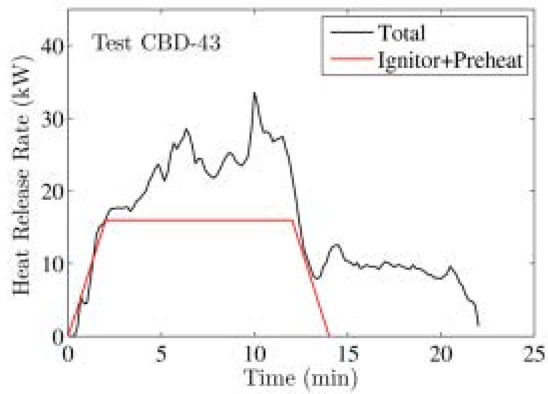


Table 5-45. Summary of Test 44

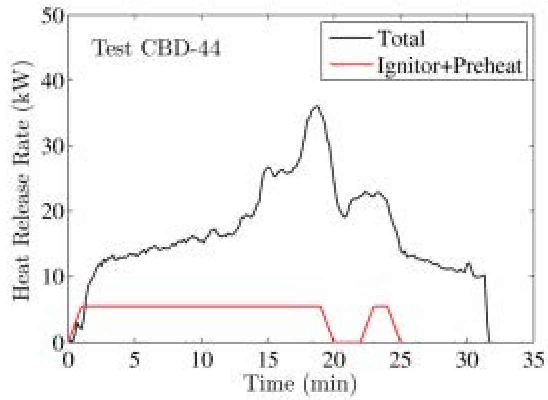
Test: 44 **Enclosure:** 5 **Fuel Load:** 10 cables (#813), 1.8 m (6 ft) long, routed up right side of enclosure **Ignition Source:** 5.5 kW propane burner **Ventilation:** Door closed **Notes:** The door was opened at approximately 14 min. The propane burner was turned off at approximately 19 min; turned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

Table 5-46. Summary of Test 45

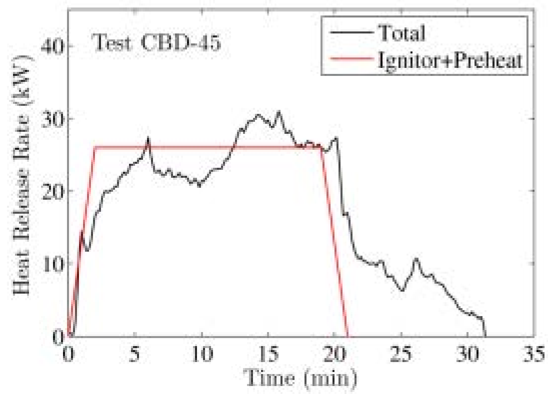
Test: 45 **Enclosure:** 5 **Fuel Load:** 10 cables (#813), 1.8 m (6 ft) long, routed up left side of enclosure **Ignition Source:** 5.5 kW propane burner **Preheating Source:** 1 L acetone pan fire **Ventilation:** Door closed **Notes:** The pan fire was placed away from the cables. The acetone was exhausted 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.	
	

Table 5-47. Summary of Test 46

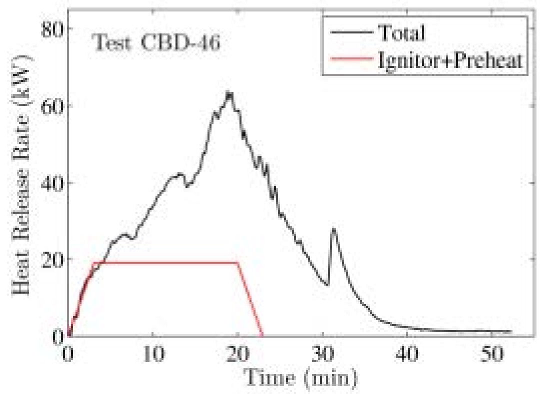
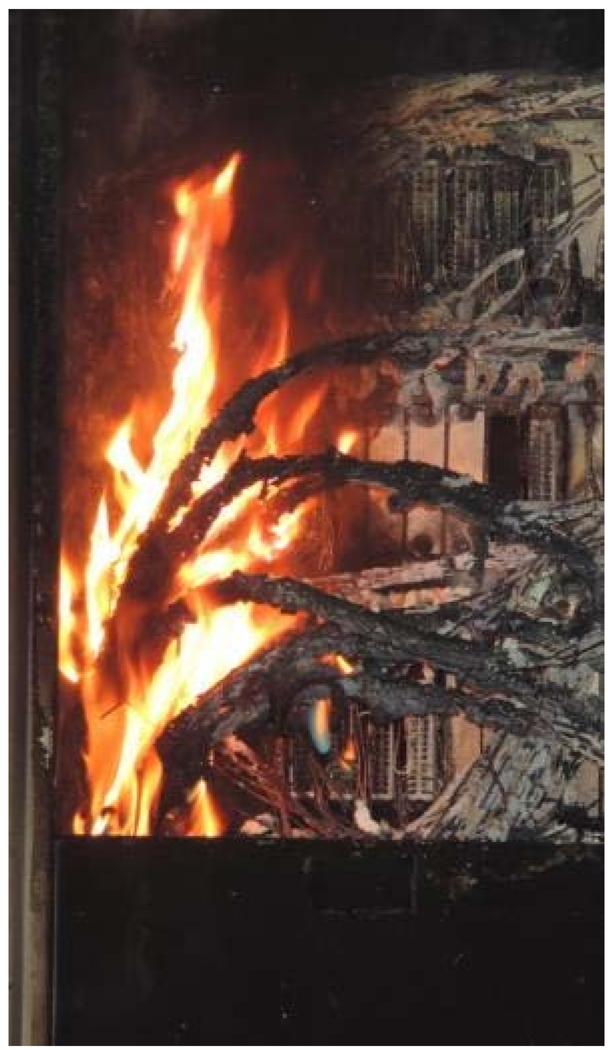
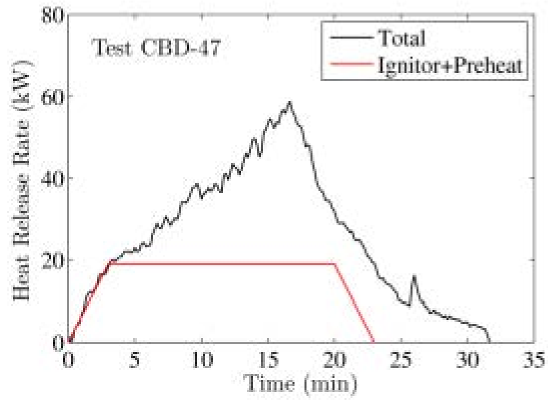
Test: 46 **Enclosure:** 4 **Fuel Load:** Two cable bundles; one on each side. Each bundle contained 10 cables (#807), stripped 20 cm (8 in) and overlapping near the top **Ignition Source:** 1 L acetone pan fire **Ventilation:** Door closed **Notes:** The pan was placed on the right side of the enclosure 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 5-48. Summary of Test 47

Test: 47 **Enclosure:** 4 **Fuel Load:** Two cable bundles; one on each side. Each bundle contained 5 cables (#807), 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, 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.	
	

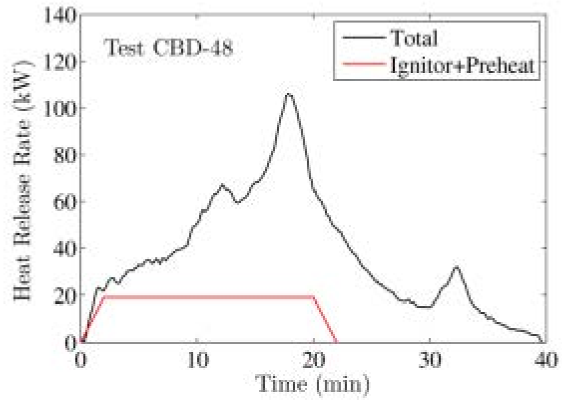
 Draft Report for Comment

Table 5-49. Summary of Test 48

<table>
<tr>
<td>

Test: 48
Enclosure: 4
Fuel Load: Two cable bundles; one on each side. Each bundle contained 10 cables (#807), 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.

</td>
<td>



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

</td>
<td>

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

Table 5-50. Summary of Test 49

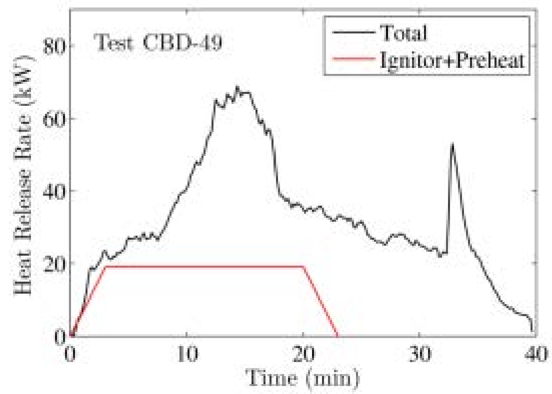
Test: 49 **Enclosure:** 4 **Fuel Load:** Two cable bundles; one on each side. Each bundle contained 10 cables (#807), stripped 20 cm (8 in) and overlapping near the top **Ignition Source:** 1 L acetone pan fire **Ventilation:** Door closed **Notes:** This test was a repeat of Test 46 because there was 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.	
	

Table 5-51. Summary of Test 50

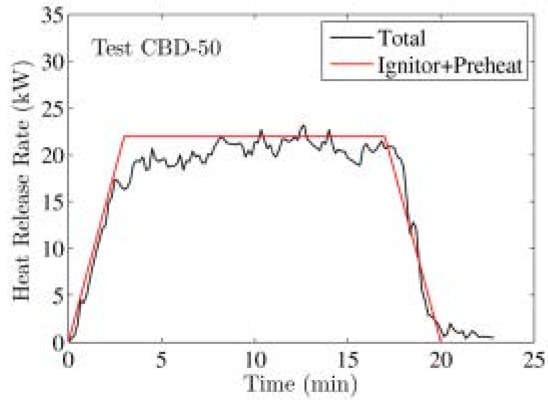
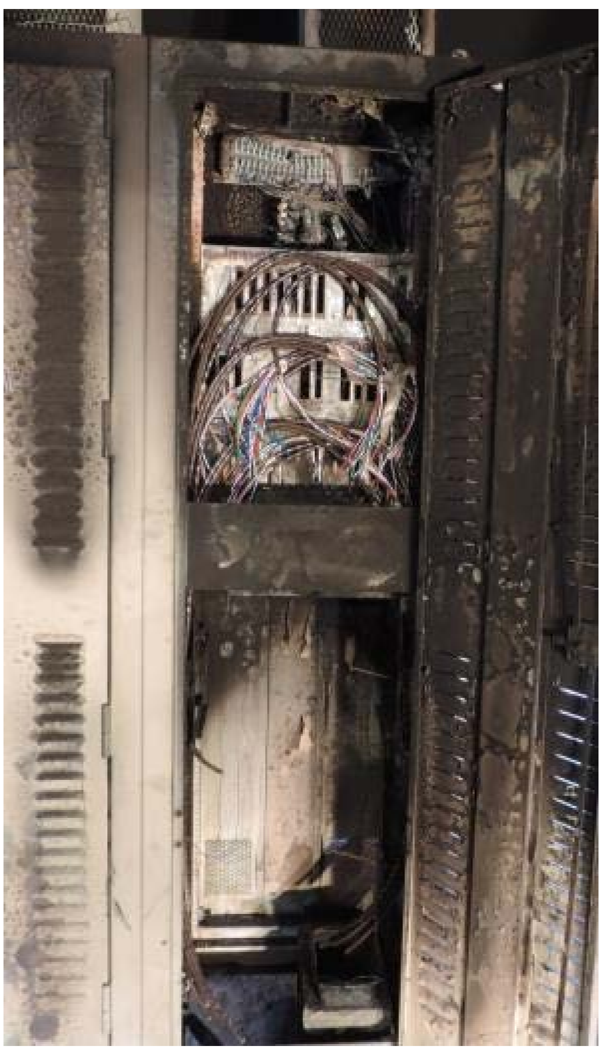
Test: 50 **Enclosure:** 4 **Fuel Load:** Two cable bundles; one on each side. Each bundle contained 10 cables (#805) stripped 20 cm (8 in) near the top **Ignition Source:** 1 L acetone pan fire **Ventilation:** Door closed **Notes:** Even though the cables were immersed in the liquid fuel, the fire did not spread upwards. The acetone was exhausted at 20 min.	
	

Table 5-52. Summary of Test 51

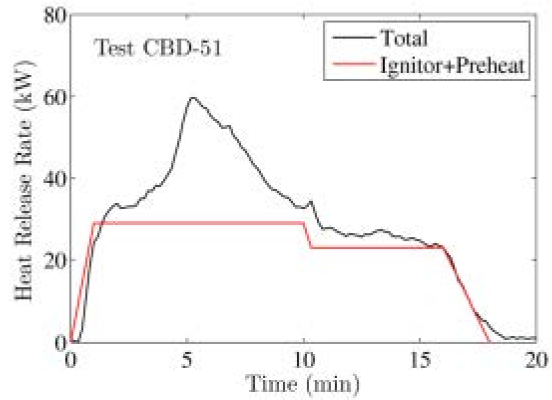
Test: 51 **Enclosure:** 4 **Fuel Load:** The unburned left side bundle from Test 50 **Ignition Source:** 5.5 kW propane burner and 1 L acetone pan fire **Ventilation:** Door open **Notes:** The fire spread halfway to the top of the enclosure. The propane burner was turned off at 10 min.	
	

Table 5-53. Summary of Test 52

Test: 52

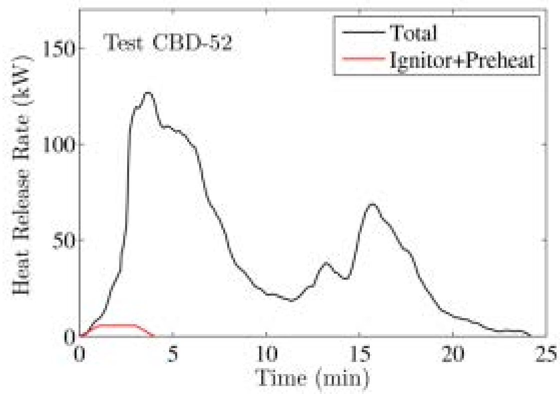
Enclosure: 4

Fuel Load: Two cable bundles; one on each side. Each bundle contained 70 insulated conductors stripped from Cable #807

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.



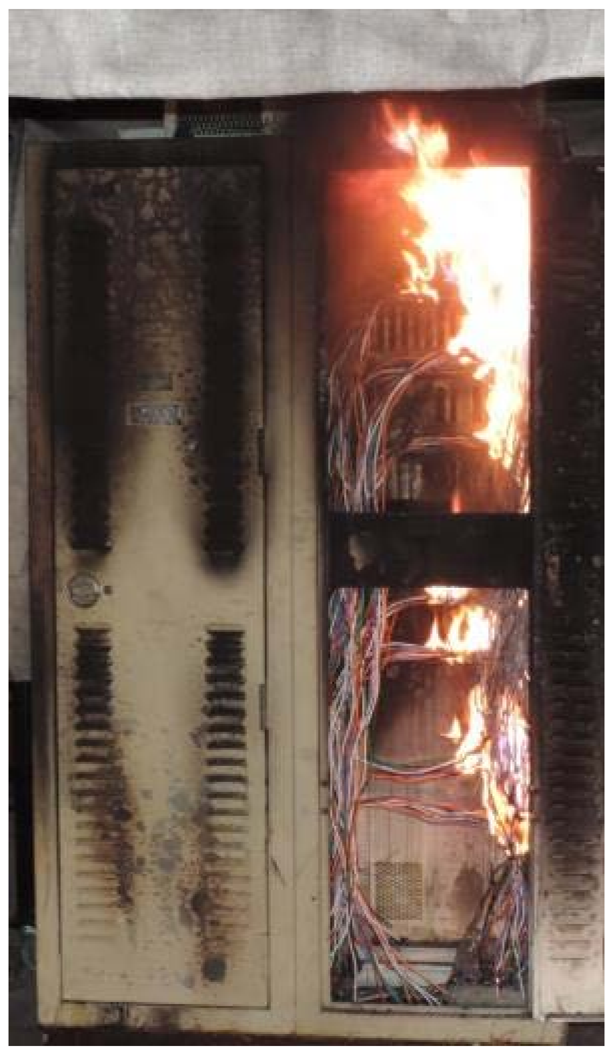
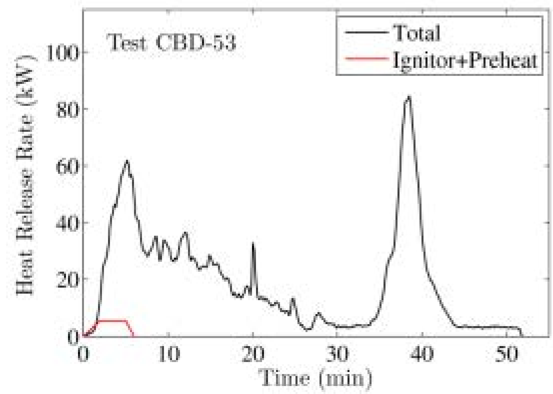


Table 5-54. Summary of Test 53

Test: 53 **Enclosure:** 4 **Fuel Load:** Two cable bundles; one on each side. Each bundle contained 70 insulated conductors stripped from Cable #807 **Ignition Source:** 5.5 kW propane burner **Ventilation:** Door closed **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, 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.	
	

 Draft Report for Comment

Table 5-55. Summary of Test 54

Test: 54

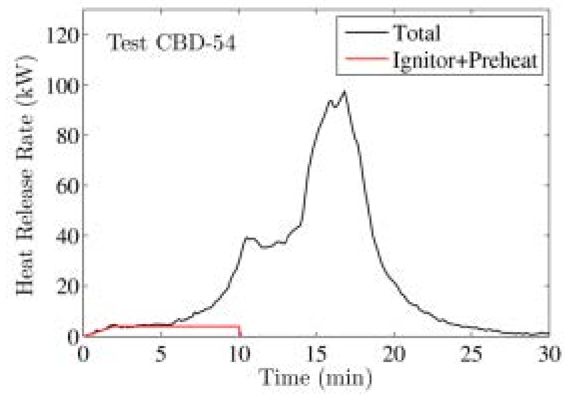
Enclosure: 4

Fuel Load: 2 bundles of surplus power cord (#841); one per side; 10 cords per bundle

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.



 Draft Report for Comment

Table 5-56. Summary of Test 55

Test: 55

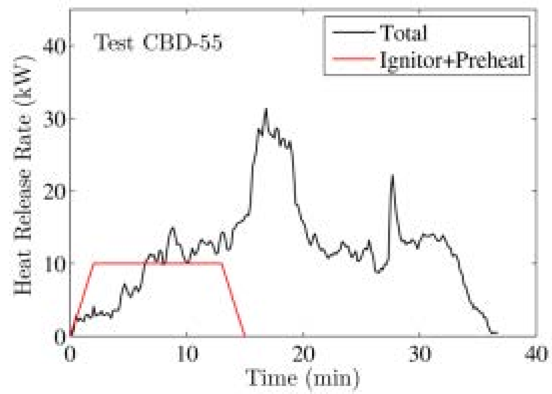
Enclosure: 4

Fuel Load: Same as Test 54

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

Ventilation: Door closed

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.



 Draft Report for Comment

Table 5-57. Summary of Test 56

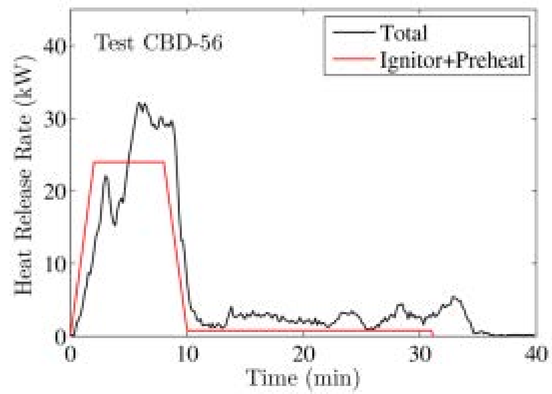
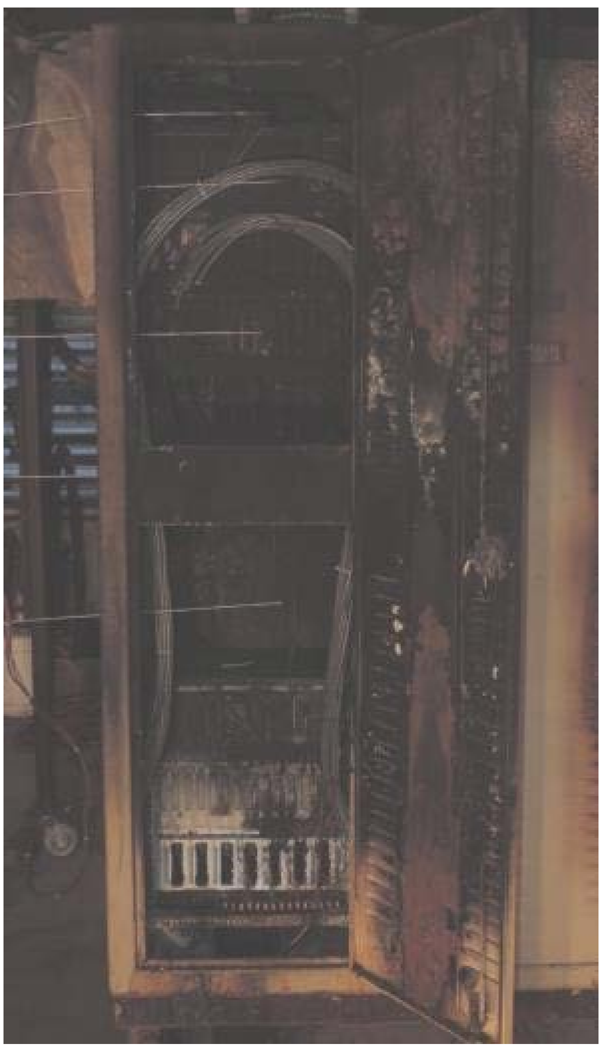
Test: 56 **Enclosure:** 5 **Fuel Load:** 10 cable bundle (#844) routed up right side of enclosure **Ignition Source:** 0.8 kW propane burner **Preheating Source:** 500 mL acetone pan fire **Ventilation:** Door closed **Notes:** The acetone pan fire was used for pre-heating only and burned for about 10 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.	
	

Table 5-58. Summary of Test 57

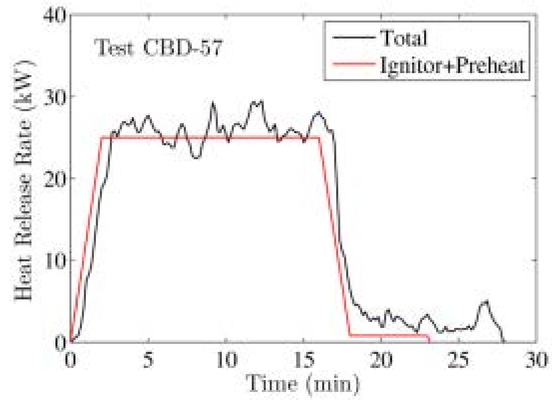
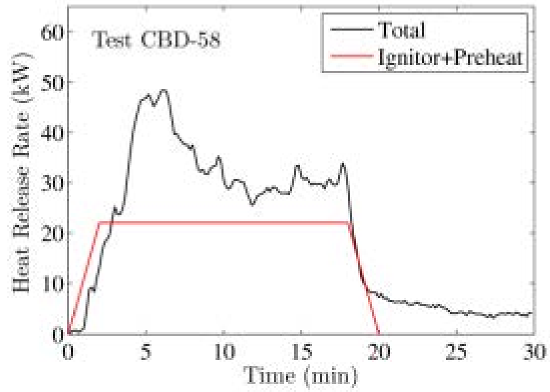
Test: 57 **Enclosure:** 5 **Fuel Load:** 10 cable bundle (#844) routed up left side of enclosure **Ignition Source:** 0.8 kW propane burner **Preheating Source:** 1 L acetone pan fire **Ventilation:** Door closed **Notes:** The acetone pan fire was used for pre-heating only and burned for about 18 min. 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.	
	

Table 5-59. Summary of Test 58

Test: 58 **Enclosure:** 5 **Fuel Load:** 10 jacketed cables and 10 stripped cables (#844). 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.	
	

 Draft Report for Comment

Table 5-60. Summary of Test 59

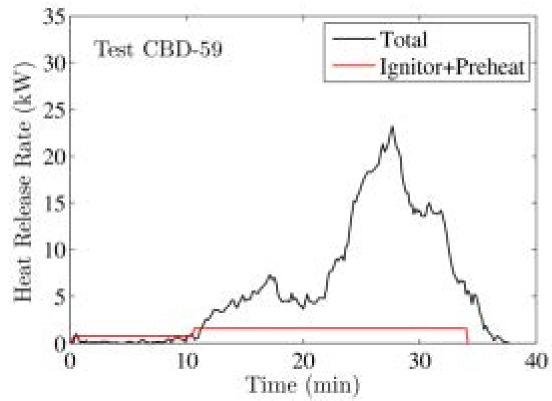
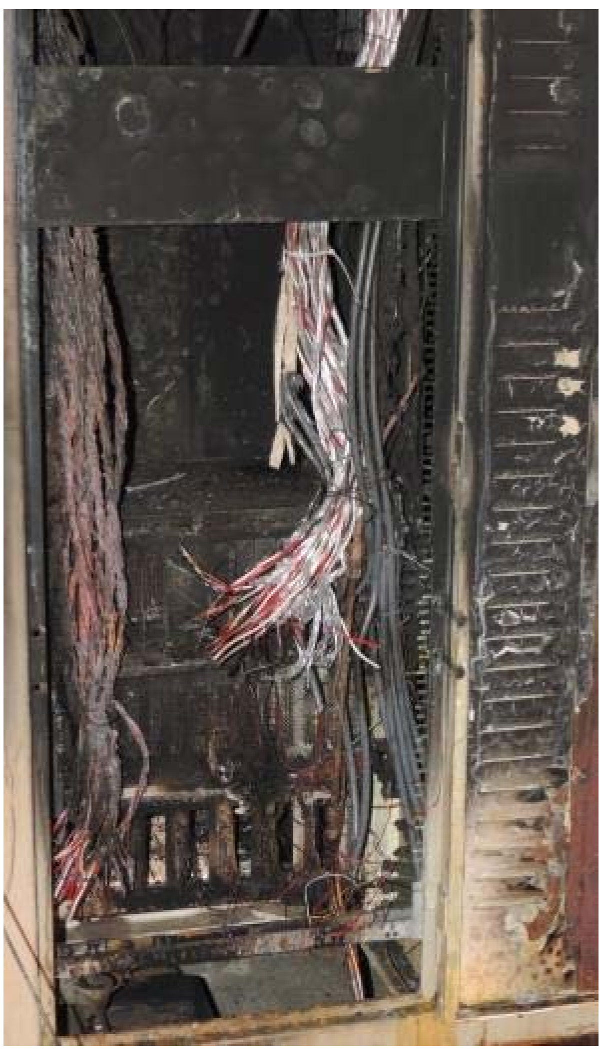
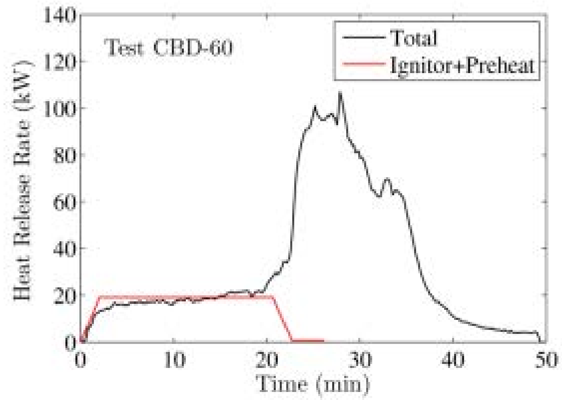
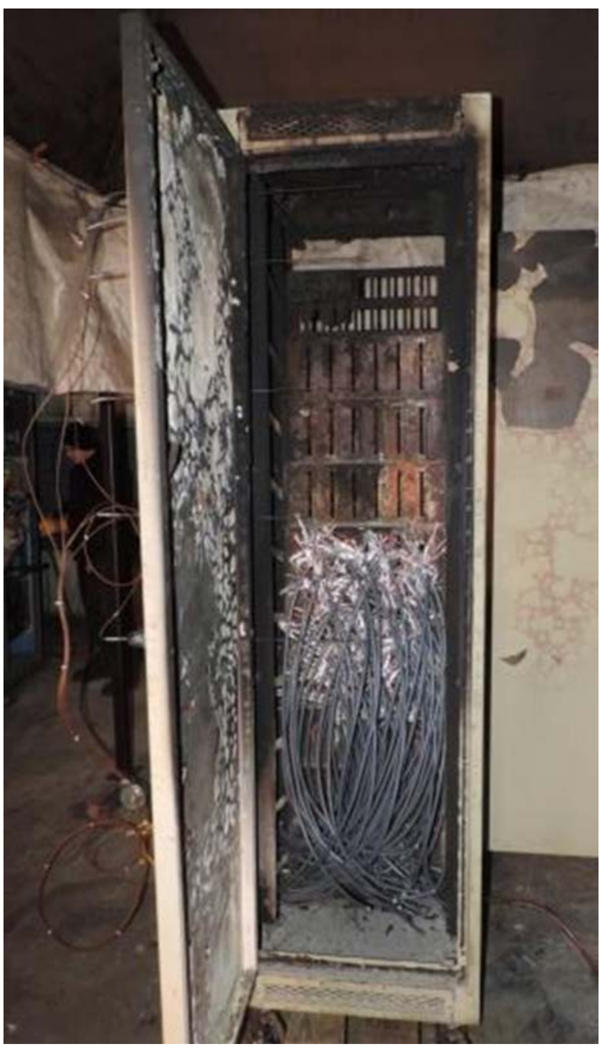
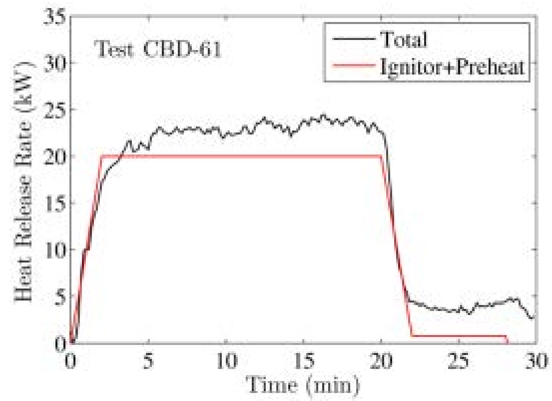
Test: 59 **Enclosure:** 5 **Fuel Load:** 10 jacketed cables and 10 stripped cables (#844). The jacketed cable was left over from Tests 56 and 57. **Ignition Source:** 0.8 kW propane burner **Ventilation:** Door open **Notes:** The propane burner was increased to 2 kW after 10 min, 30 s, at which point the fire began to spread upwards, extending about 60 cm above the burner by 20 min. At 21 min, 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 5-61. Summary of Test 60

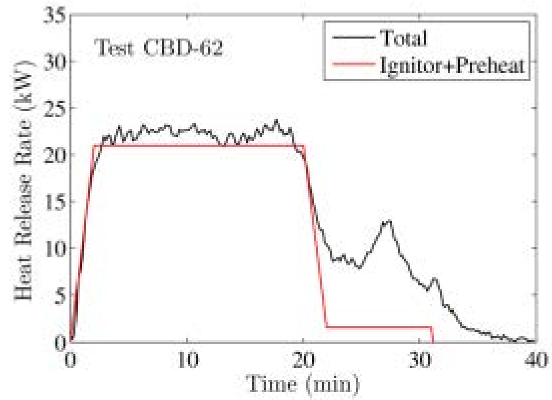
Test: 60 **Enclosure:** 1 **Fuel Load:** 72 cables (#844) of various lengths, 73 m (240 ft) total **Ignition Source:** 0.8 kW propane burner **Preheating Source:** 1 L acetone pan fire **Ventilation:** Door closed **Notes:** The acetone pan fire was placed in the back of the enclosure, behind a steel partition. The acetone was exhausted at 22 min, 40 s. The propane burner was turned off at 26 min.	
	

 Draft Report for Comment

Table 5-62. Summary of Test 61

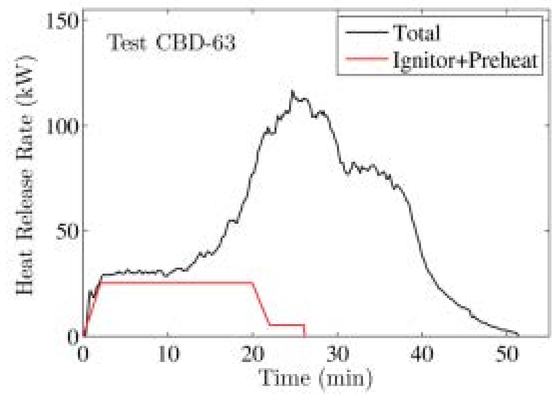
Test: 61 **Enclosure:** 1 **Fuel Load:** 60 cables (#807) of various lengths; 63 m (208 ft) total **Ignition Source:** 0.8 kW propane burner **Preheating Source:** 1 L acetone pan fire **Ventilation:** Door closed **Notes:** The acetone pan was placed at the back of the enclosure behind a steel partition, 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.	
	

1 **Table 5-63. Summary of Test 62**

Test: 62 **Enclosure:** 1 **Fuel Load:** Same as Test 61 **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.	
	No picture available

2

Table 5-64. Summary of Test 63

Test: 63 **Enclosure:** 1 **Fuel Load:** Same as Test 61 **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.	
	

 Draft Report for Comment

Table 5-65. Summary of Test 64

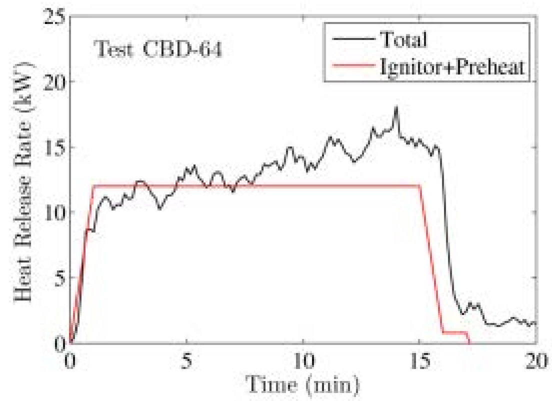
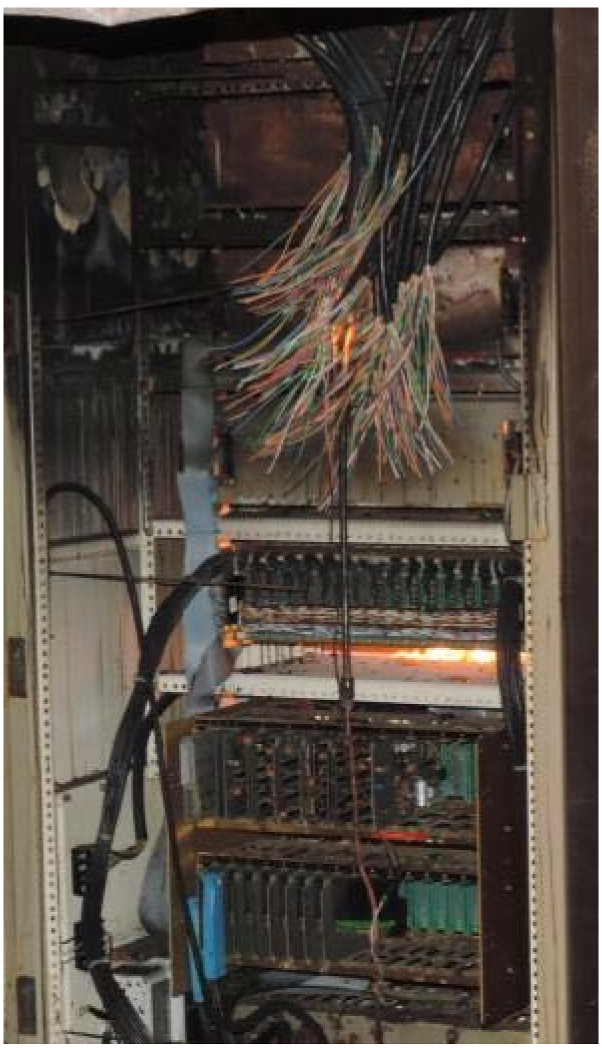
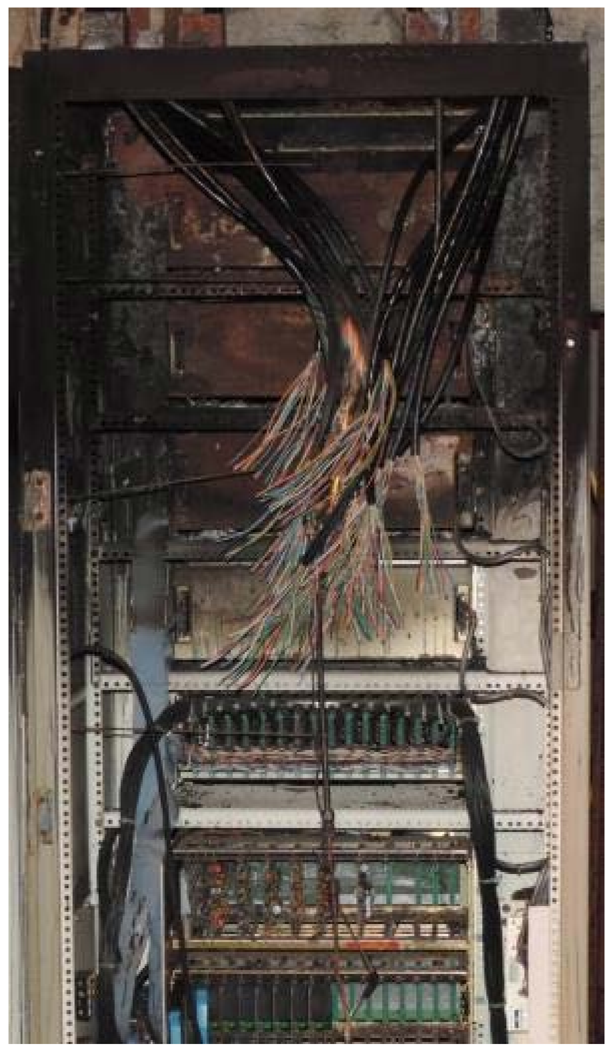
Test: 64 **Enclosure:** 8 **Fuel Load:** 21 cables (#813), each 1.8 m (6 ft) long, routed through channels in top of enclosure and onto a cable tray 30 cm (1 ft) above **Ignition Source:** 0.8 kW propane burner **Preheating Source:** 500 mL acetone pan fire **Ventilation:** Door closed **Notes:** The 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	
	

Table 5-66. Summary of Test 65

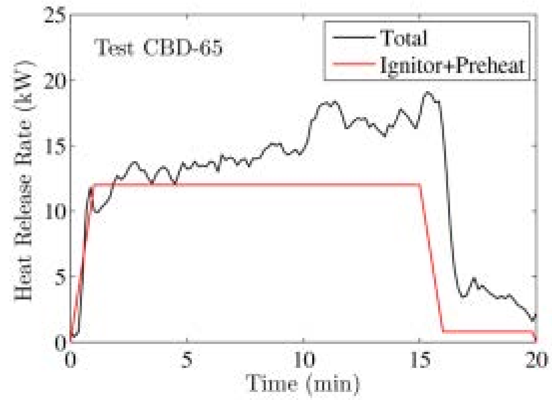
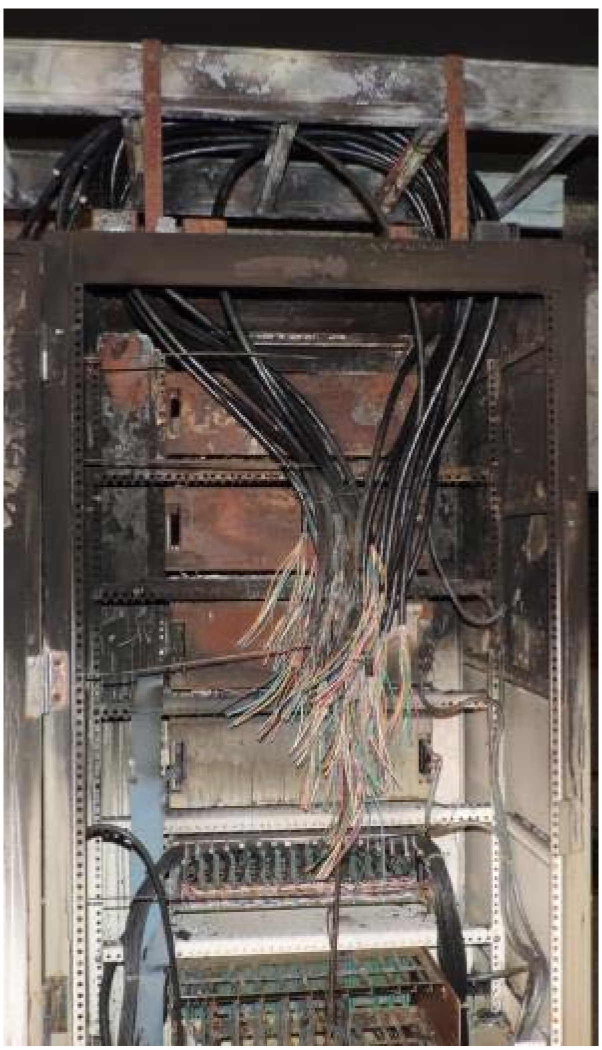
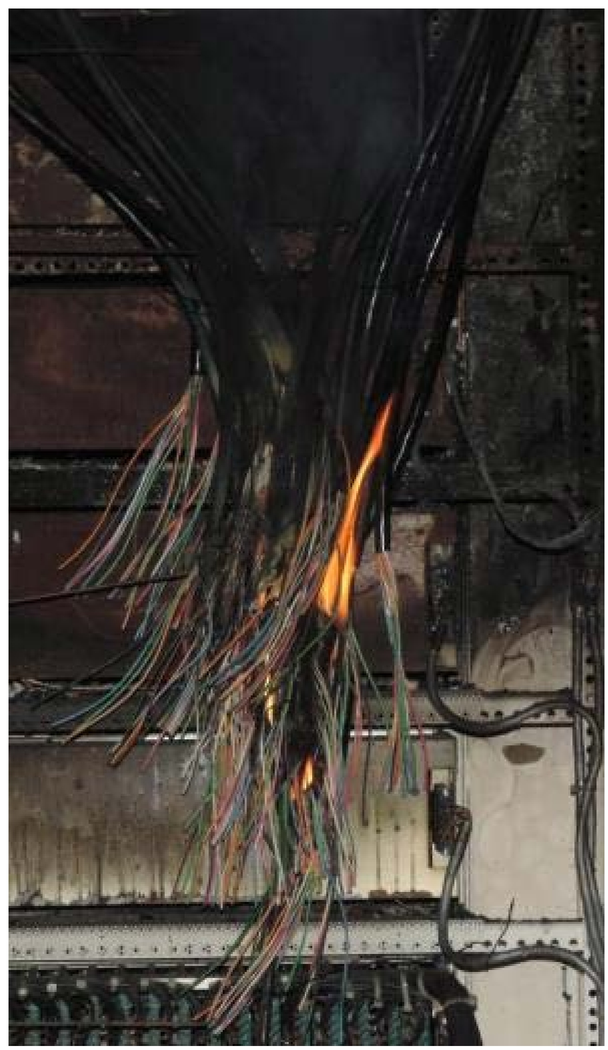
Test: 65 **Enclosure:** 8 **Fuel Load:** Same as Test 64 **Ignition Source:** 0.8 kW propane burner **Preheating Source:** 500 mL acetone pan fire **Ventilation:** Door closed **Notes:** The acetone pan was placed at the back of the enclosure and the fire did not directly impinge on cables. The acetone was exhausted at 16 min. The propane burner was turned off at 20 min. The fire did not spread beyond igniter.	
	

Table 5-67. Summary of Test 66

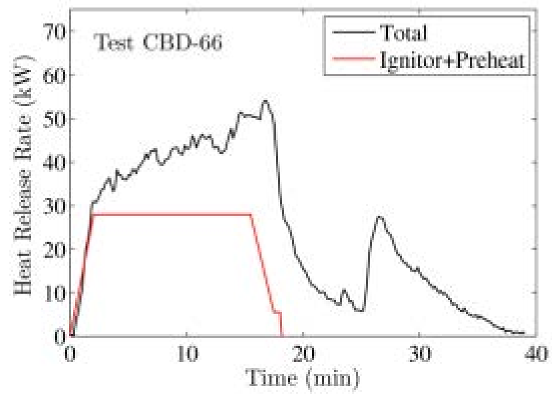
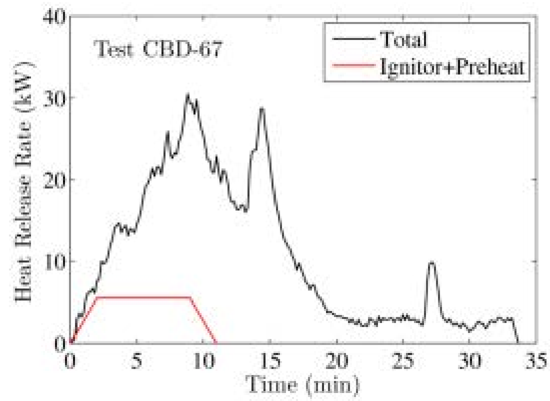
Test: 66 **Enclosure:** 4 **Fuel Load:** 20 cable bundle (#844), 1.8 m (6 ft) long, routed up right side of enclosure **Ignition Source:** 5.5 kW propane burner **Preheating Source:** 1 L acetone pan fire **Ventilation:** Door closed **Notes:** The acetone pan was placed at the rear of the enclosure, 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, 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 5-68. Summary of Test 67

Test: 67 **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 **Notes:** The propane burner was turned off at 9 min. At 13 min, 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.	
	

 Draft Report for Comment

Table 5-69. Summary of Test 68

Test: 68

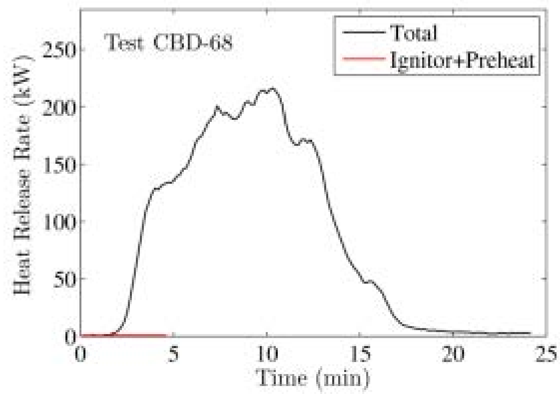
Enclosure: 1

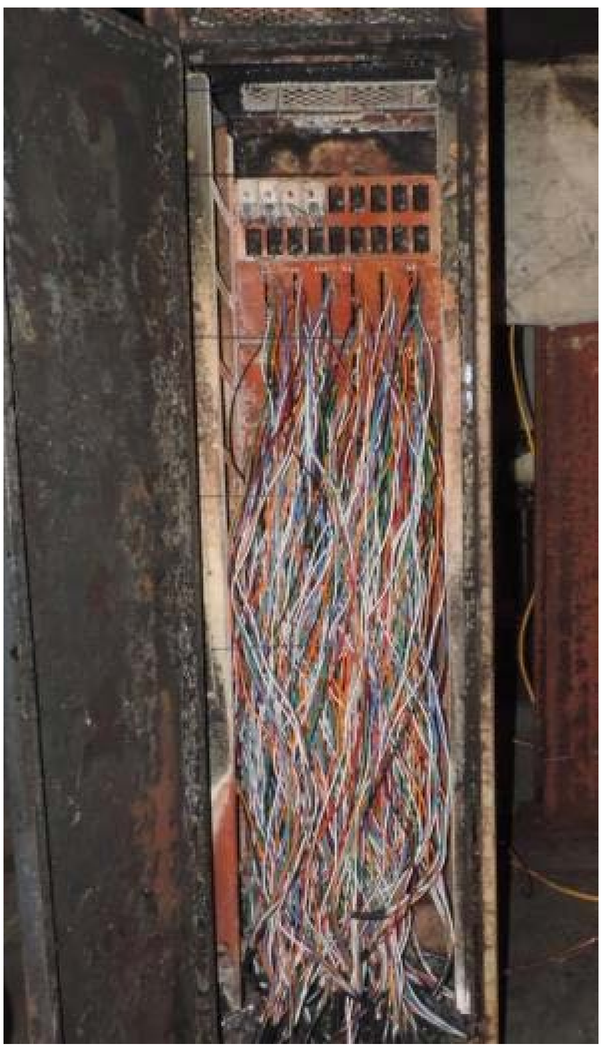
Fuel Load: 420 insulated conductors extracted from Cable #807; 540 m (1770 ft) total

Ignition Source: 0.8 kW propane burner

Ventilation: Door closed

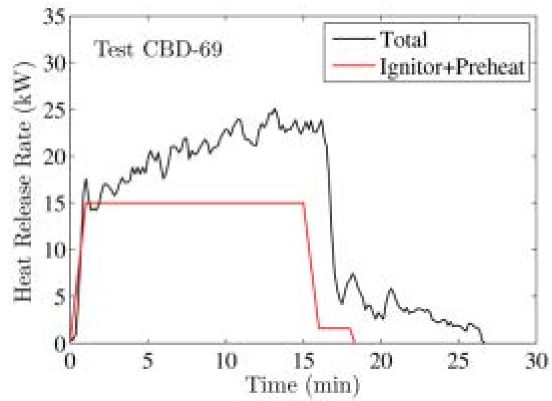
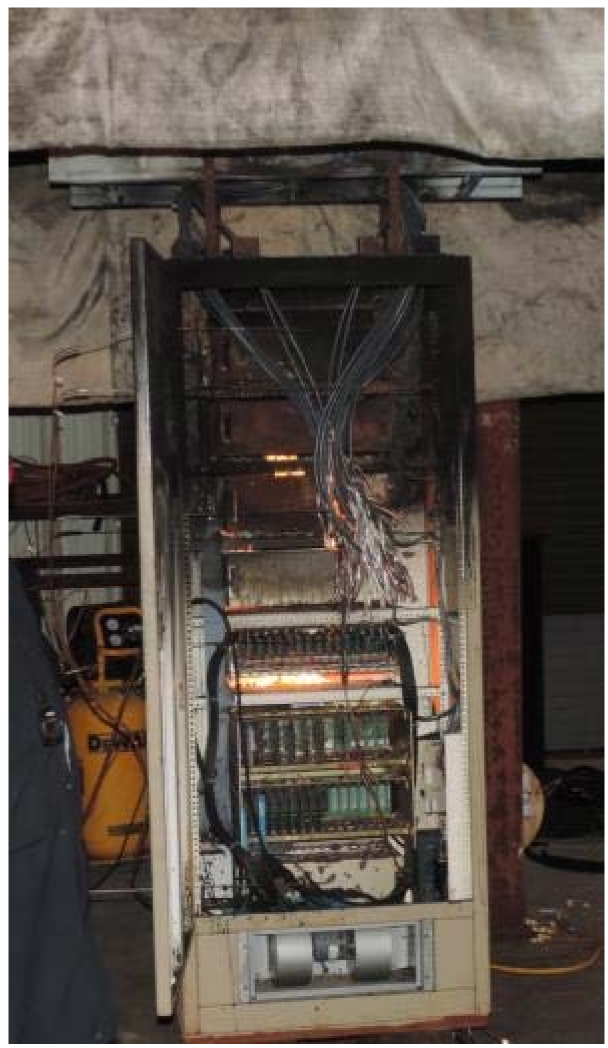
Notes: The burner was turned off at 4 min, 30 s. The door was opened at 15 min and it was observed that all the wire had burned.





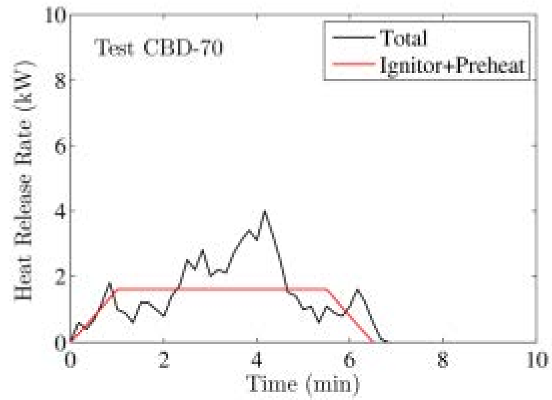
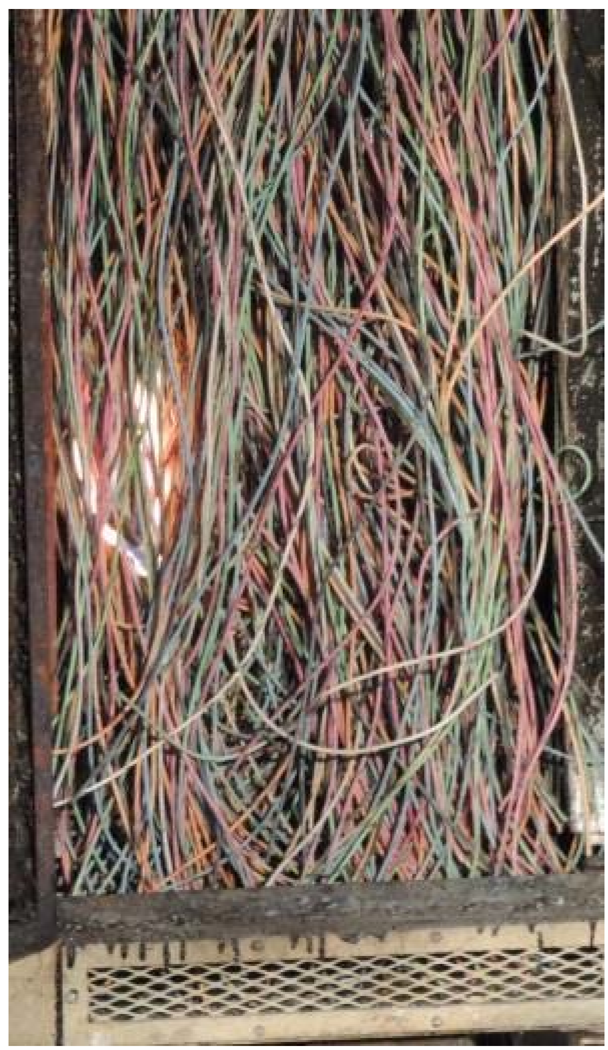
Draft Report for Comment

Table 5-70. Summary of Test 69

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.	
	

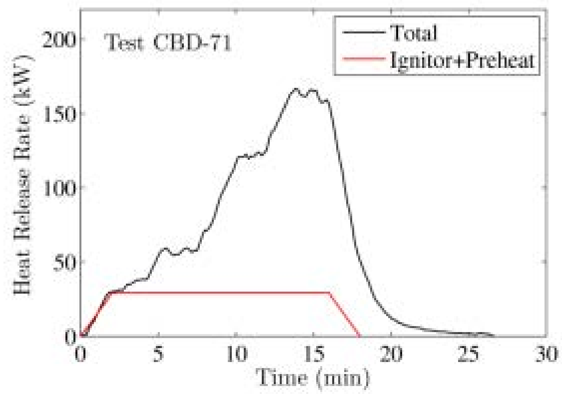
 Draft Report for Comment

Table 5-71. Summary of Test 70

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.	
	

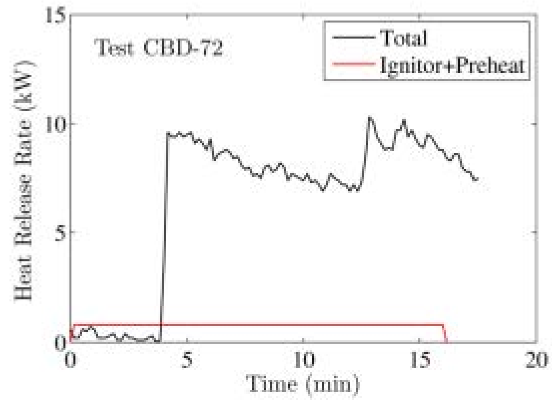
 Draft Report for Comment

Table 5-72. 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.	
	

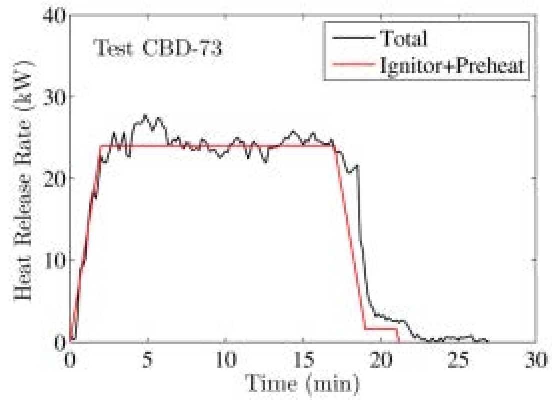
 Draft Report for Comment

Table 5-73. 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 **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 measurement is flawed – there was nothing observed that indicates a jump of 10 kW. It is likely that the HRR was never greater than 5 kW.	
	

 Draft Report for Comment

Table 5-74. Summary of Test 73

Test: 73 **Enclosure:** 4 **Fuel Load:** 10 cable bundle (#813) **Ignition Source:** 1.6 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 acetone was exhausted at 19 min, at which time the door was opened and the cables were jostled with a crowbar. The propane burner was turned off at 21 min. The fire spread approximately 45 cm (18 in) above the burner.	
	

Draft Report for Comment

Table 5-75. Summary of Test 74

Test: 74

Enclosure: 5

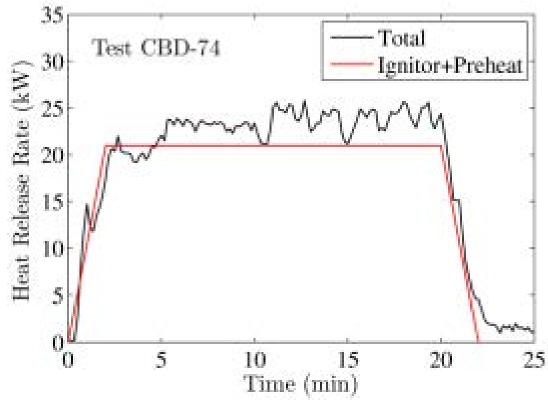
Fuel Load: 10 cable bundle (#809)

Ignition Source: 1.6 kW propane burner

Preheating Source: 1 L acetone pan fire

Ventilation: Door closed

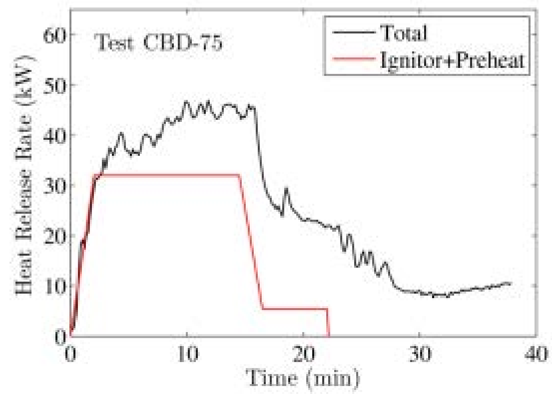
Notes: The acetone pan fire did not directly impinge upon the cables. The acetone was exhausted at 22 min, at which time the door was open. The propane burner was turned off at 22 min. The fire spread approximately 60 cm (2 ft) above the burner.



 Draft Report for Comment

Table 5-76. Summary of Test 75

Test: 75
Enclosure: 4
Fuel Load: 10 cable bundle (#813)
Ignition Source: 5.5 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 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.



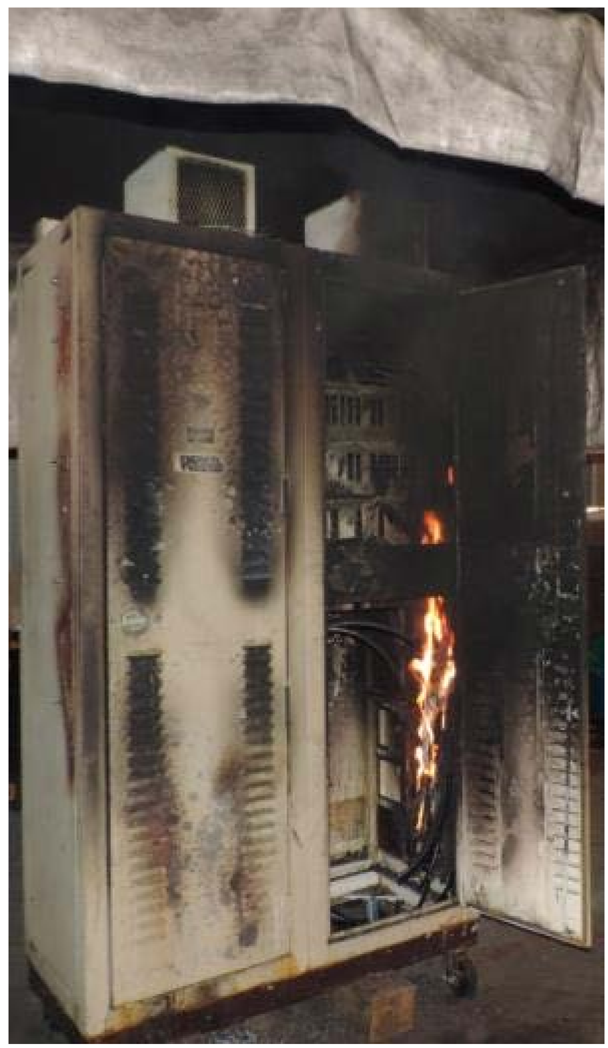


Table 5-77. Summary of Test 76

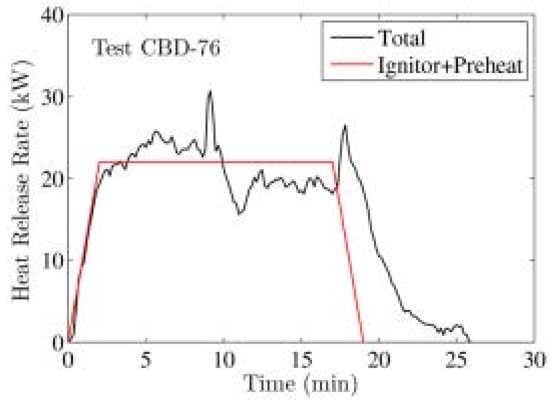
Test: 76 **Enclosure:** 5 **Fuel Load:** 10 cable bundle (#813) **Ignition Source:** 1 L acetone pan fire **Ventilation:** Door closed **Notes:** The acetone pan was placed directly under the cable bundle so that the ends of the cables were immersed in the liquid. The door was opened at 8 min, 30 s and 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 5-78. Summary of Test 77

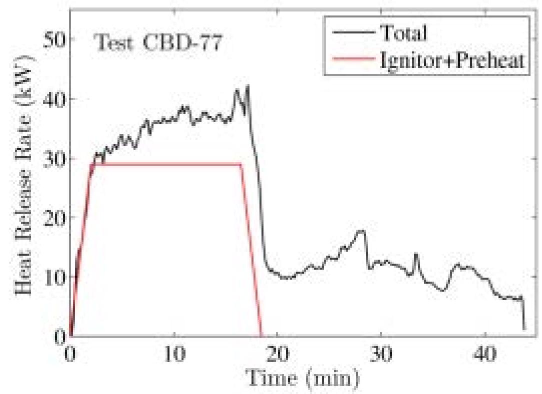
Test: 77 **Enclosure:** 5 **Fuel Load:** 10 cable bundle (#809) **Ignition Source:** 5.5 kW propane burner **Preheating Source:** 1 L acetone pan fire **Ventilation:** Door closed **Notes:** The acetone pan fire did not directly impinge upon the cables. The door was opened at 16 min, 30 s, and was left 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 5-79. Summary of Test 78

Test: 78

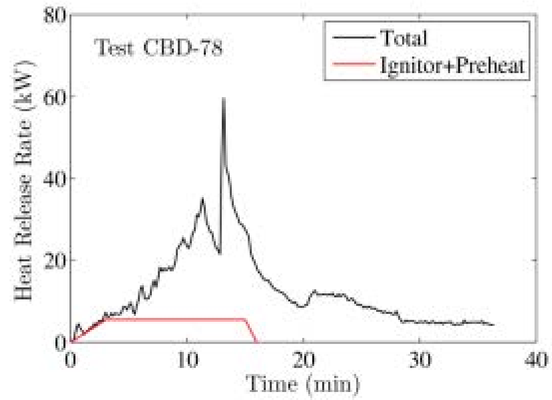
Enclosure: 5

Fuel Load: 10 cable bundle (#809)

Ignition Source: 5.5 kW propane burner

Ventilation: Door closed

Notes: The fire spread steadily to the top of the bundle. The burner was turned off at 15 min.



1 **Table 5-80. Summary of Test 79**

Test: 79

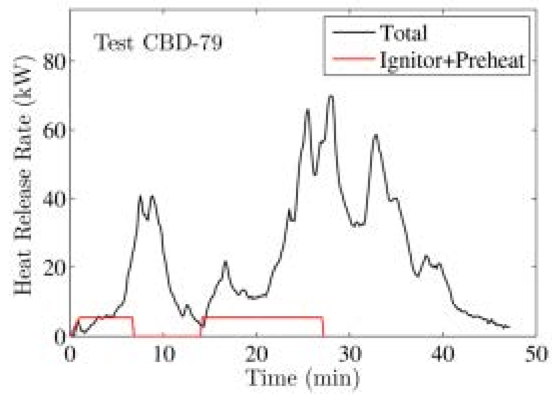
Enclosure: 4

Fuel Load: 310 insulated wires stripped from Cable #834, arranged in 4 loose bundles

Ignition Source: 5.5 kW propane burner

Ventilation: Door closed

Notes: The propane burner was turned off at 6 min, 40 s. The door was opened at 12 min. 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.



2

 Draft Report for Comment

Table 5-81. Summary of Test 80

Test: 80

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

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 acetone was exhausted at 18 min, and the propane burner was turned off at 21 min. The fire spread to the top of the bundles.

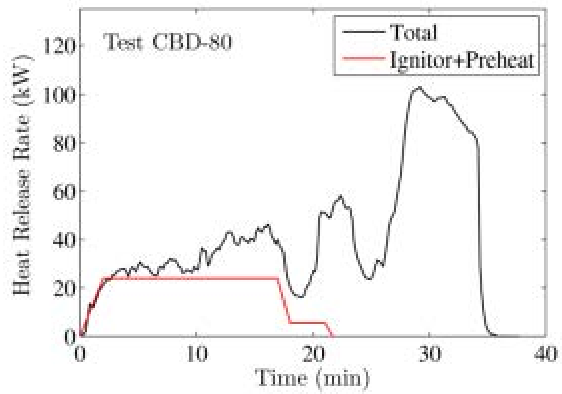


Table 5-82. Summary of Test 81

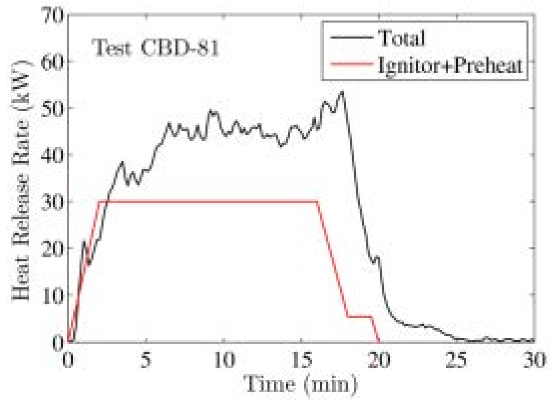
Test: 81 **Enclosure:** 5 **Fuel Load:** 10 cable bundle (#813) **Ignition Source:** 5.5 kW propane burner and 1 L acetone pan fire **Ventilation:** Door closed **Notes:** The acetone pan fire was placed near the base of the cable bundle. The acetone was exhausted at 18 min. The door was opened at 19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

Table 5-83. Summary of Test 82

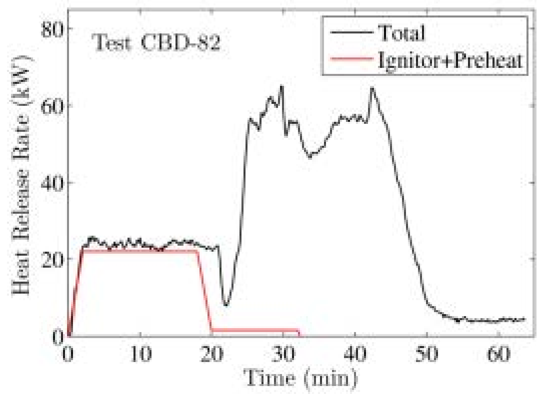
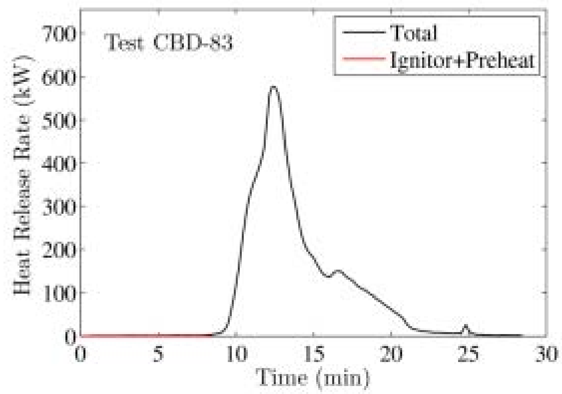
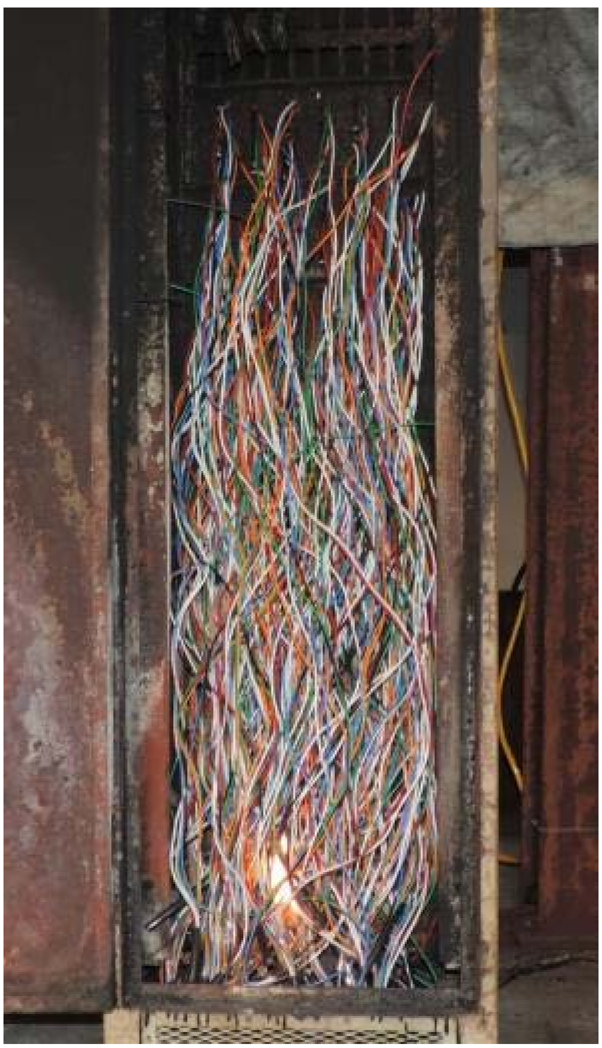
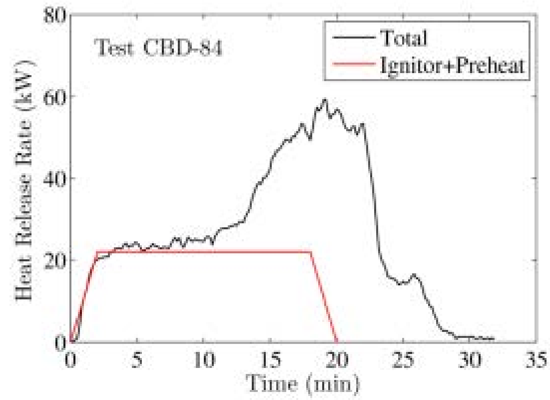
Test: 82 **Enclosure:** 1 **Fuel Load:** 72 cables (#844) of various lengths; 73 m (240 ft) total **Ignition Source:** 1.6 kW propane burner **Preheating Source:** 1 L acetone pan fire **Ventilation:** Door closed **Notes:** The acetone pan was placed in the rear of the compartment behind a steel partition. 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 and left open. The propane burner was turned off at 32 min.	
	

Table 5-84. Summary of Test 83

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.	
	

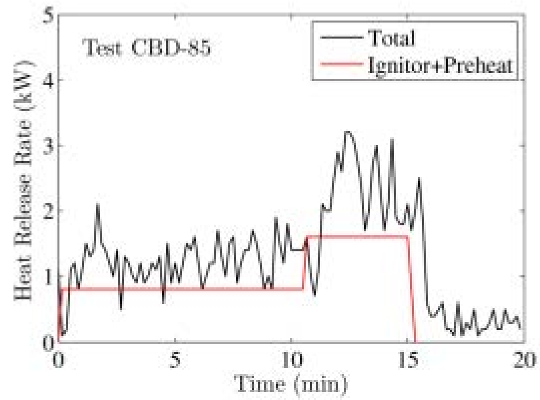
 Draft Report for Comment

Table 5-85. Summary of Test 84

Test: 84 **Enclosure:** 7 **Fuel Load:** 36 cable bundle (#818) **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.	
	

 Draft Report for Comment

Table 5-86. Summary of Test 85

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.	
	

 Draft Report for Comment

Table 5-87. Summary of Test 86

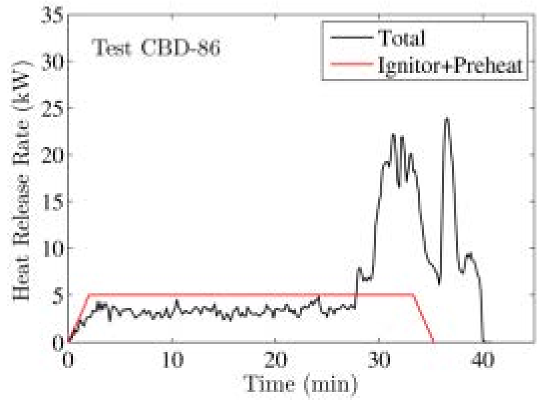
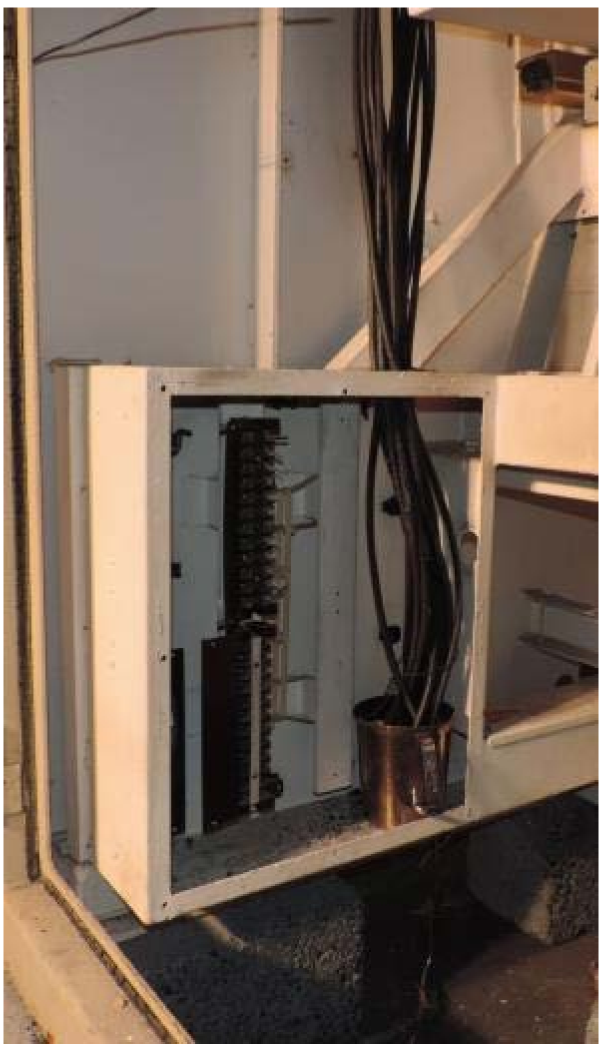
Test: 86 **Enclosure:** 7 **Fuel Load:** Same as Test 85 **Ignition Source:** 500 mL acetone pan fire **Ventilation:** Door open **Notes:** The acetone was poured into a stainless steel beaker with a 10 cm (4 in) opening. The cables inside the small box burned, but the fire did not spread through the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

Table 5-88. Summary of Test 87

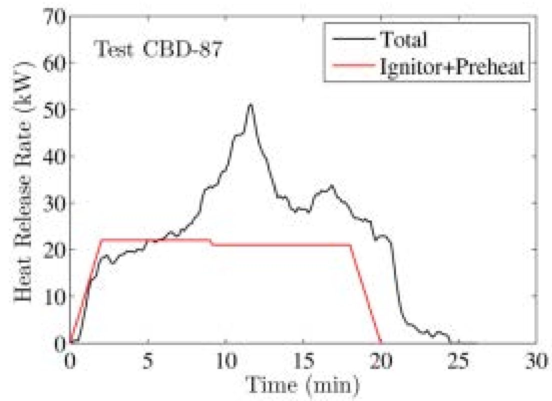
Test: 87 **Enclosure:** 7 **Fuel Load:** 36 cables (#818), 2.4 m (8 ft) long, routed up left right side of enclosure **Ignition Source:** 0.8 kW propane burner **Preheating Source:** 1 L acetone pan fire **Ventilation:** Door closed **Notes:** The acetone pan fire did not directly impinge upon the cables. 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.	
	

Table 5-89. Summary of Test 88

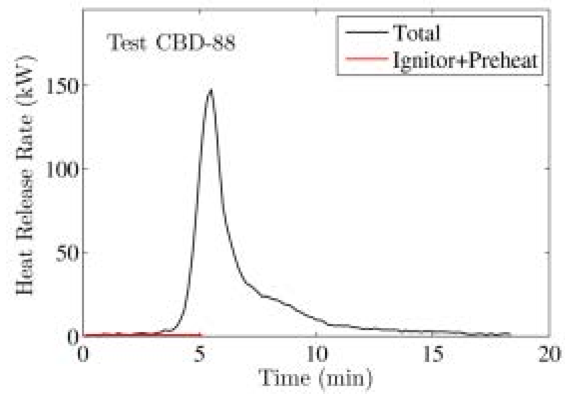
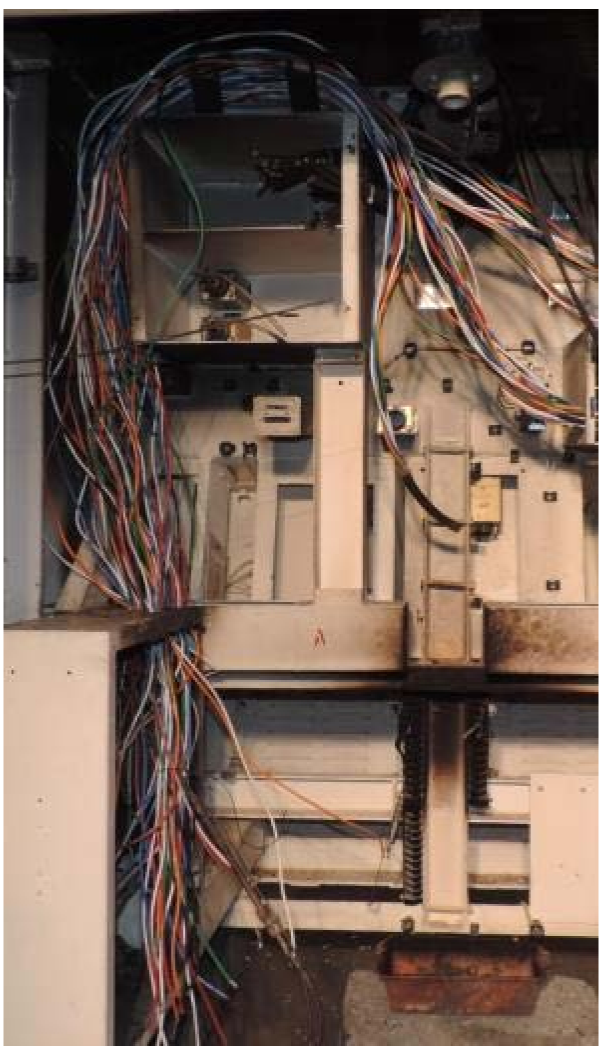
Test: 88 **Enclosure:** 7 **Fuel Load:** 56 insulated conductors extracted from Cable #807, 2.4 m (8 ft) long, routed from enclosed box up left side of enclosure **Ignition Source:** 0.8 kW propane burner **Ventilation:** Door closed **Notes:** The propane burner was turned off at 5 min. The fire spread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

Table 5-90. Summary of Test 89

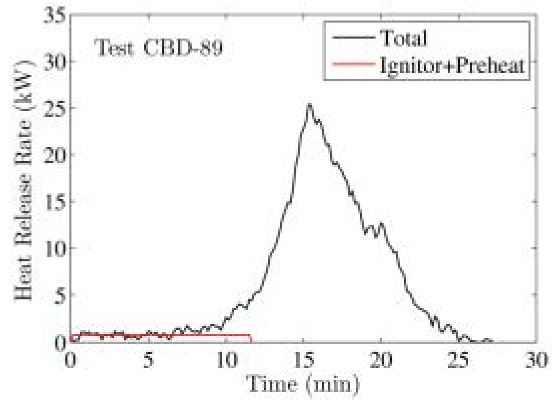
Test: 89 **Enclosure:** 7 **Fuel Load:** Same set-up as Test 88, except the wires were left tightly bundled in groups of 7 **Ignition Source:** 0.8 kW propane burner **Ventilation:** Door closed **Notes:** The burner was turned off at 11 min, 30 s. The fire spread more slowly than Test 88, and it consumed only the vertical portion of the bundles.	
	

Table 5-91. Summary of Test 90

Test: 90

Enclosure: 7

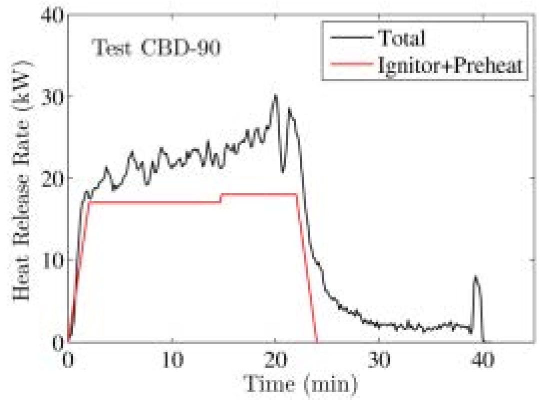
Fuel Load: 10 cables (#809) routed up the left side of the enclosure, 2.4 m (8 ft) long

Ignition Source: 0.8 kW propane burner

Preheating Source: 1 L acetone pan fire

Ventilation: Door closed

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 fire spread slowly upwards, but only burned the vertical portion of the bundle, approximately 1.2 m (4 ft) above the burner.



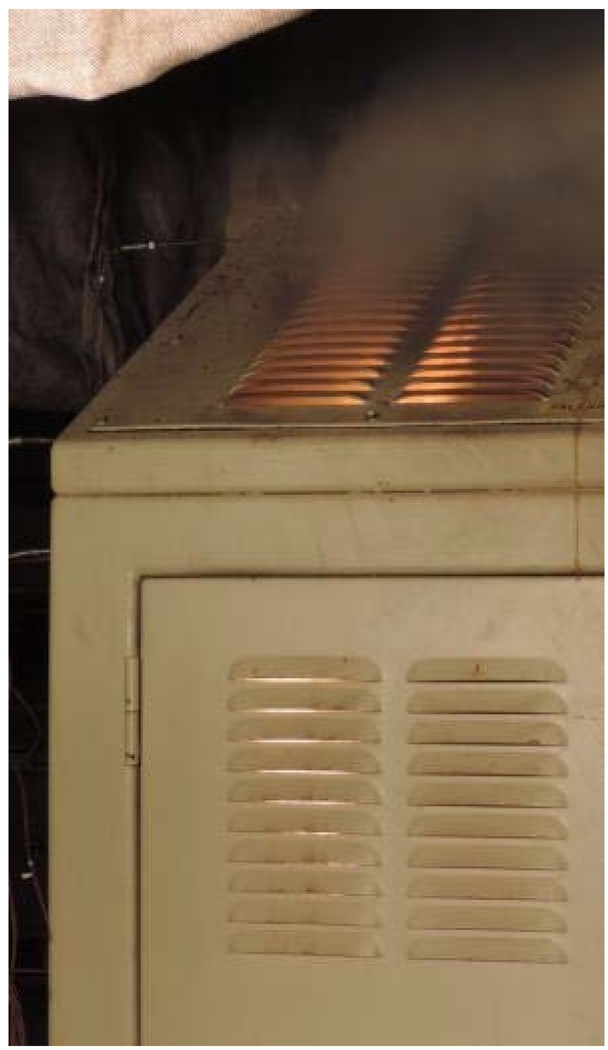
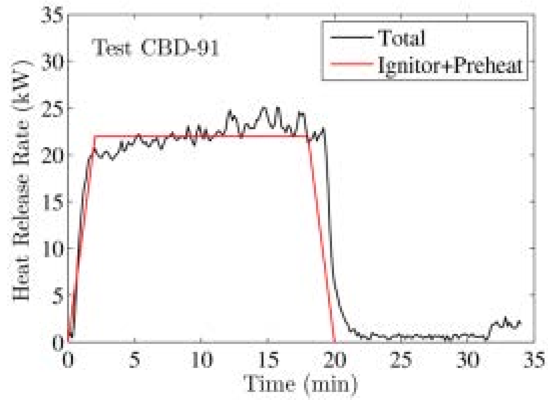


Table 5-92. Summary of Test 91

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 **Notes:** The acetone pan fire did not directly impinge upon the wire. The acetone was exhausted and the burner turned off at 20 min. There was little damage to the wire.	
	

 Draft Report for Comment

Table 5-93. Summary of Test 92

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.

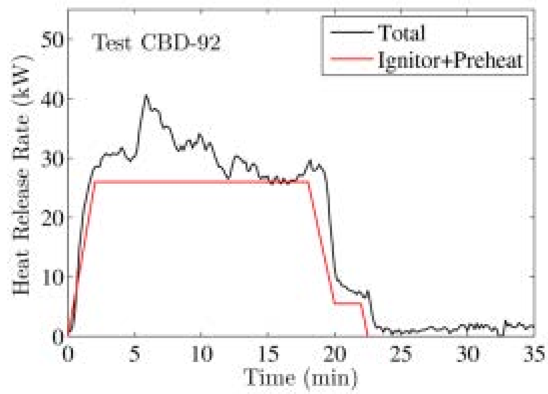
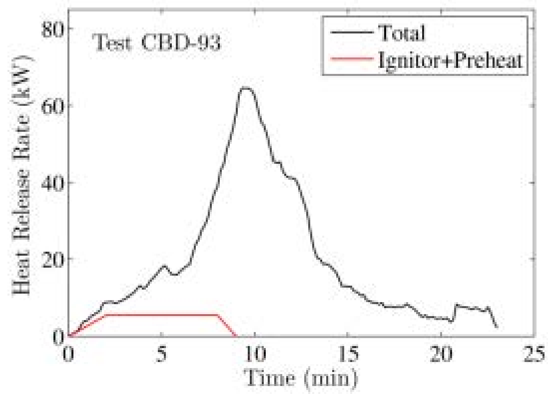
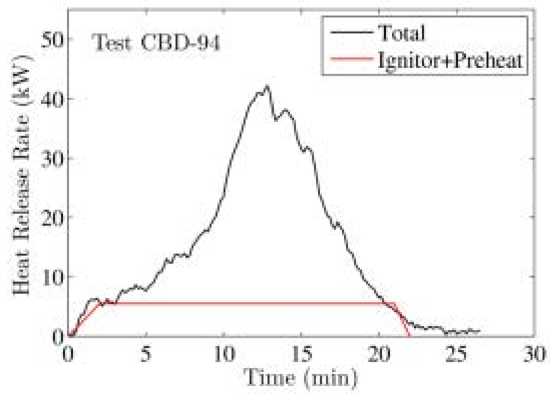


Table 5-94. Summary of Test 93

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 **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.	
	

1 **Table 5-95. 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 **Notes:** The door was opened at 20 min and the propane burner was turned off at 21 min. The fire spread vertically and approximately 30 cm (1 ft) horizontally.	
	

2

Table 5-96. Summary of Test 95

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

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

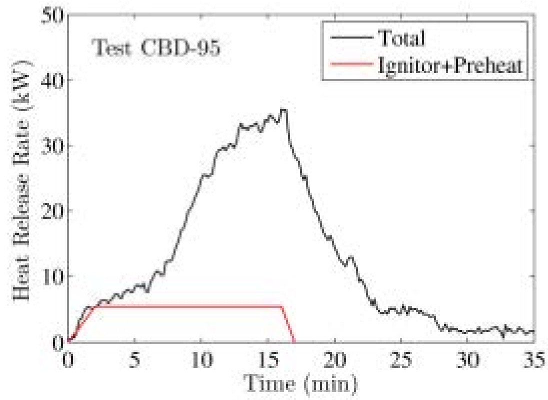
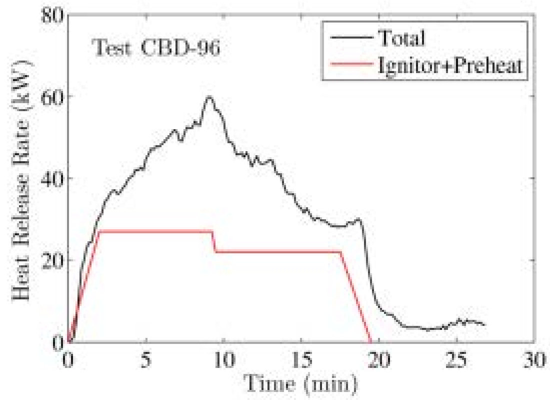
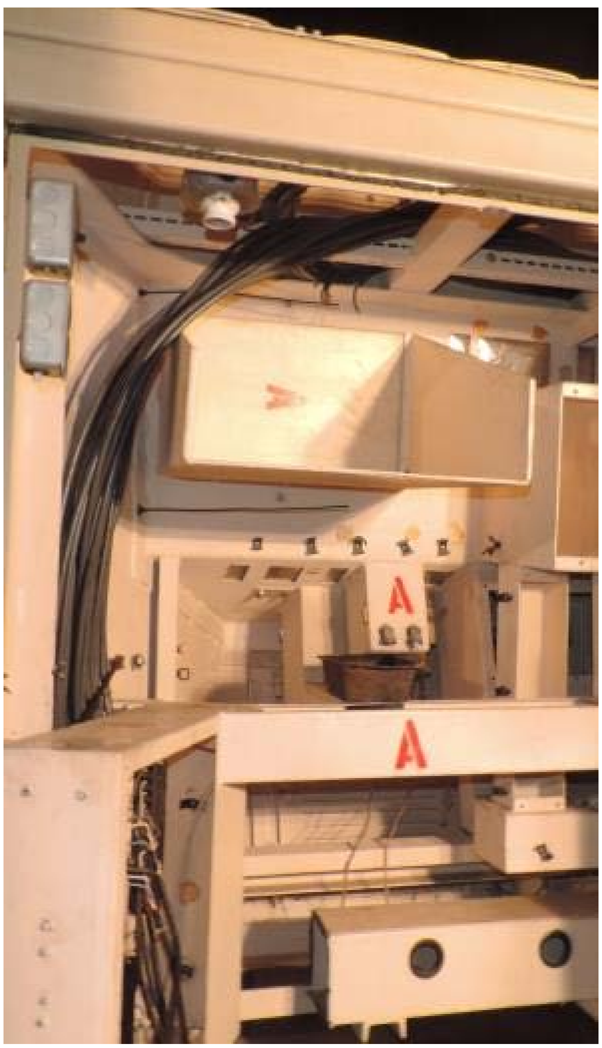
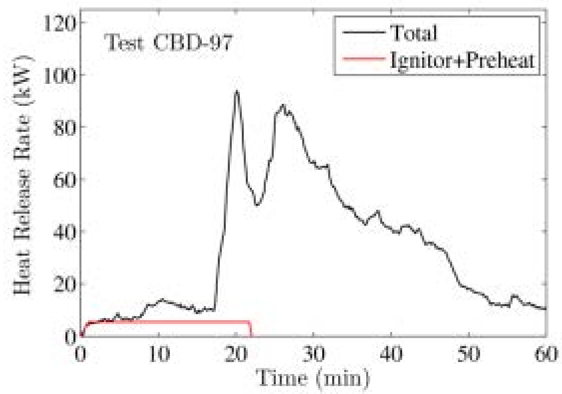


Table 5-97. Summary of Test 96

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 **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.	
	

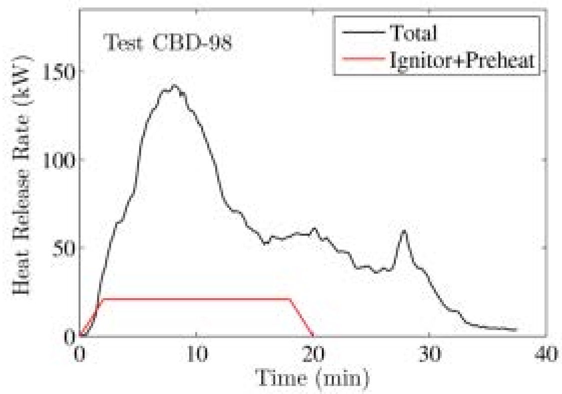
 Draft Report for Comment

Table 5-98. Summary of Test 97

Test: 97 **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, 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.	
	

 Draft Report for Comment

Table 5-99. 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 **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.	
	

 Draft Report for Comment

Table 5-100. Summary of Test 99

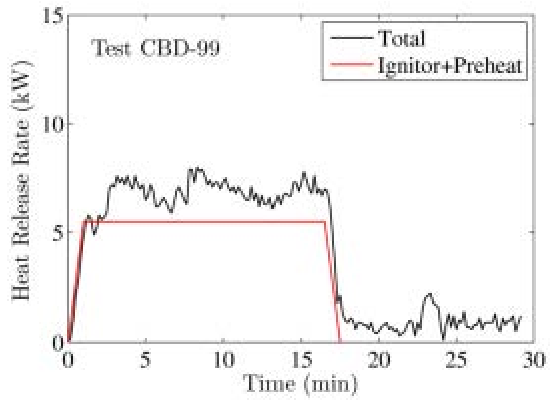
Test: 99 **Enclosure:** 6 **Fuel Load:** 20 coaxial cables (#832), 2.4 m (8 ft) long, routed through a narrow, open-topped steel duct **Ignition Source:** 5.5 kW propane burner **Ventilation:** Door open **Notes:** This experiment was to determine if a fire could propagate from the box at the left of 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.	
	

Table 5-101. Summary of Test 100

Test: 100

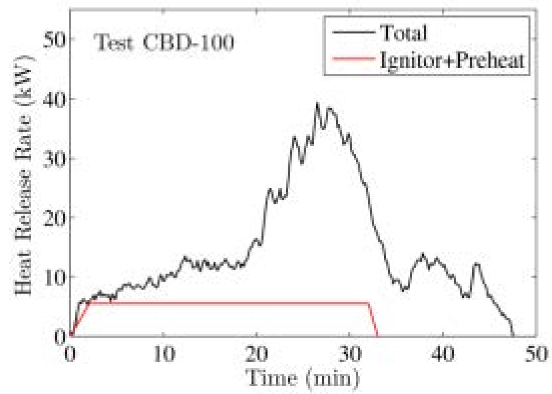
Enclosure: 6

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

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 spread approximately 1 m (3 ft) along the top.



 Draft Report for Comment

Table 5-102. Summary of Test 101

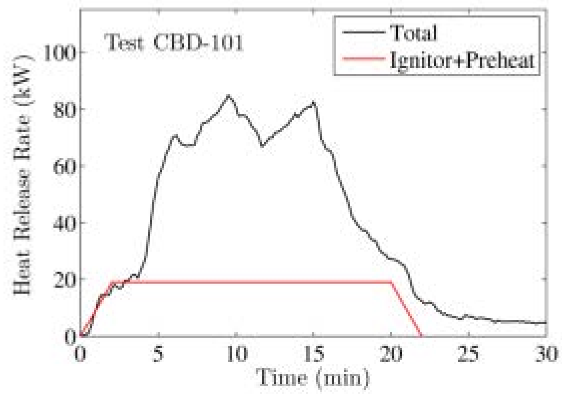
Test: 101 **Enclosure:** 6 **Fuel Load:** The unburned right side portion of the cables from Test 100, approximately 1.2 m (4 ft) of horizontal cable extending downward into fuel pan **Ignition Source:** 1 L acetone pan fire **Ventilation:** Door closed **Notes:** The fire spread rapidly upwards and 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 5-103. Summary of Test 102

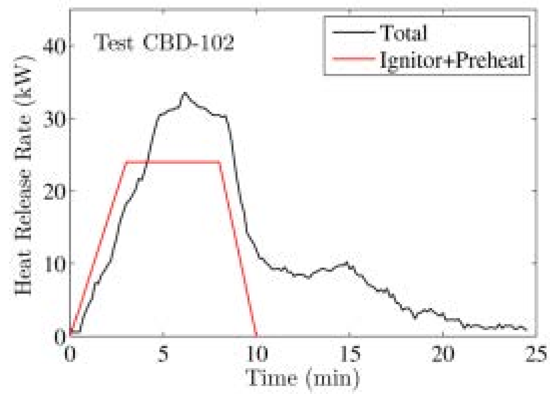
Test: 102 **Enclosure:** 6 **Fuel Load:** 60 insulated wires extracted from Cable #834, routed through a horizontal duct with 20 cm (8 in) square cross section and 5 cm (2 in) openings every 30 cm (1 ft) **Ignition Source:** 500 mL acetone pan fire **Ventilation:** Door open **Notes:** The acetone pan 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 5-104. Summary of Test 103

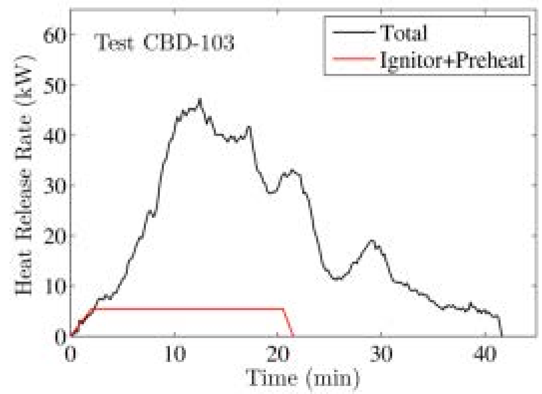
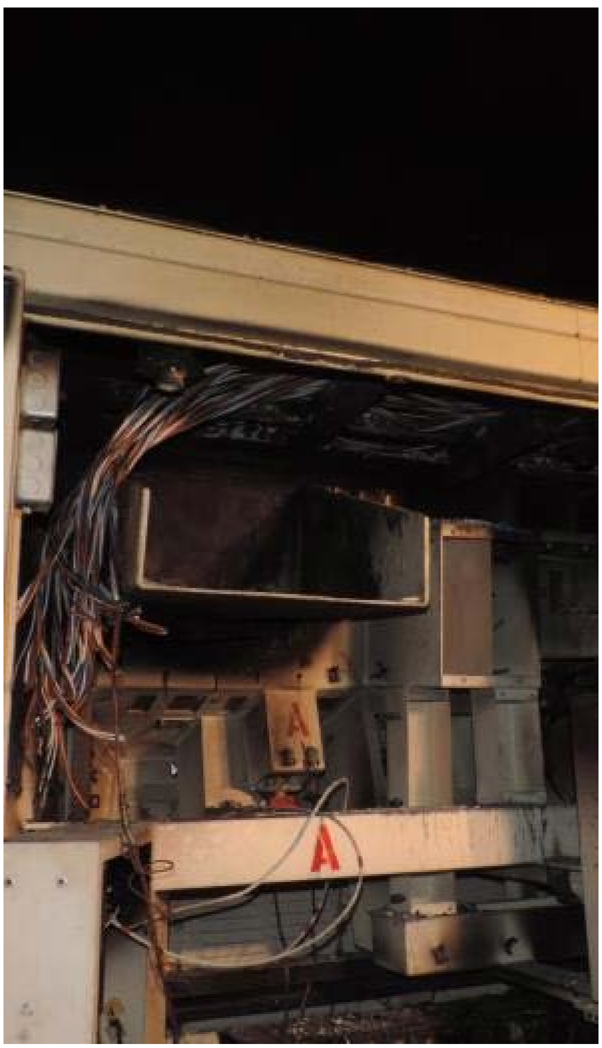
Test: 103 **Enclosure:** 6 **Fuel Load:** 56 insulated conductors extracted from Cable #807, tightly bound in bundles of 7, 2.4 m (8 ft) long, routed along top of enclosure **Ignition Source:** 5.5 kW propane burner **Ventilation:** Door closed **Notes:** The propane burner was turned off at 20 min, 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 5-105. Summary of Test 104

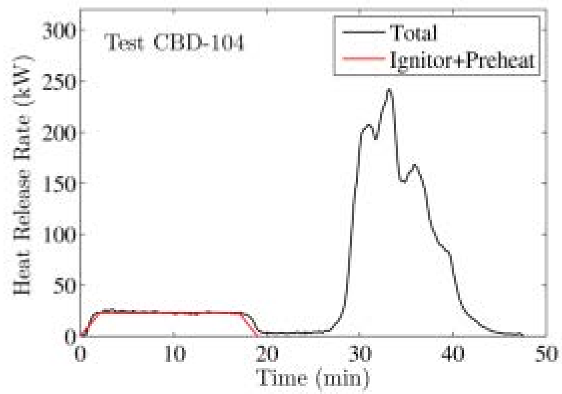
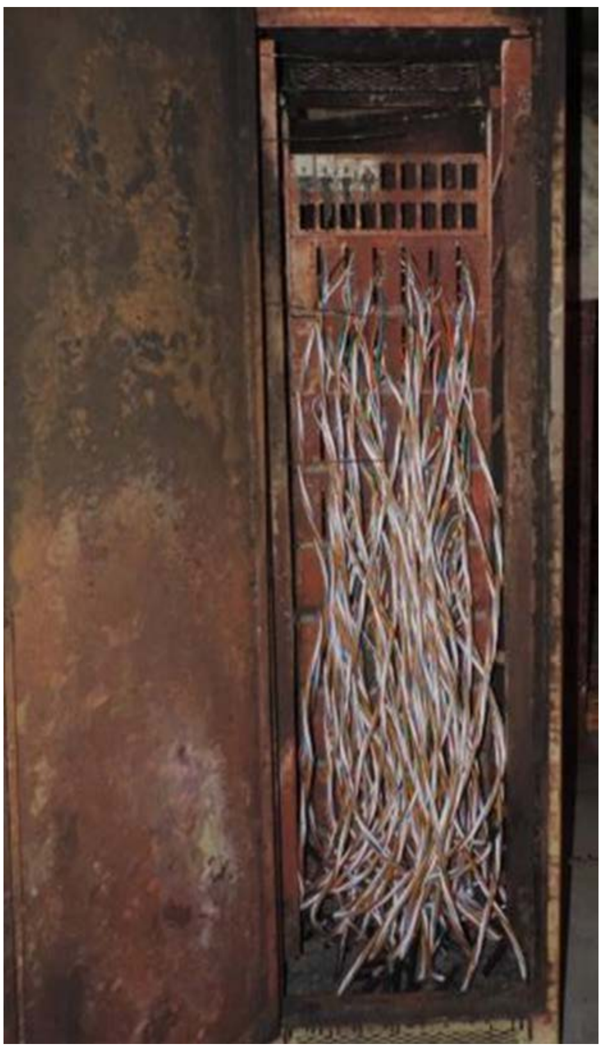
Test: 104 **Enclosure:** 1 **Fuel Load:** 420 insulated conductors extracted from Cable #807, tightly bound in groups of 7, various lengths, 540 m (1768 ft) total **Ignition Source:** 0.8 kW propane burner **Preheating Source:** 1 L acetone pan fire **Ventilation:** Door open **Notes:** The acetone pan 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 5-106. Summary of Test 105

Test: 105

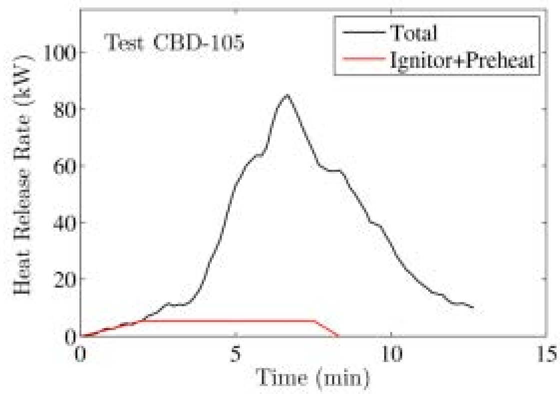
Enclosure: 1

Fuel Load: A variety of cable remnants

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.



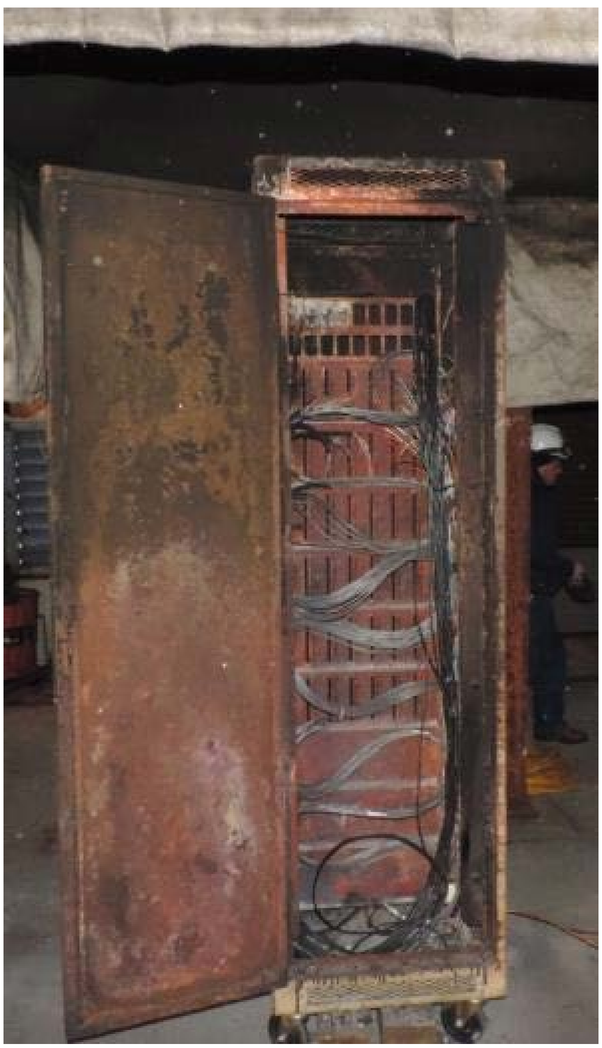
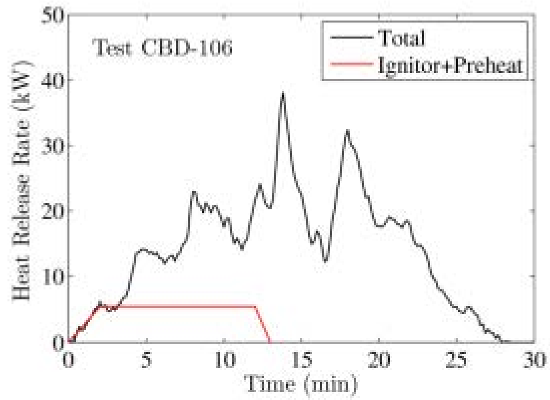


Table 5-107. Summary of Test 106

Test: 106 **Enclosure:** 1 **Fuel Load:** Unburned portion of Test 105 along left side of enclosure **Ignition Source:** 5.5 kW propane burner **Ventilation:** Door closed **Notes:** The door was opened at 9 min and left open. 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.	
	

 Draft Report for Comment

Table 5-108. Summary of Test 107

<table>
<tr>
<td>

Test: 107

Enclosure: 1

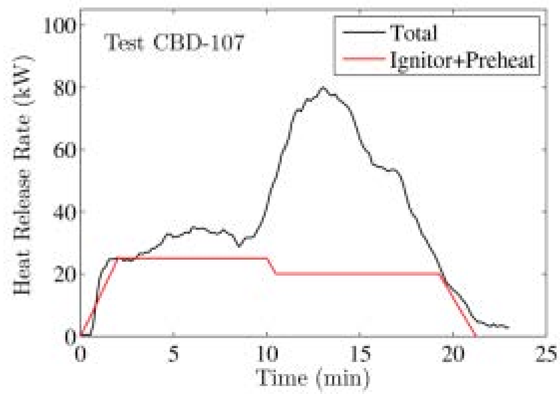
Fuel Load: 280 insulated conductors (#834), arranged in 4 bundles, 1.8 m (6 ft) long, hanging in front of steel partition

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.

</td>
<td>



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

</td>
<td>

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

 Draft Report for Comment

Table 5-109. Summary of Test 108

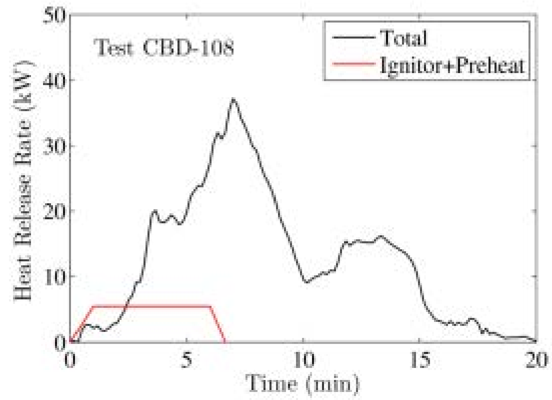
Test: 108 **Enclosure:** 1 **Fuel Load:** Unburned wire from Test 107 **Ignition Source:** 5.5 kW propane burner **Ventilation:** Door closed **Notes:** The propane burner was turned off at 6 min. The door was opened at 11 min. All of the remaining cable insulation from Test 107 was consumed.	
	

Table 5-110. Summary of Test 109

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

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. The fire consumed the cable within the enclosure, and scorched approximately 15 cm (6 in) of cable outside.

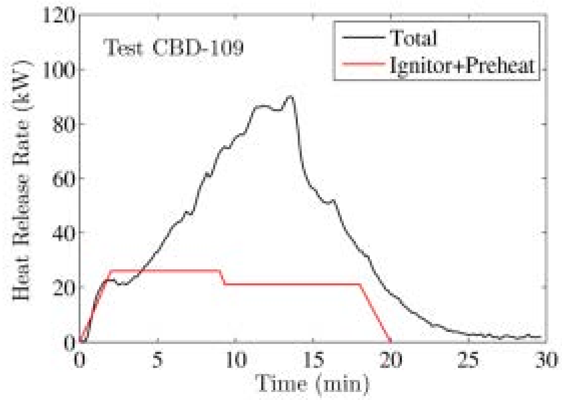
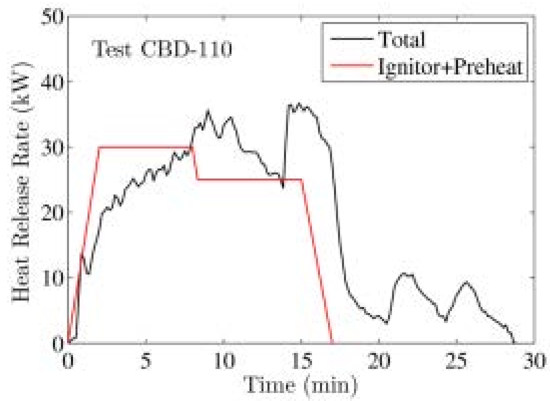


Table 5-111. Summary of Test 110

Test: 110 **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 **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. 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.	
	

154

Table 5-112. Summary of Test 111

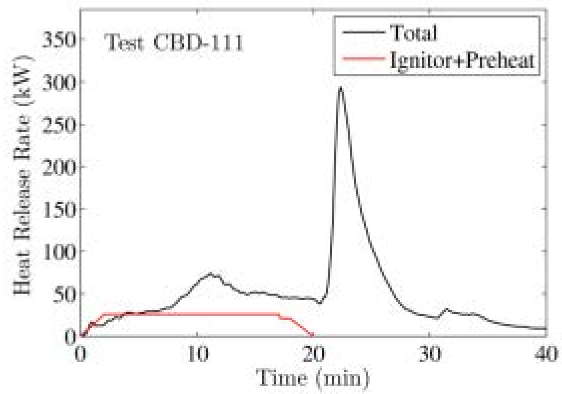
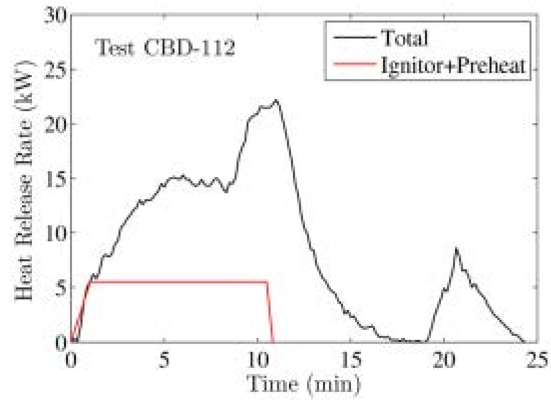
<table>
<tr>
<td>Test: 111
Enclosure: 5
Fuel Load: 2 bundles of 20 cables each (#845), one on each side of enclosure, 2.4 m (8 ft) long
Ignition Source: 5.5 kW propane burner
Preheating Source: 1 L acetone pan fire
Ventilation: Door closed for 20 min, then open
Notes: The acetone pan was placed on a 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 fire spread rapidly on both sides following the door opening. All of the cable insulation was consumed.</td>
<td>
</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</table>

Table 5-113. 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.	
	

5.2 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.

5.2.1 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 heat release rates 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.

5.2.2 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, even though many of these experiments were deliberately set up to test whether this was possible.

5.2.3 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 were not operated during the experiments because the smoke from the fire would have been blown outside of the exhaust product collection hood. 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.

5.2.4 Peak Heat Release 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 0.3 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.

5.2.5 Growth Time

The mean time to peak was 16 min; the median was 13 min. All but 4 of the 112 fires reached their peak in 40 min or less. The longest time to peak was nearly 80 min, where a closed cabinet with a relatively large load of qualified cable was ignited with a small burner and smoldered for

 Draft Report for Comment

over an hour, like an underground coal or tire fire. Most of the other cases with relatively long times to peak had negligibly small heat release rates. Others were cases where the door was opened at some arbitrary time, leading to a larger fire. Most of the fires with significant heat release rates reached the peak in 10 to 15 minutes. This is consistent with current guidance in NUREG/CR-6850.

Draft Report for Comment

6 CONCLUSION AND FUTURE WORK

During the HELEN-Fire (Heat Release Rate in Electrical Enclosures) 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 is to be used to provide the energy source term for fire models used to assess the potential consequences of fires within nuclear power plants.

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 develop statistical distributions of heat release rates 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 heat release rate 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 heat release rate 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 HELEN-Fire heat release rates to simplified models and to validate CFD models used to assess enclosure geometries not tested in HELEN-Fire.

Draft Report for Comment

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.

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.

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, 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

 Draft Report for Comment

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.

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

 Draft Report for Comment

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.

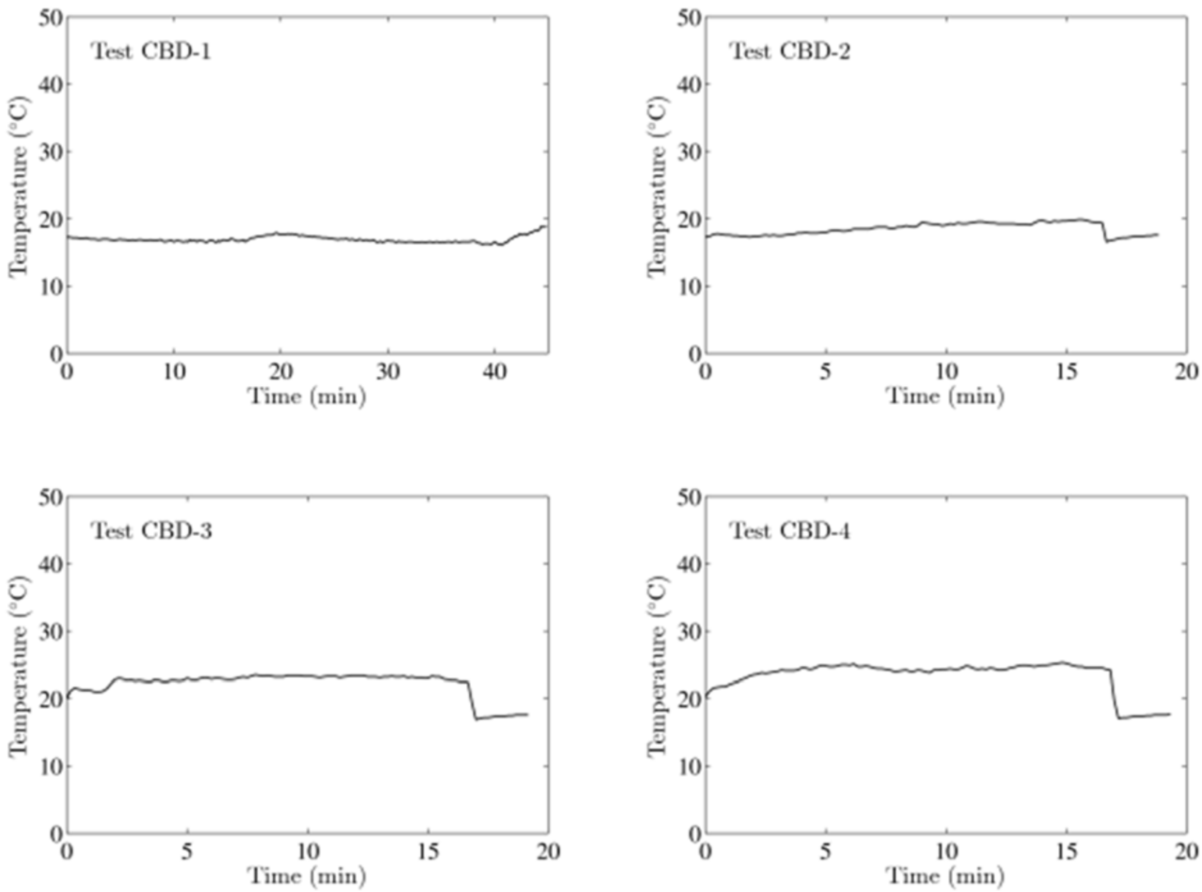
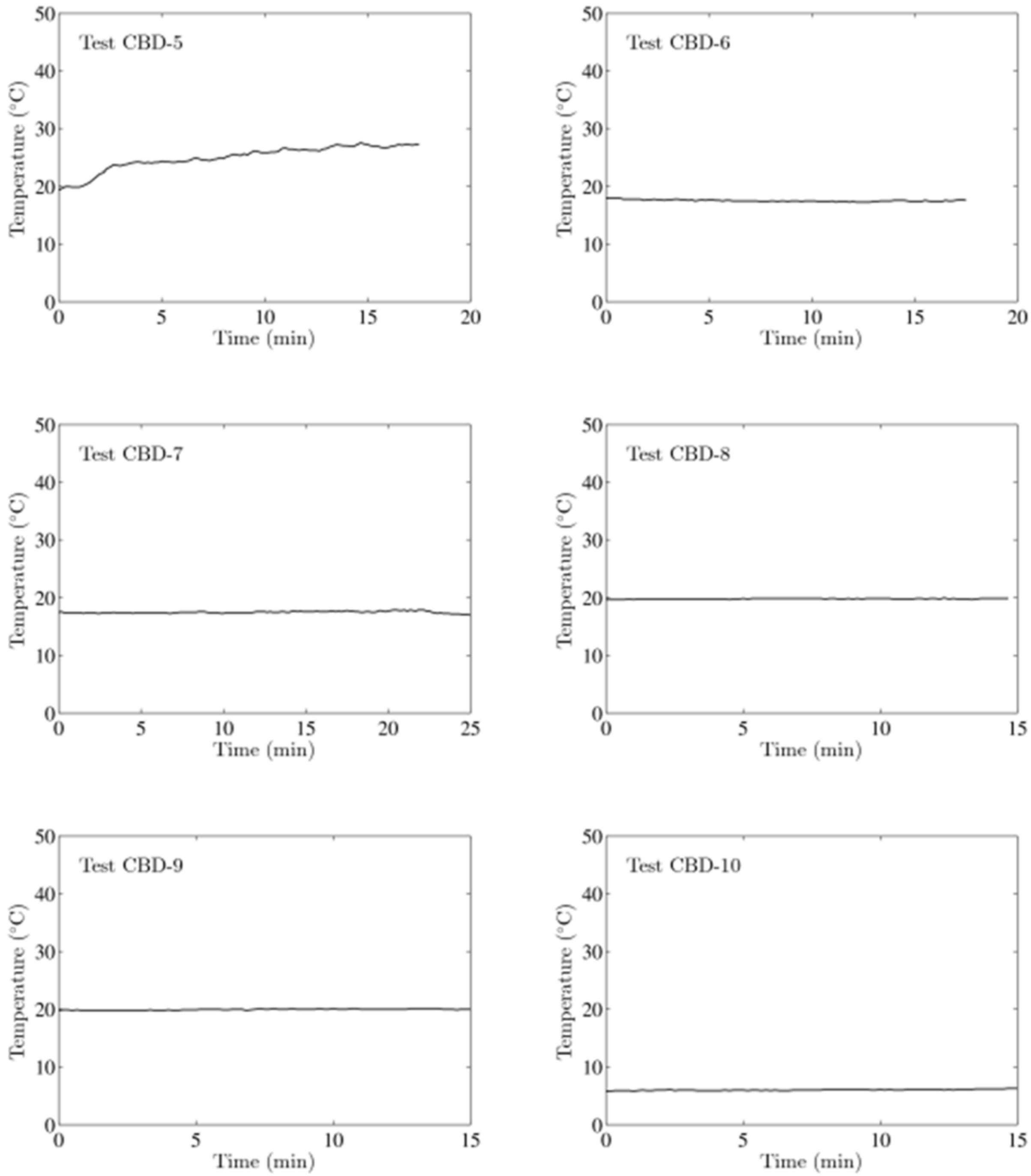


Figure A-1. Enclosure temperatures, Tests 1-4.



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

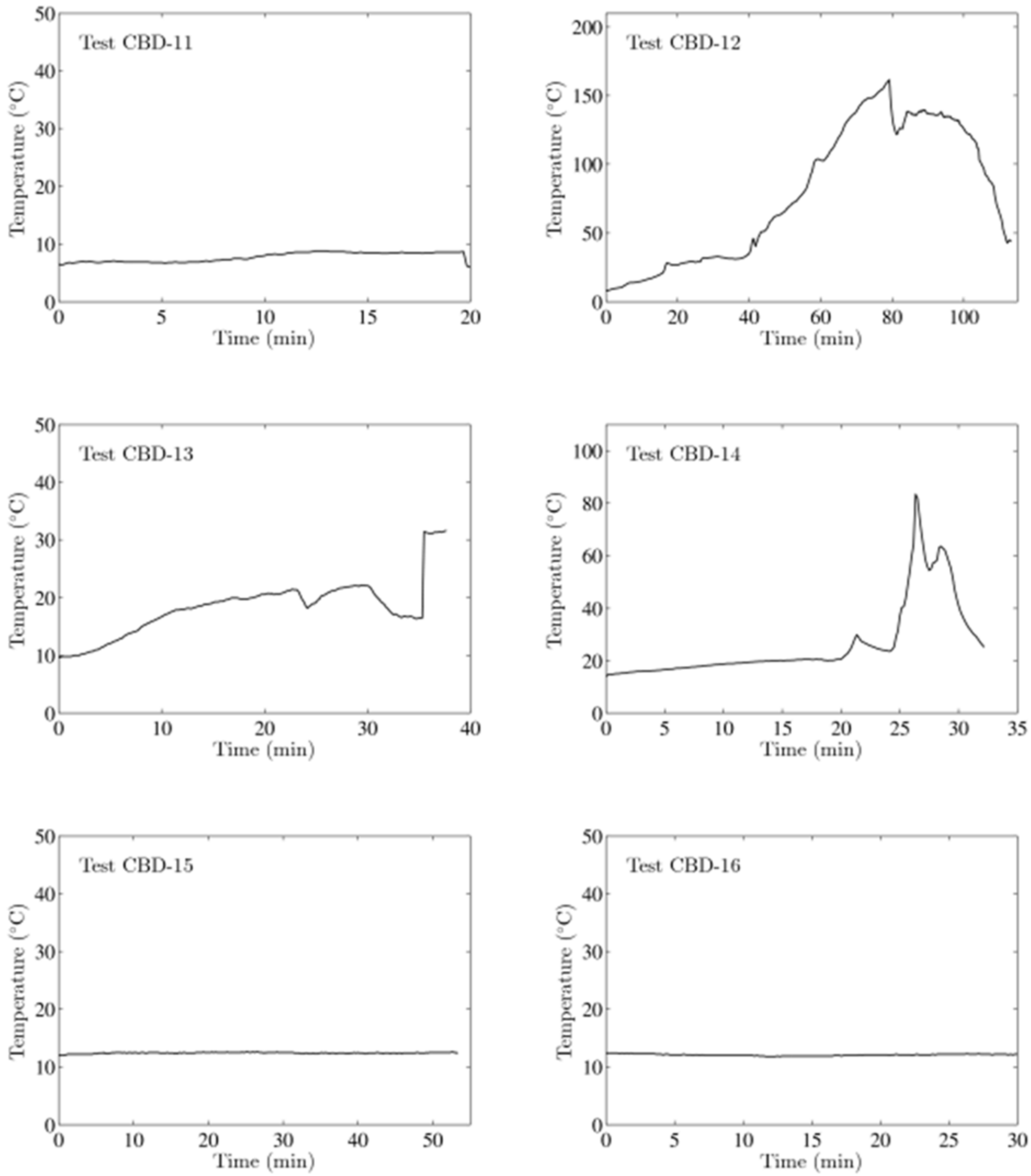


Figure A-3. Enclosure temperatures, Tests 11-16.

 Draft Report for Comment

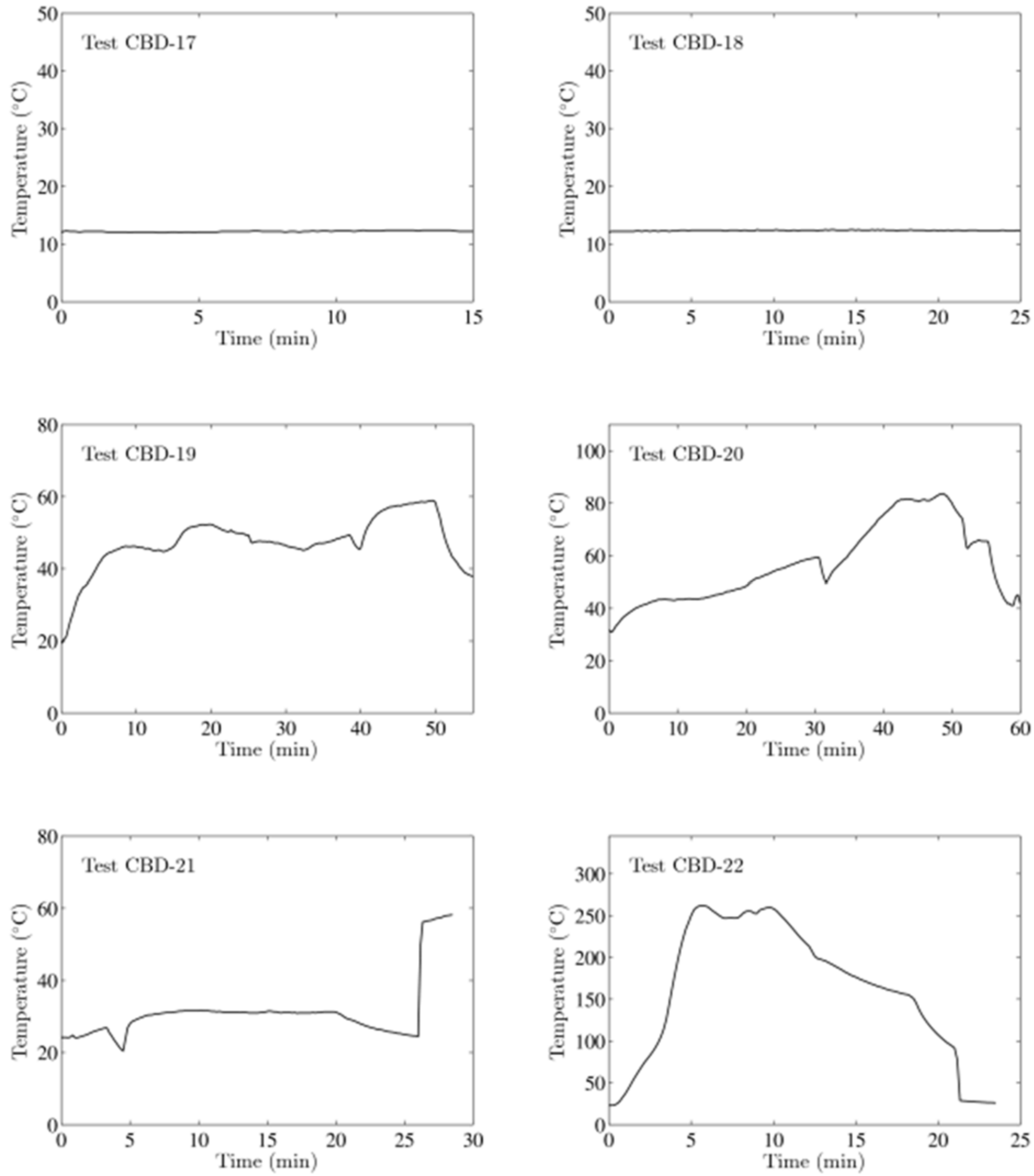


Figure A-4. Enclosure temperatures, Tests 17-22.

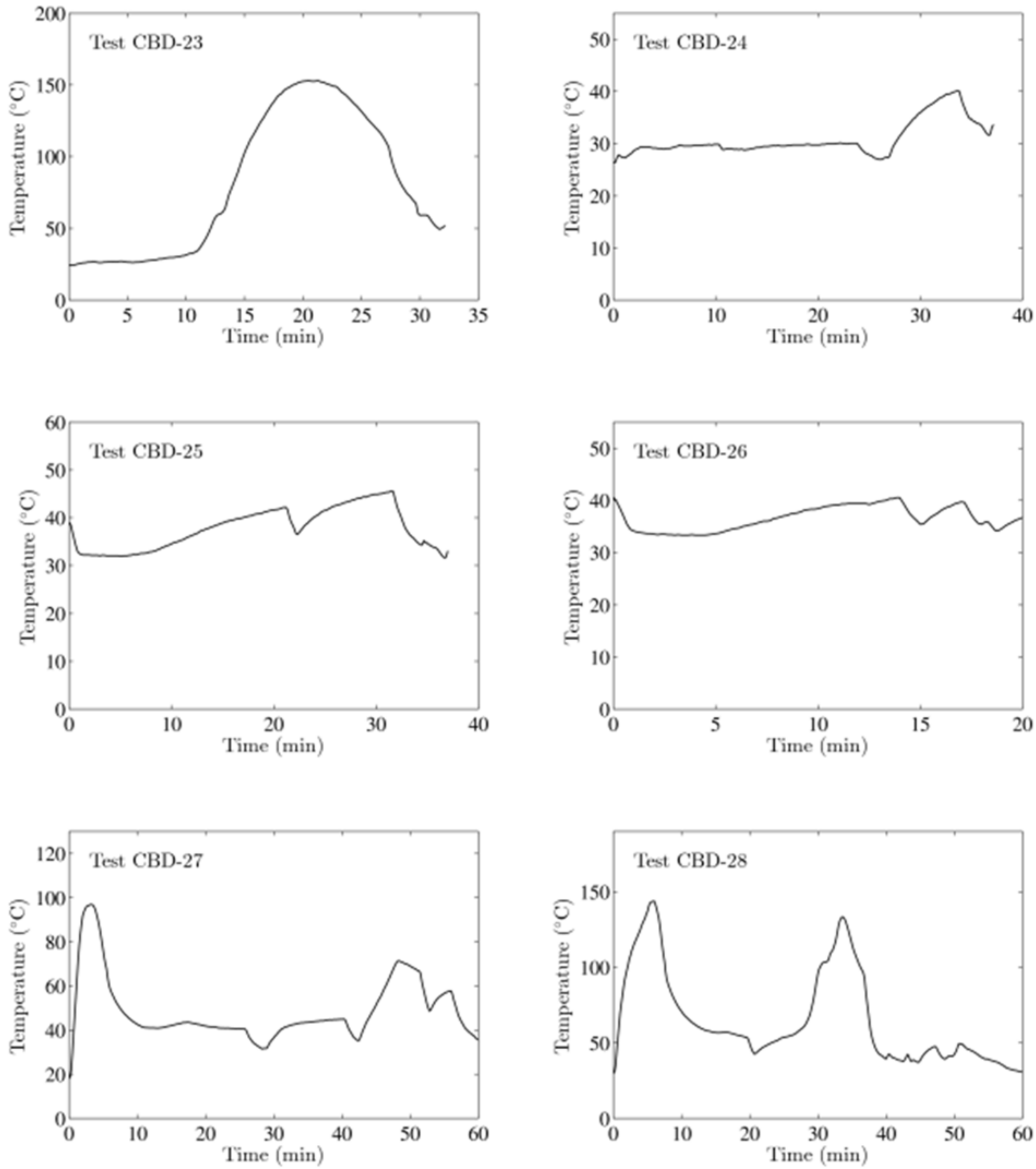


Figure A-5. Enclosure temperatures, Tests 23-28.

 Draft Report for Comment

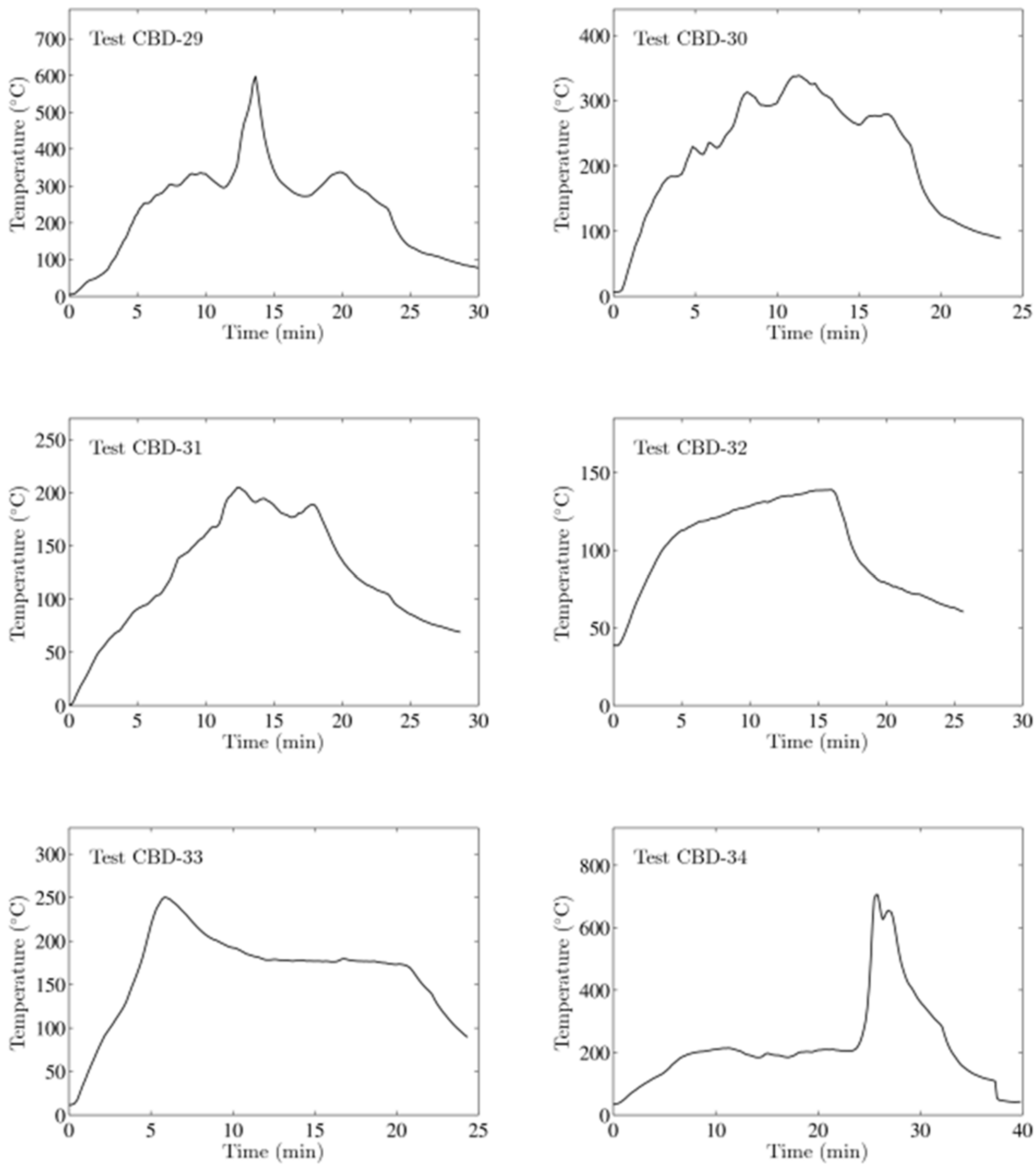


Figure A-6. Enclosure temperatures, Tests 29-34.

 Draft Report for Comment

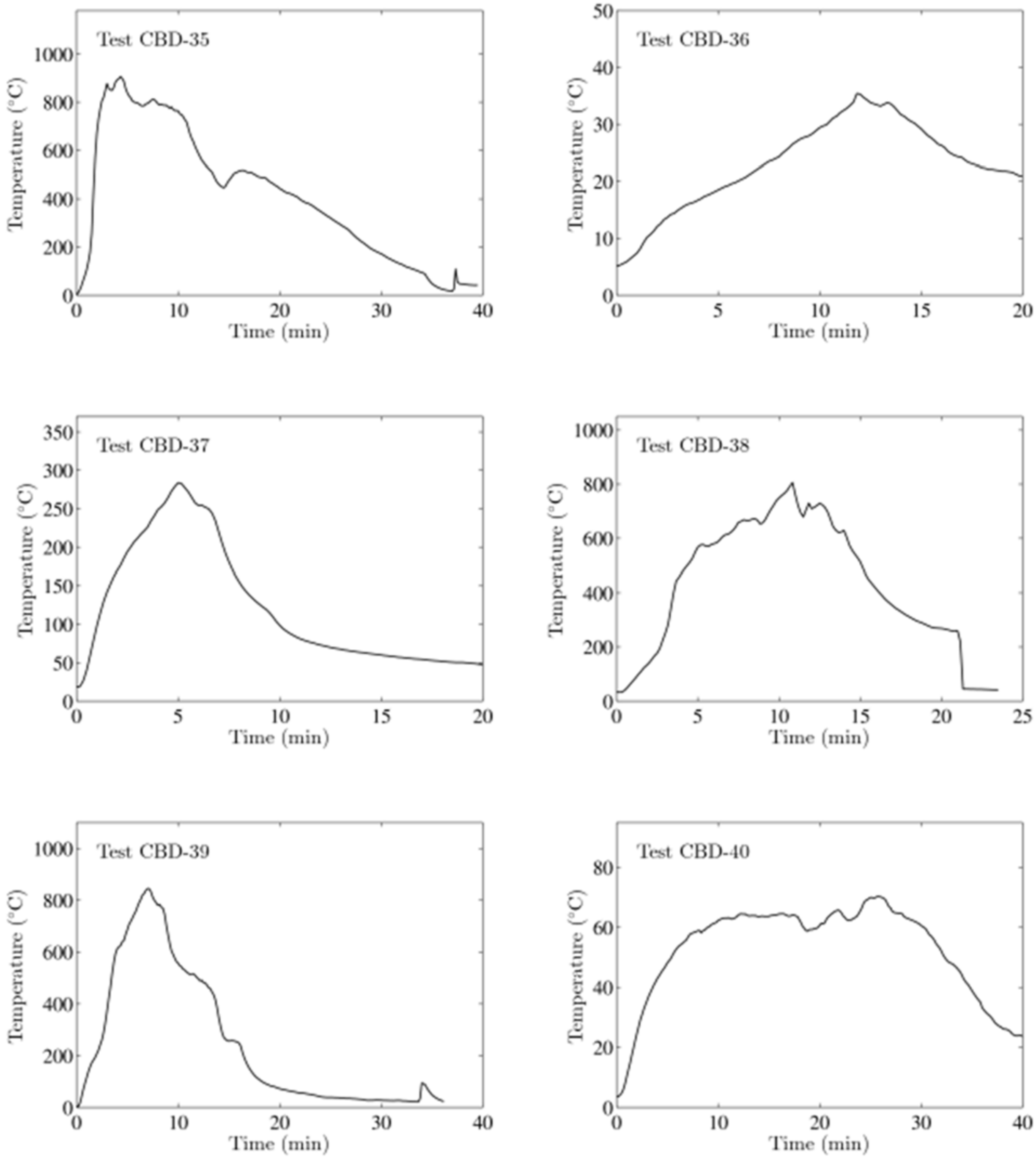
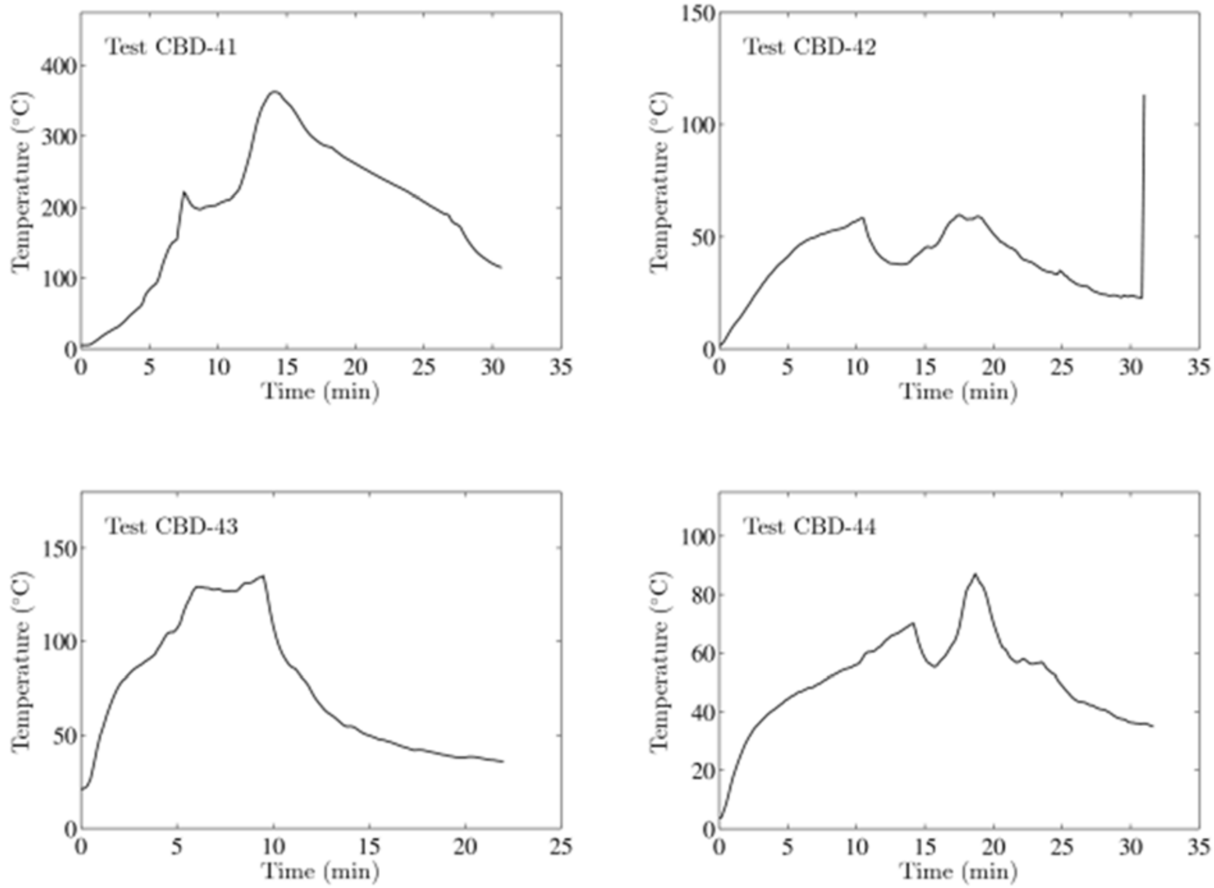
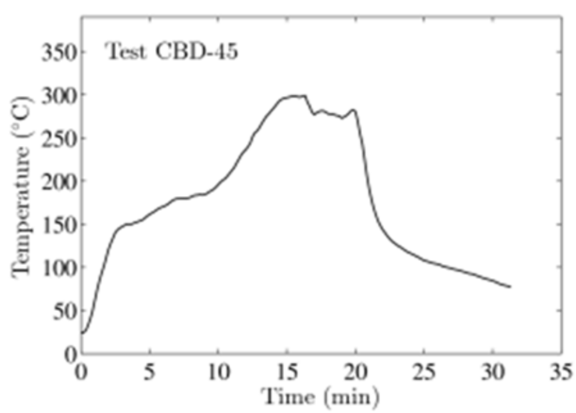


Figure A-7. Enclosure temperatures, Tests 35-40.

Draft Report for Comment





Enclosure temperatures were not measured for Test CBD-46.

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

Draft Report for Comment

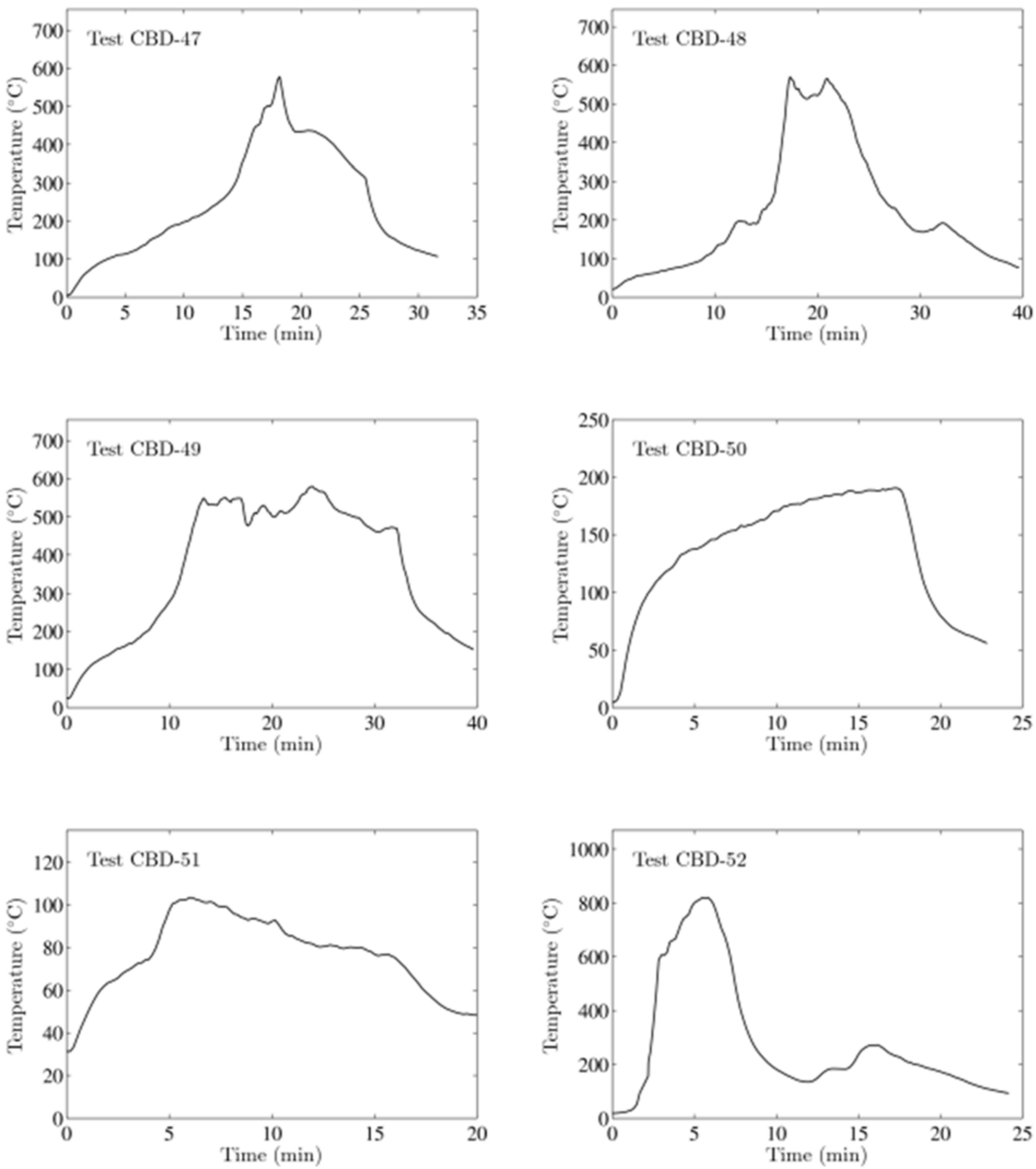


Figure A-9. Enclosure temperatures, Tests 47-52.

 Draft Report for Comment

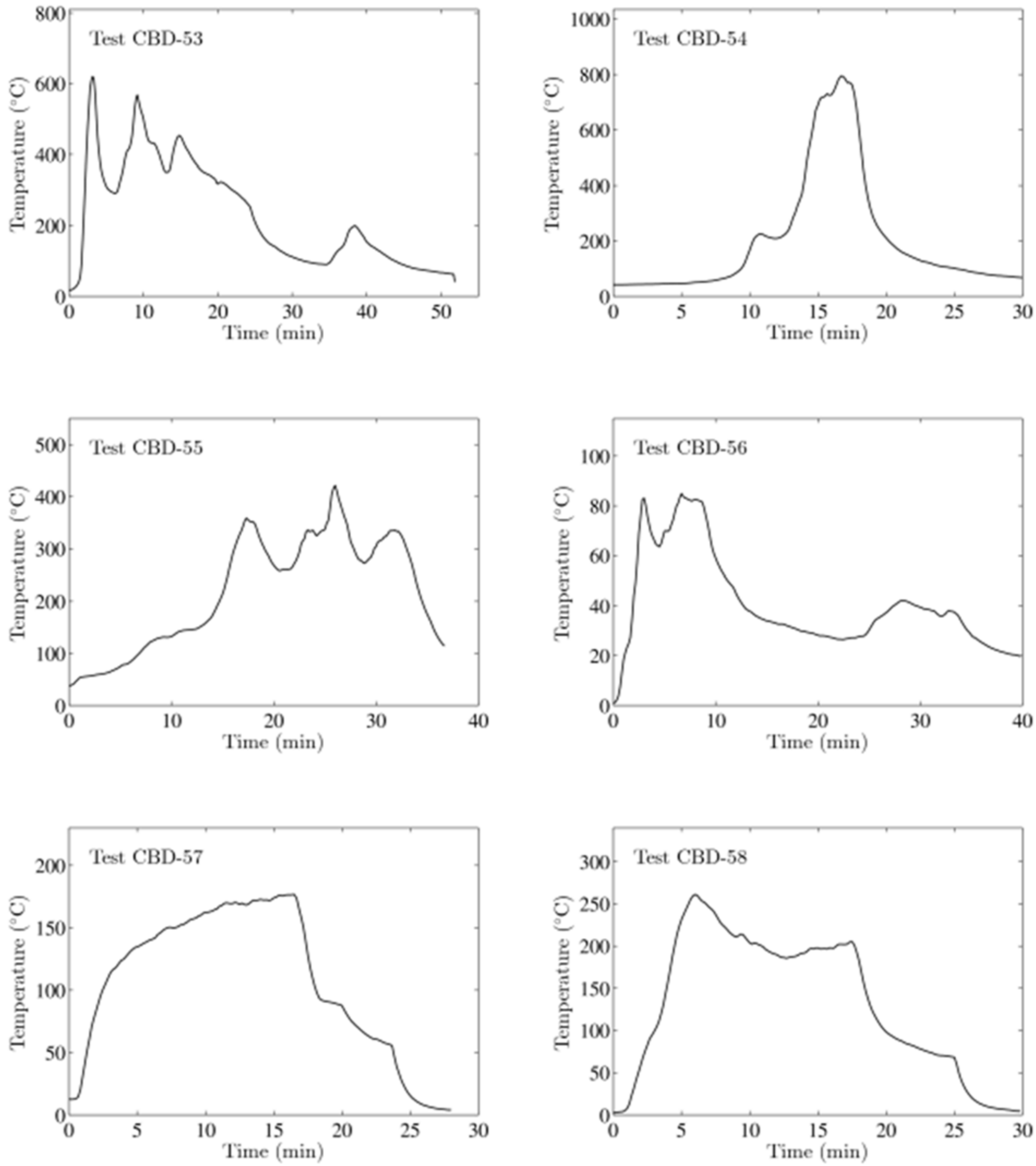


Figure A-10. Enclosure temperatures, Tests 53-58.

 Draft Report for Comment

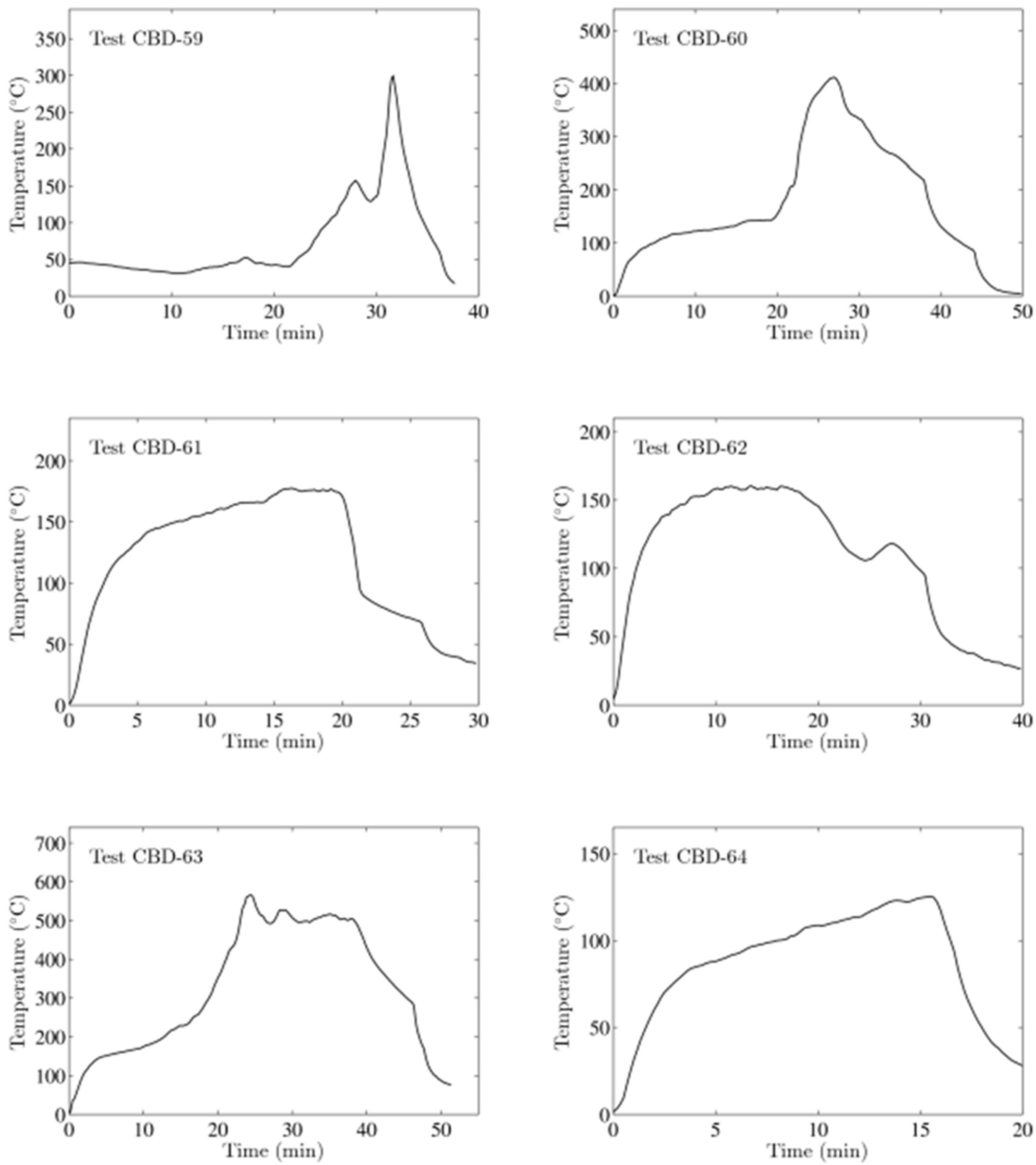


Figure A-11. Enclosure temperatures, Tests 59-64.

Draft Report for Comment

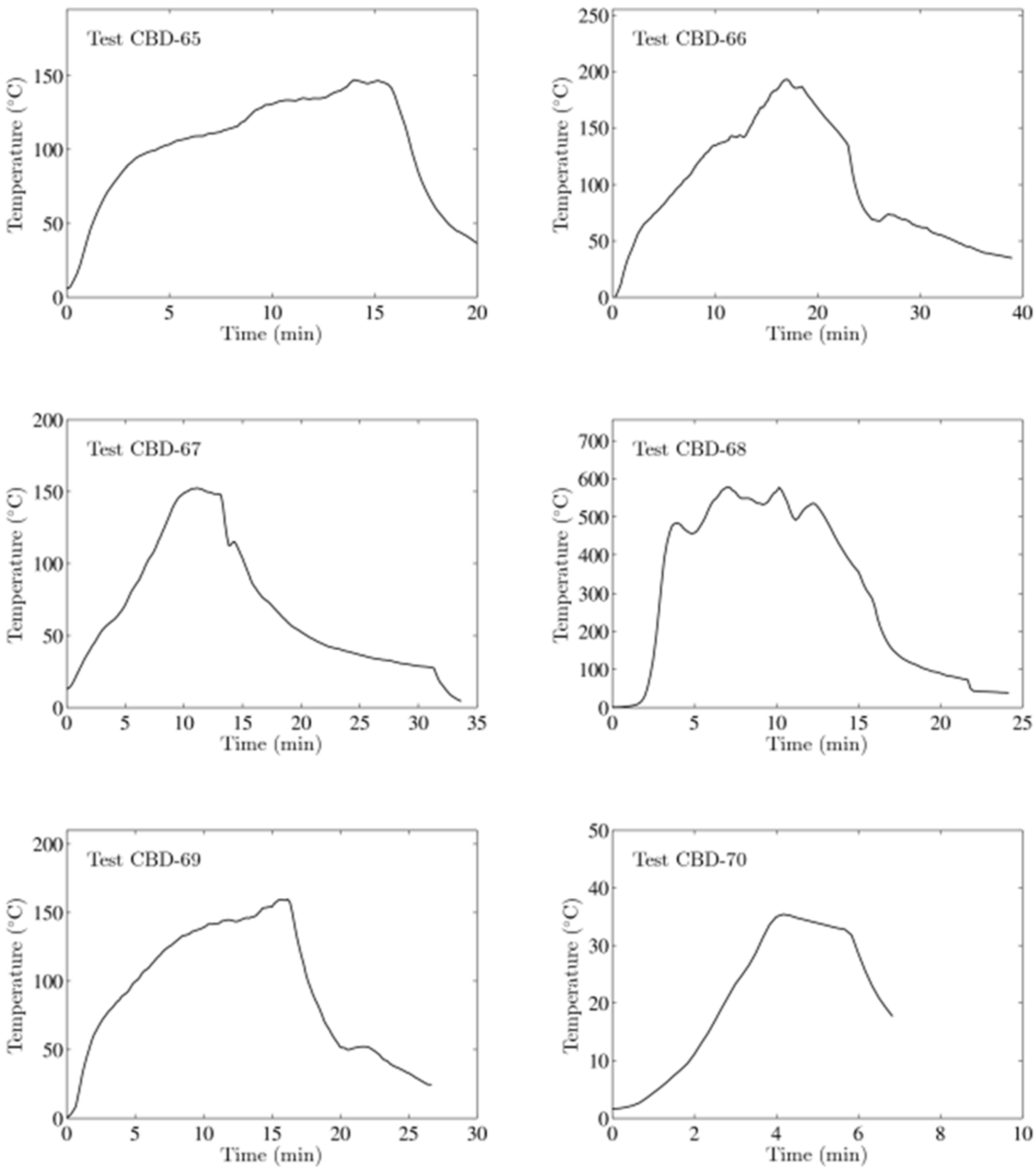


Figure A-12. Enclosure temperatures, Tests 65-70.

Draft Report for Comment

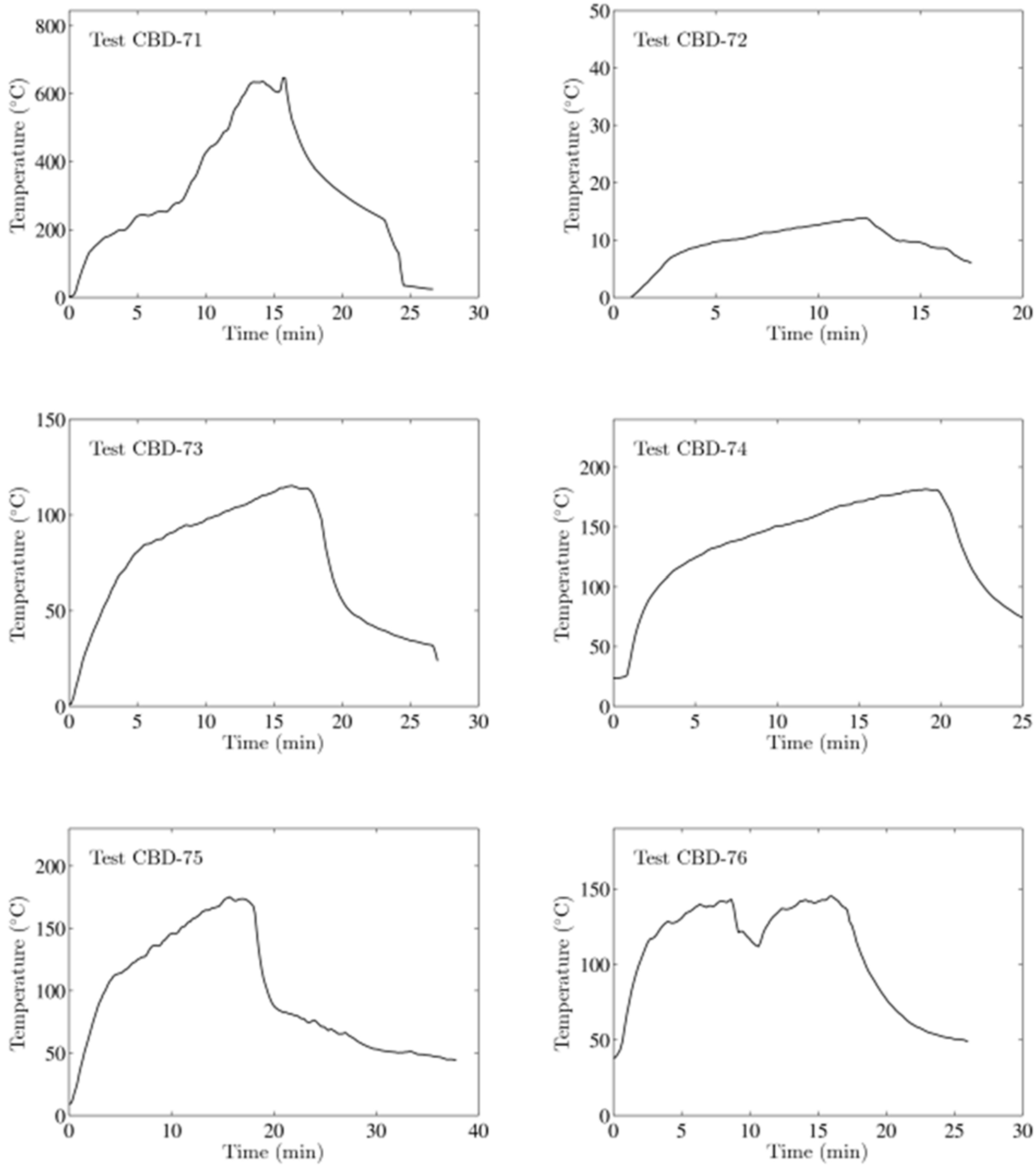


Figure A-13. Enclosure temperatures, Tests 71-76.

 Draft Report for Comment

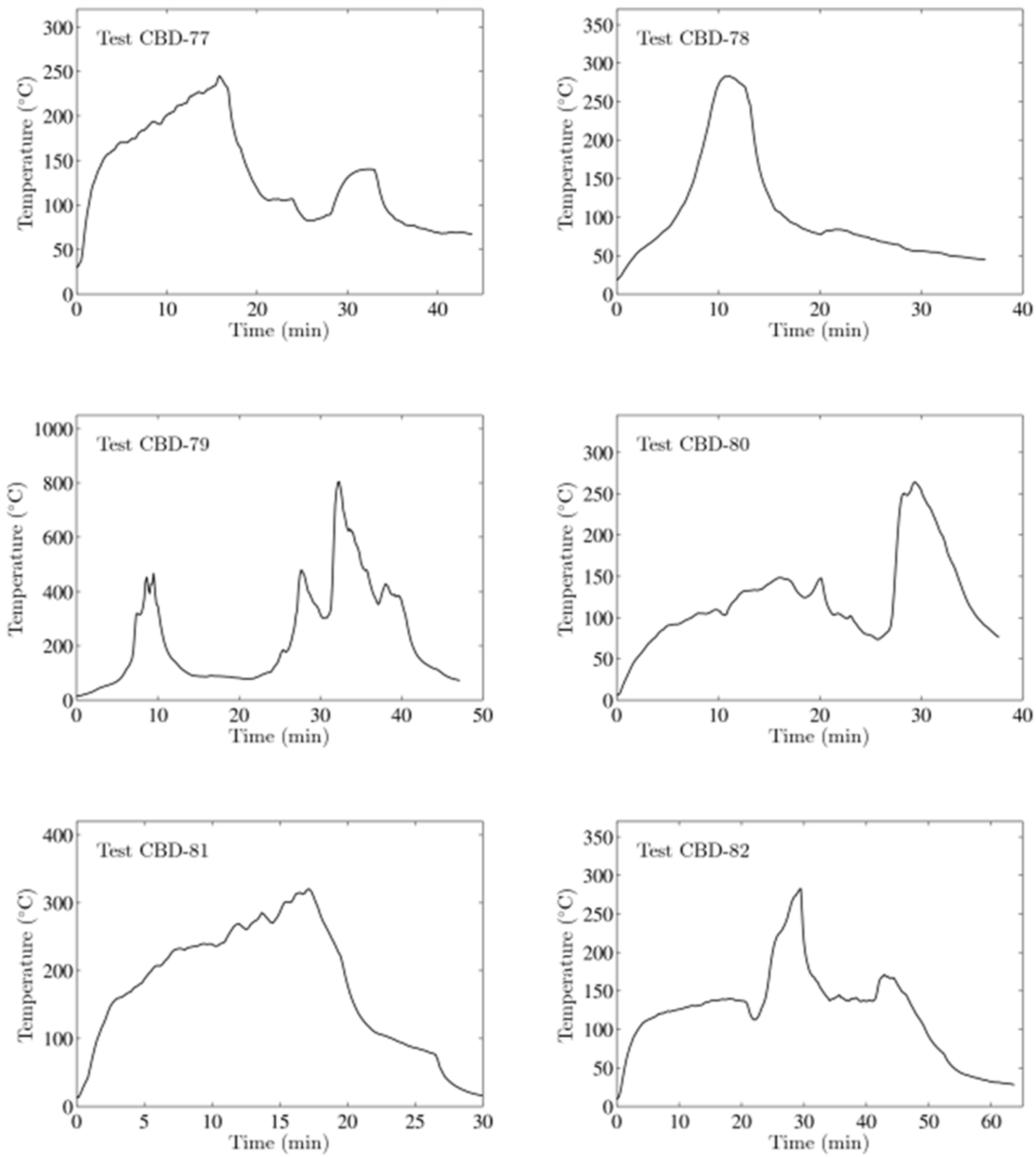


Figure A-14. Enclosure temperatures, Tests 77-82.

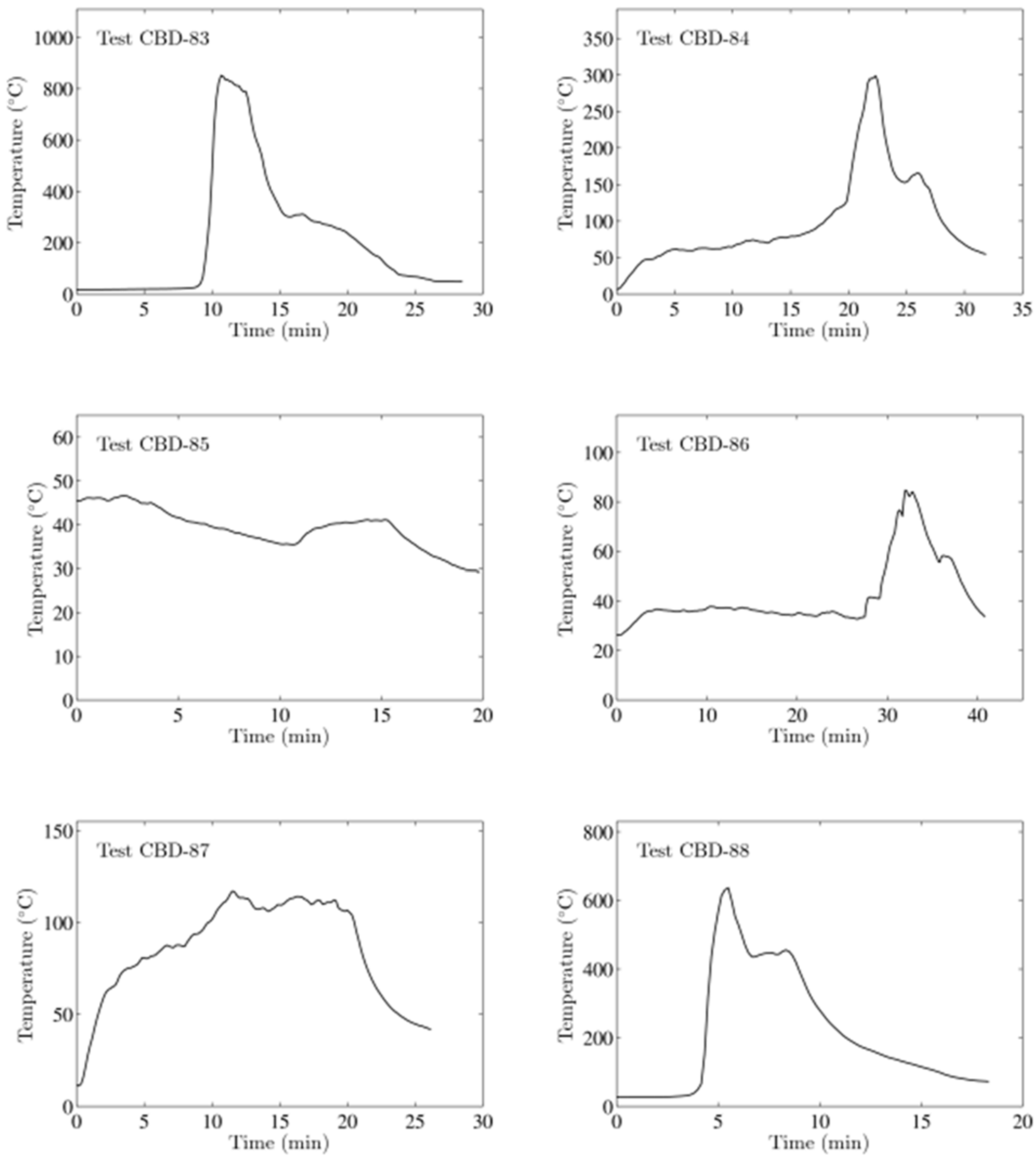


Figure A-15. Enclosure temperatures, Tests 83-88.

Draft Report for Comment

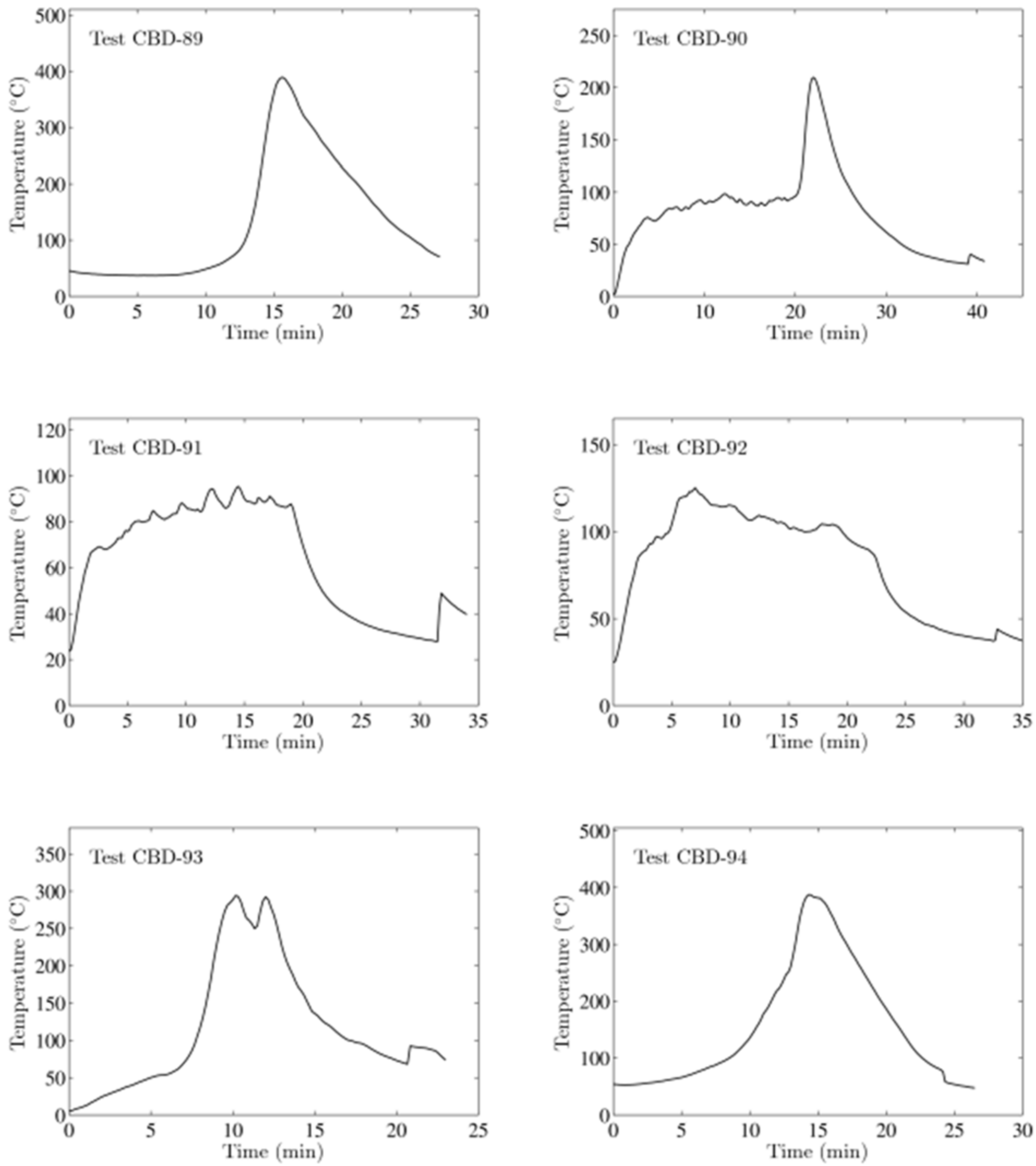


Figure A-16. Enclosure temperatures, Tests 89-94.

Draft Report for Comment

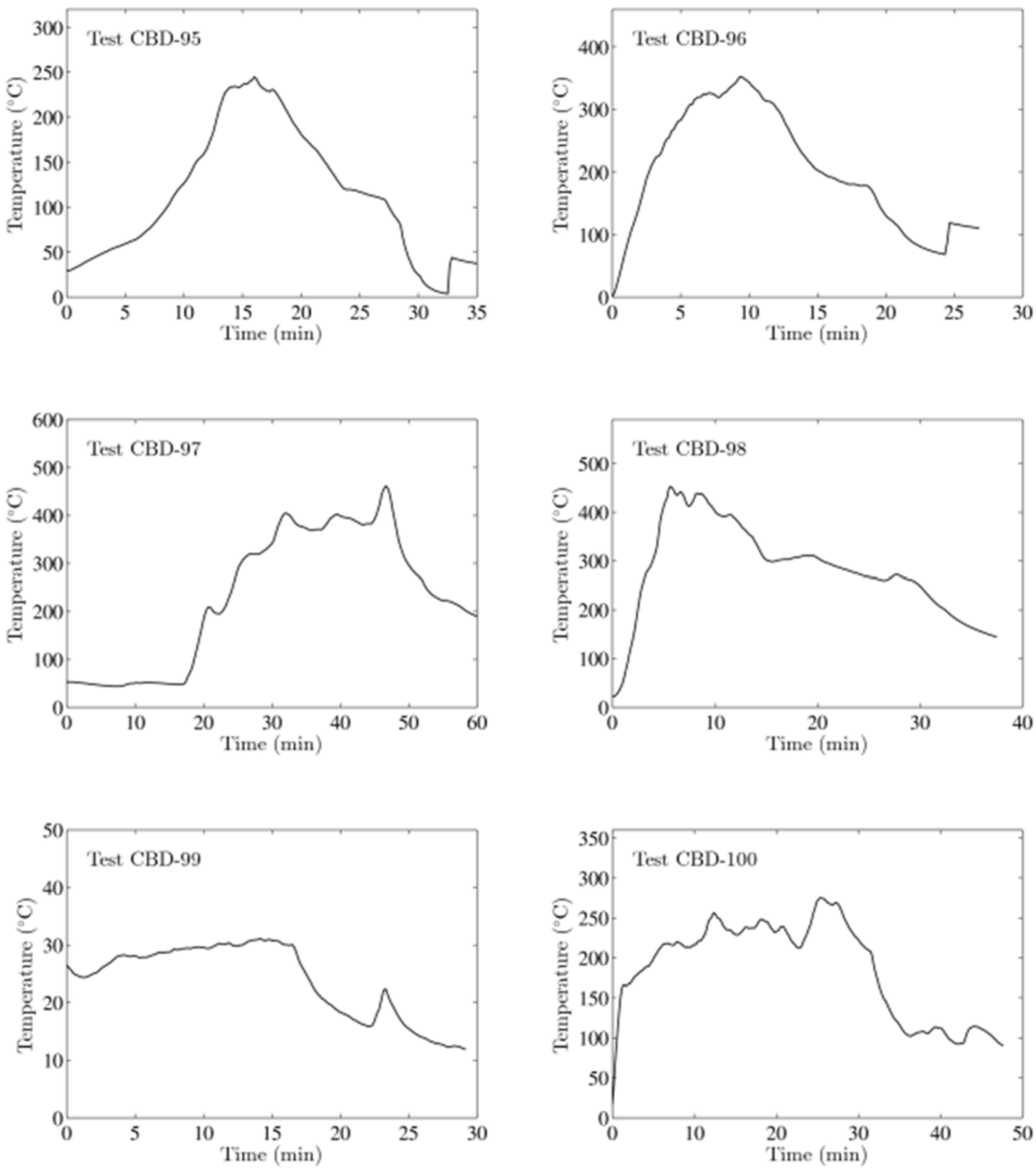


Figure A-17. Enclosure temperatures, Tests 95-100.

Draft Report for Comment

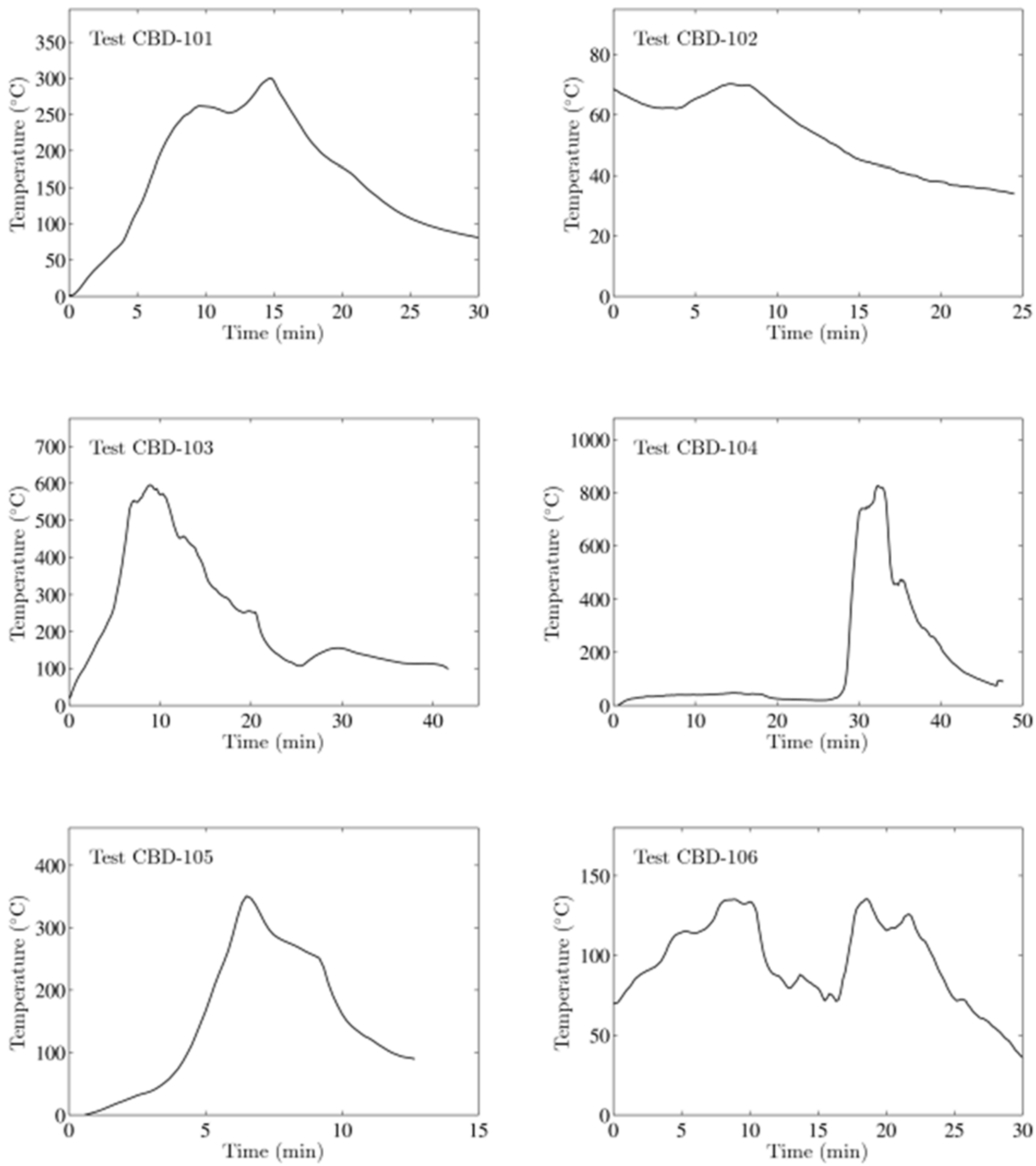


Figure A-18. Enclosure temperatures, Tests 101-106.

 Draft Report for Comment

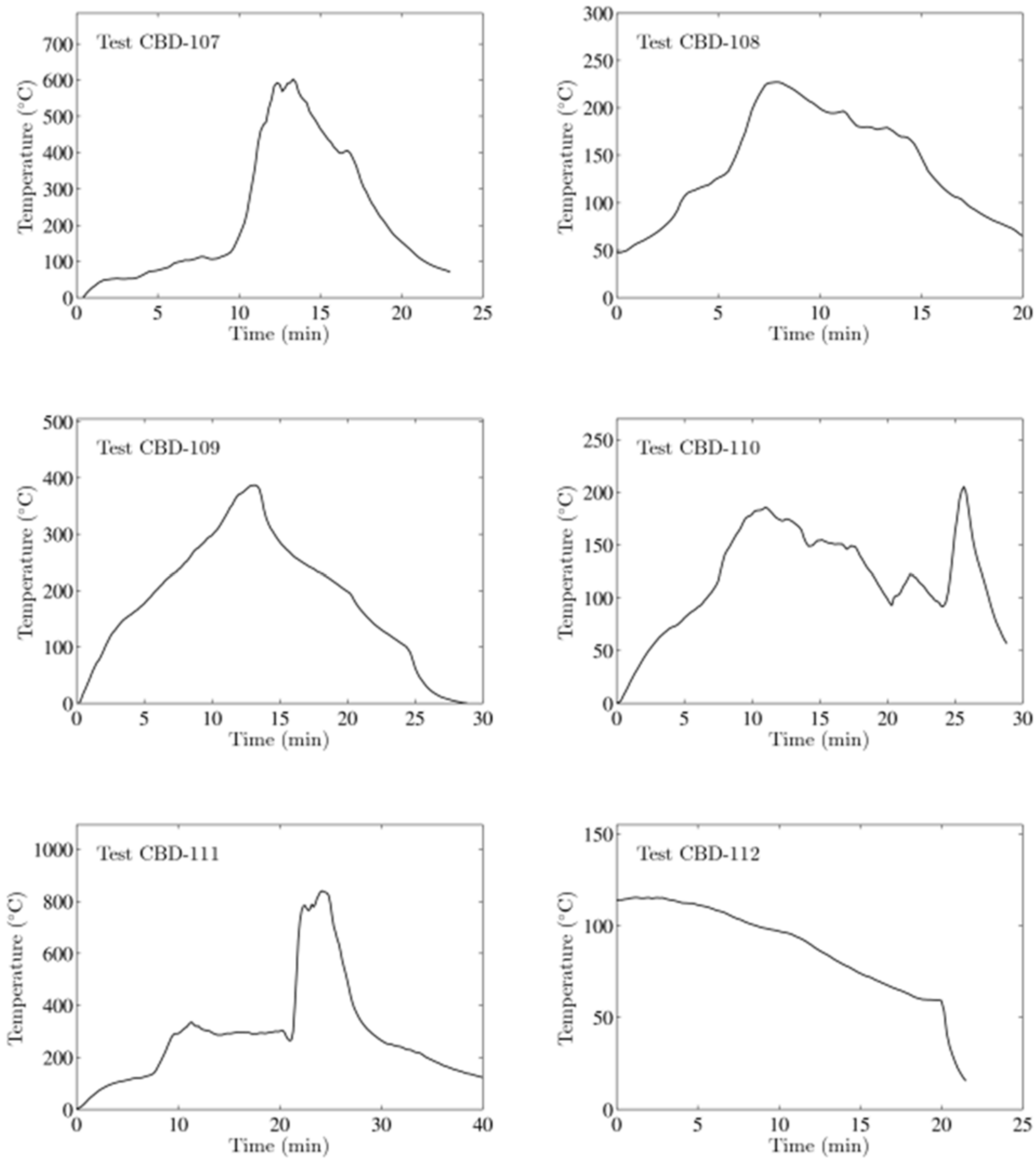


Figure A-19. Enclosure temperatures, Tests 107-112.

Draft Report for Comment

Draft Report for Comment