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Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE) Phase 2: Vertical Shafts and Corridors

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Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE) Phase 2: Vertical Shafts and Corridors

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ABSTRACT

This report documents the second phase of a multi-year program called CHRISTIFIRE (Cable Heat Release, Ignition, and Spread in Tray Installations during Fire). The overall goal of the program is to quantify the burning characteristics of grouped electrical cables. This second phase of the program involved bench-scale and large-scale experiments. Bench-scale experiments were performed using a cone calorimeter in which 10 cm (4 in) by 10 cm (4 in) cable segments were exposed to a relatively high heat flux to determine their burning rate, heat of combustion, and other properties. The large scale experiments consisted of loaded cable trays situated in vertical and horizontal configurations. For the vertical experiments, two cable trays were positioned either in the open air, or in a vertical shaft that was open at the top and bottom. For the horizontal experiments, from one to four loaded cable trays were positioned horizontally with a 30 cm (1 ft) separation from the ceiling and tray to tray. The purpose of both sets of full-scale experiments was to determine the heat release and spread rates of burning cables in a variety of realistic configurations.

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EXECUTIVE SUMMARY

Fires in grouped electrical cable trays pose a distinct fire hazard in nuclear power plants (NPPs). In the past, cable tray installations have fueled fires that resulted in serious damage to NPPs. The 1975 fire at the Browns Ferry Nuclear Power Plant demonstrated the vulnerability of electrical cables when exposed to elevated temperatures as a result of a fire. The behavior of cables in a fire depends on a number of factors, including their constituent material and construction, as well as their location and installation geometry.

While there has been a considerable amount of work done over the past 40 years to measure cable properties and model their fire behavior, it is still a considerable challenge to predict the actual heat release rate (HRR) of an array of cable trays. Guidance documents like NUREG/CR-6850, NUREG-1805, and the *SFPE Handbook of Fire Protection Engineering* contain lengthy tables of material properties, burning rates, flame spread equations, and other information gleaned from past experimental and modeling efforts. Still, there is no consensus on how to calculate the heat release rate of a stack of cable trays using either a simple or a detailed fire model.

The CAROLFIRE (Cable Response to Live Fire, NUREG/CR-6931) project provided information on the electrical failure mechanisms of cables in fire, including a relatively simple model to predict a cable's thermally-induced electrical failure (THIEF). However, the measurements and modeling of CAROLFIRE did not provide information about the HRR and flame spread rates of burning cables.

This report describes Phase 2 of the CHRISTIFIRE (Cable Heat Release, Ignition, and Spread in Tray Installations during Fire) research program conducted by the National Institute of Standards and Technology (NIST). The overall goal of this multi-year program is to quantify the burning characteristics of grouped electrical cables installed in cable trays. The first phase of the program focused on horizontal open tray configurations that were relatively clear of walls and ceilings (McGrattan et al. 2012). This second phase of the program focuses on horizontal open cable trays located near the ceiling of a corridor, and vertical open cable trays located in the open air and enclosed in a relatively narrow shaft.

The CHRISTIFIRE program addresses the burning behavior of cables in a fire beyond the point of electrical failure. The data obtained from this project can be used for the development of fire models to calculate the HRR and flame spread of a cable fire. The experiments performed during Phase 1 of CHRISTIFIRE provided measurements of the HRR and spread rate of cables burning within typical ladder-back, open cable trays. The results provide the most extensive set of cable thermal response and failure data to date and are valuable as validation data for fire models.

The CHRISTIFIRE Phase 2 experiments and modeling efforts are summarized as follows:

Bench-Scale Calorimetry: Following the procedure set forth in ASTM D 6113, Standard Test Method for Using a Cone Calorimeter to Determine Fire-Test-Response Characteristics of Insulating Materials Contained in Electrical or Optical Fiber Cables, the standard cone calorimeter apparatus was used to measure the burning rate of electrical cables. Twenty-three cables were measured. In the experiments, 10 cm (4 in) by 10 cm (4 in) cable arrays were exposed to heat fluxes of 50 kW/m^2 and 75 kW/m^2. Three replicate experiments for each cable were performed at both heat fluxes resulting in 136 total experiments[1]. The heat release rate per unit area (HRRPUA) was measured. It was found that the time-averaged HRRPUA for thermoset cables falls in the range of 100 kW/m^2 and 200 kW/m^2, while thermoplastic cables typically fall in the range of 200 kW/m^2 to 300 kW/m^2.

Full-Scale Calorimetry: Two series of experiments were conducted; the first referred to as the Vertical Tray Experiments and the second as the Corridor Experiments. Both series utilized 3.6 m (12 ft) long and 0.45 m (18 in) wide ladder type cable trays. Cable loadings and tray separations were based on IEEE Standard 384-2008.

There were 17 vertical tray experiments performed. They were divided into two configurations. Both configurations consisted of two vertical cable trays spaced either 0.15 m (6 in) or 0.3 m (1 ft) apart. The lower cable tray was attached to a 3.6 m (12 ft) tall by 1.2 m (4 ft) wide sheet of cement board. Configuration 1 consisted of experiments conducted in the open air. Configuration 2 consisted of experiments conducted in a 1.2 m (4 ft) wide by 0.6 m (2 ft) deep by 3.6 m (12 ft) vertical shaft. The shaft was open at both ends. The purpose of these tests was to determine if the fire would spread vertically with the cable trays filled with various amounts of cable.

There were 10 corridor experiments conducted in a 2.4 m (8 ft) wide by 2.4 m (8 ft) tall by 7.3 m (24 ft) long fabricated corridor. The inner walls of the apparatus were lined with cement board. From one to four loaded cable trays were positioned horizontally with 0.3 m (1 ft) spacing from each other. The uppermost trays were positioned approximately 0.3 m (1 ft) from the ceiling. The left tier of trays was located approximately 0.15 m (6 in) from the left inner wall. For all but one test, a 0.3 m (1 ft) soffit was attached to each end of the corridor to simulate the wall space above a doorway. This attachment created a region where the smoke and heat from the fire was trapped thus creating a “hot gas layer”. The purpose of the corridor experiments was to determine the effect of the enclosure on the spread rate of the fire. Both ends of the corridor were open; thus, the fire scenarios should be considered well-ventilated. No experiments were conducted in an under-ventilated compartment.

Both the Vertical Tray and Corridor tests provided experimental data for model evaluation. Videos of the experiments are included on the DVD that accompanies this report.

Modeling: Following the current guidance set forth in NUREG/CR-6850, Appendix R, a simple model of upward fire spread in horizontal tray configurations was developed during Phase 1 of the CHRISTIFIRE program. The model, referred to as FLASH-CAT (Flame Spread over Horizontal Cable Trays), makes use of semi-empirical estimates of lateral and vertical flame spread, and measured values of combustible mass, heat of combustion, heat release rate per unit area, and char yield. Because the measured values of these parameters were found to be scale and configuration-dependent, the model makes use of effective values that are selected only on the basis of whether the cable is judged to be of the thermoset or thermoplastic type. The only

[1] For one of the cable samples, only two replicates could be performed, which is why the total number of experiments is 136 rather than 138.

other necessary information specific to an individual cable is its mass per unit length, combustible mass fraction, and whether it is considered a thermoset or thermoplastic cable. The model was compared to the Vertical Tray and Corridor Experiments, and it was observed that the FLASH-CAT predicted HRR was similar to or greater than the measured values.

Finally, a DVD is included in this report that contains videos of the vertical tray and corridor tests.

ACKNOWLEDGMENTS

The work described in this report was supported by the Office of Nuclear Regulatory Research (RES) of the US Nuclear Regulatory Commission (USNRC). The CHRISTIFIRE program was directed by David Stroup. Mark Henry Salley contributed valuable advice on the design and objectives of the experiments. Gabriel Taylor provided information on the cable composition and typical installation practice.

The large-scale experiments described in this report were conducted at NIST in the Large Fire Laboratory. Matthew Bundy, the laboratory supervisor, helped plan the testing schedule. He also managed the sizeable clean-up operation that was needed because of the highly corrosive nature of the cable combustion effluent. Laurean DeLauter, Anthony Chakalis, and Marco Fernandez built the various experimental apparatus. Doris Rinehart and Artur Chernovsky managed the data acquisition equipment and software. Jay McElroy assisted in the preparation, installation, and removal of the cables.

The bench-scale experiments described in this report were conducted by Roy McLane and John Shields.

DISCLAIMER

ABBREVIATIONS

ASTM	American Society for Testing and Materials
AWG	American Wire Gauge
CAROLFIRE	Cable Response to Live Fire
CDRS	Conductors
CHRISTIFIRE	Cable Heat Release, Ignition, and Spread in Tray Installations
CLPE	Cross Linked Polyethylene
CPE	Chlorinated Polyethylene
CSPE	Chloro-Sulfonated Polyethylene
CVTC	Continuous Vulcanization Tray Cable
DEG C	Degrees Celsius
DIR BUR	Direct Burial
EN	European standard test designation
EPR	Ethylene-Propylene Rubber
EPRI	Electric Power Research Institute
FAA	Federal Aviation Administration
FLASH-CAT	Flame Spread over Horizontal Cable Trays
FMRC	Factory Mutual Research Corporation
FR	Flame Retardant
FT4	Flame Test 4
FR-XLP	Flame Retardant Cross-Linked Polyethylene
FR-XLPE	Flame Retardant Cross-Linked Polyethylene
FTIR	Fourier Transform Infrared Spectroscopy
FMRC GP-1	Factory Mutual Research Corporation Group 1
HRR	Heat Release Rate
HRRPUA	Heat Release Rate Per Unit Area
HW	Hallway
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
LSZH	Low Smoke Zero Halogen
MCC	Micro-Combustion Calorimetry
MT	Multiple Tray
NDIR	Non-Dispersive Infrared
NEC	National Electric Code
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
NRR	NRC Office of Nuclear Reactor Regulation
OD	Outer Diameter
OIL RES	Oil Resistant
PCFC	Pyrolysis Combustion Flow Calorimeter
PE	Polyethylene
PRA	Probabilistic Risk Assessment

PVC	Poly-vinyl Chloride
RES	NRC Office of Nuclear Regulatory Research
ROHS	Restriction of Hazardous Substances
RP	Radiant Panel
SIS	Switchboard Wire
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
THHN	Thermoplastic High Heat resistant Nylon coated
THWN	Thermoplastic Heat and Water resistant Nylon coated
THIEF	Thermally-Induced Electrical Failure
TP	Thermoplastic
TS	Thermoset
UL	Underwriters Laboratories
VNTC	Vinyl Nylon Tray Cable
XHHW	Cross-linked High Heat Water resistant
VT	Vertical Tray
VTT	Valtion Teknillinen Tutkimuskeskus (Technical Research Centre, Finland)
XLPE, XLP or XPE	Cross-Linked Polyethylene
XLPO	Cross-Linked Polyolefin

1 BACKGROUND

Electrical cables perform numerous functions in nuclear power plants (NPP). Power cables supply electricity to motors, transformers, heaters, light fixtures, fire suppression equipment, and reactor cooling equipment. Control cables connect plant equipment such as motor-operated valves (MOVs) and motor starters to remote initiating devices (e.g., switches, relays, and contacts). Instrumentation cables transmit low-voltage signals between input devices and readout display panels. NPPs typically contain hundreds of miles of electrical cables. A typical boiling-water reactor (BWR) requires approximately 97 km (60 miles) of power cable, 80 km (50 miles) of control cable and 400 km (250 miles) of instrument cable. A pressurized-water reactor (PWR) may require even more cables. The containment building of Waterford Steam Electric Generating Station, Unit 3 requires nearly 1,600 km (1,000 miles) of cable (US NRC, NUREG/CR-6384).

The *in situ* fire fuel load is clearly dominated by electrical cable insulating materials in most areas of a nuclear power plant. These electrical cables are found in both the cable routing raceways throughout the plant and in the electrical control cabinets. In a postulated NPP fire scenario, they can be an ignition source, an intervening combustible, and/or a device that can potentially lose functionality. These cables are made up of a variety of thermoplastic and thermoset materials. The primary characteristics that distinguish one cable type from another with respect to fire behavior include cable jacket formulation, conductor insulator formulation, multiple versus single-conductor, conductor size, and flammable to non-flammable material mass ratios.

Electrical cables have been responsible for a number of fires in NPP’s over the years. In 1975, a serious fire involving electrical cables occurred at the Browns Ferry Nuclear Power Plant operated by the Tennessee Valley Authority (NUREG-0050). The fire caused damage to more than 1,600 cables resulting in loss of all Unit 1 and many of Unit 2 emergency core cooling system equipment. The damage was extensive because of the flammability of the cables, including their ease of ignition, flame spread, and heat release rate.

The amount of experimental evidence and analytical tools available to calculate the development and effects of cable tray fires is relatively small when compared to the vast number of possible fire scenarios that can be postulated for NPPs in the U.S. Many of the large-scale fire tests conducted on cables are qualification tests in which the materials are tested in a relatively large-scale configuration and qualitatively ranked on a comparative basis. Appendix A in the CHRISTIFIRE Phase 1 report (McGrattan et al. 2012) provides a summary of these tests. While providing a relative ranking of cables, this type of test typically does not address the details of fire growth and spread, and does not provide any useful data for model calculations.

There have also been a variety of studies focused on small scale material characterization tests. Many investigators have questioned the degree to which small-scale test results reflect full-scale fire behavior, especially for plastic materials. Until these small-scale test results have been more fully evaluated through larger-scale test data, caution must be exercised in the use of small-scale test results in the prediction of full-scale fire behavior.

The need for data about the fire hazards of cables also relates to the methods contained in NUREG/CR-6850 “Fire PRA Methodology for Nuclear Power Facilities.” The fire PRA (Probabilistic Risk Assessment) method requires data on cable flame spread and heat release rates and fire spread from cable tray to cable tray. As mentioned above, the currently available data is limited. As such, there is a need for more data to reduce the uncertainty associated with the PRA methods.

2 TECHNICAL APPROACH

2.1 Objective of CHRISTIFIRE, Phase 2

The CHRISTIFIRE (Cable Heat Release, Ignition, and Spread in Tray Installations during FIRE) experimental program is a U.S. Nuclear Regulatory Commission (US NRC) Office of Nuclear Regulatory Research (RES) initiated effort to quantify the mass loss and heat release rates from burning electrical cables. The project is a collaborative effort that includes the NRC Office of Nuclear Reactor Regulation (NRR) as peer reviewers and the National Institute of Standards and Technology (NIST) as the primary experimental laboratory.

CHRISTIFIRE addresses the burning behavior of cables in a fire beyond the point of electrical failure. Its primary aim is to provide data for the development of fire models that can predict the heat release rate (HRR) of a cable fire. To predict the HRR, the model must account for the ignition and spread of a fire within stacks of multiple cable trays in a variety of configurations. Unlike most standard fire tests involving cables, these experiments are not intended as qualification or classification tests. In fact, typical qualification tests focus on vertical cable trays, but CHRISTIFIRE considers a wide range of configurations found in operating NPPs.

Phase 1 of CHRISTIFIRE (McGrattan et al. 2012) focused on arrays of horizontal trays of unprotected cables that were relatively clear of walls or ceilings. Experiments were performed at a variety of scales. Bench-scale and medium-scale experiments were performed to gather basic thermo-physical property data for a variety of models. Full-scale experiments were performed to provide data to validate the models. The result of Phase 1 was a validated model, FLASH-CAT, whose purpose is to predict the flame spread over horizontal cable trays. However, its use is limited to horizontal trays loaded with unprotected cables that are relatively clear of walls or ceilings. The primary purpose of CHRISTIFIRE Phase 2 is to extend the applicability of the FLASH-CAT model to both horizontal and vertical cable trays inside and outside of compartments, corridors, or ducts.

2.2 Overview of CHRISTIFIRE, Phase 2

CHRISTIFIRE Phase 2 includes the following experimental program:

1. A series of 17 experiments involving two vertical cable trays that are installed either inside or outside of a relatively narrow duct;

2. A series of 11 experiments involving multiple horizontal trays running along a corridor relatively close to the wall and ceiling;

3. A series of standard cone calorimeter measurements of all cables used in the full-scale experiments at heat fluxes of 50 kW/m^2 and 75 kW/m^2.

The results of the full-scale experiments will be used to extend the applicability of the FLASH-CAT model. The cone calorimeter measurements will supplement the existing database from Phase 1, and will identify cables that are outside of the ranges of heat release rate that characterize thermoset and thermoplastic cables.

3 CABLE PROPERTIES

3.1 Properties of Cables used in CHRISTIFIRE, Phase 2

In the summer of 2006, two shipping containers filled with new, used, and aged electrical cables were shipped from Brookhaven National Laboratories to NIST. Most of the cables were manufactured in the late 1970s and early 1980s. The cables had been used for environmental qualification studies (10 CFR 50.49) in the 1980's and 1990's. These cables were surplus from that program with substantial amount that had never even been unrolled from the spool. Three of these cables were tested in CHRISTIFIRE Phase 2.

In 2010, 20 spools of cable were shipped from Sandia National Laboratories in Albuquerque, New Mexico to the Large Fire Laboratory at NIST. Twelve of the cables that had been tested in Cable Response to Live Fire (CAROLFIRE, NUREG/CR-6931, Nowlen et al. 2008) were tested in CHRISTIFIRE Phase 2. Additional cable manufactured in 2011 was also purchased.

The tables on the following pages contain a general description of the cables used in Phase 2 of the project. Note that the "Item No." or "Cable #" is merely an identifier and has no relevance beyond this project. Photographs of the cables are shown in Figure 3-1 and Figure 3-2. 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.

A cross reference of the cables used in CHRISTIFIRE Phase 2, CAROLFIRE, and those purchased and those received from Brookhaven are listed in Table 3-1.

800 801 802 803 804 805 806 807 808 809 810 811

Figure 3-1. Photograph of Cables 800-811.

812 813 814 815 816 817 818 819 822 823 824

Figure 3-2. Photograph of Cables 812-824.

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

Cable No.	Source	Manufacturer*	Date	Cable Markings
800	CAROLFIRE #1	General Cable	2006	GENERAL CABLE® BICC® BRAND (WC) VNTC 7/C 12 AWG (UL) TYPE TC-ER THHN/THWN CDRS DIR BUR SUN RES 600V 03 FEB 2006
801	Purchased	General Cable	2011	GENERAL CABLE® (WC) VNTC 7/C 12AWG (UL) TYPE TC-ER THHN/THWN CDRS DIR BUR SUN RES 600V ROHS 03/FEB/2011
802	CAROLFIRE #10	Rockbestos	2006	7/C 12 AWG COPPER ROCKBESTOS-SURPRENANT (G) 600V 90DEG C FIREWALL(R) III XHHW-2 SUN RES DIR BUR OIL RES II NEC TYPE TC (UL) XLPE CSPE FT4 C52-0070 2006 6C-326
803	Purchased	Rockbestos	2011	7/C 12 AWG COPPER ROCKBESTOS-SURPRENANT (G) 600V 90 DEG C FIREWALL(R) III XHHW-2 SUN RES DIR BUR OIL RES II NEC TYPE TC (UL) XLPE CSPE FT4 C52-0070 2011 1C-136
804	CAROLFIRE #3	General Cable	2006	GENERAL CABLE® BICC® BRAND (WC) CVTC 7C 12AWG FR-XLP/PVC (UL) TYPE TC-ER XHHW-2 CDRS DIR BUR SUN RES 90C WET OR DRY 600V 08 MAR 2006
805	CAROLFIRE #12	Cable USA	Unknown	No Markings
806	CAROLFIRE #8	Rockbestos	2005	7/C 12 AWG COPPER ROCKBESTOS-SURPRENANT (G) X-LINK(R) TC 600V 90 DEG C WET OR DRY SUN RES DIR BUR NEC TYPE TC (UL) FMRC GP-1 K2 COLOR CODE FRXLPE LSZH-XLPO C12-0070 2005 5D-880
807	CAROLFIRE #15	General Cable	2006	GENERAL CABLE® BICC® BRAND SUBSTATION CONTROL CABLE 7/C #12AWG 600V 30 MAY 2006
808	CAROLFIRE #11	Rockbestos	2005	7/C 14 AWG ROCKBESTOS-SURPRENANT (G) VITALINK(R) TC/NCC 600V 90 DEG C (UL) TYPE TC SUN RES FT-4 FIRE RESISTANT SILICONE LSZH C65-0070 2005 5F-052
809	CAROLFIRE #9	First Capitol		No Markings
810	Purchased	General Cable	2011	GENERAL CABLE® (WC) VNTC 3/C 8AWG WITH GRND (UL) TYPE TC-ER THHN/THWN CDRS DIR BUR SUN RES 600V ROHS 10/FEB/2011
811	CAROLFIRE #14	Rockbestos	2006	3/C 8 AWG ROCKBESTOS-SURPRENANT (G) 600V FIREWALL(R) III XHHW-2 90 DEG C SUN RES DIR BUR OIL RES II NEC TYPE TC (UL) FRXLPE CSPE FT4 P62-0084 2006 6C-399
812	Purchased	Rockbestos	2010	3/C 8 AWG COPPER ROCKBESTOS-SURPRENANT (G) 600V FIREWALL(R) III XHHW-2 90 DEG C SUN RES DIR BUR OIL RES II NEC TYPE TC (UL) FRXLPE CSPE FT4 P62-0084 2010 0D-389

Cable No.	Source	Manufacturer*	Date	Cable 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
815	Purchased	General Cable	2011	GENERAL CABLE® (WC) VNTC 12/C 18AWG (UL) TYPE TC-ER TFN CDRS SUN RES DIR BUR 600V ROHS 20 JAN 2011
816	Purchased	Rockbestos	2011	4 SHIELDED PAIRS 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 I46-5844 2011 1D-138
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
819		First Capitol	2003	No Markings
822	Brookhaven	Rockbestos	Unknown	No Markings
823	Brookhaven	Rockbestos	Unknown	12 AWG ROCKBESTOS® FIREWALL® TYPE SIS 600V (UL) NUCLEAR
824		Kerite	1989	KERITE 1989 #12 AWG CU 600V FR3 TEST # A6272

*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
800	PVC	PVC	TP	7	12.4	1.26	0.69	0.31	0.66	0.19	0.11	0.01
801	PVC/Nylon	PVC	TP	7	12.5	1.28	0.62	0.31	0.66	0.19	0.11	0.01
802	XLPE	CSPE	TS	7	15.0	2.32	1.16	0.42	0.50	0.30	0.20	0.01
803	XLPE	CSPE	TS	7	15.0	2.37	1.02	0.44	0.48	0.32	0.19	0.01
804	XLPE	PVC	Mix	7	15.1	1.63	0.96	0.41	0.52	0.23	0.22	0.01
805	Tefzel®		TP	7	10.2	0.76	0.45	0.29	0.74	0.08	0.15	0.02
806	XLPE	XLPO	TS	7	12.2	1.17	0.84	0.32	0.66	0.18	0.17	0.00
807	PE	PVC	TP	7	14.0	1.54	0.27	0.37	0.59	0.24	0.15	0.01
808	VITA-LINK®		TS	7	19.6	2.40	1.74	0.48	0.26	0.33	0.43	0.01
809	SR	Aramid Braid	TS	7	14.5	1.21	1.10	0.35	0.62	0.08	0.31	0.01
810	PVC/Nylon	PVC	TP	3	15.2	1.73	1.06	0.43	0.63	0.23	0.12	0.01
811	XLPE	CSPE	TS	3	16.3	1.86	1.72	0.43	0.55	0.29	0.16	0.03
812	XLPE	CSPE	TS	3	16.3	2.52	1.70	0.54	0.53	0.29	0.14	0.03
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
815	PVC/Nylon	PVC	TP	12	11.3	1.20	0.49	0.19	0.59	0.02	0.29	0.06
816	XLPE	CSPE	TS	4	16.7	2.93	1.10	0.42	0.26	0.45	0.22	0.07
817	XLPE	CSPE	TS	2	7.8	1.64	0.92	0.11	0.24	0.58	0.15	0.00

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
818	PE	PVC	TP	1	6.3	1.35	1.41	0.06	0.38	0.40	0.07	0.15
819	SR	Glass Braid	TS	3	16.3	1.42	20.1	0.52	0.47	0.08	0.24	0.19
822	SR	Glass Braid	TS	1	3.7	0.26	1.04	0.03	0.48	0.18	0.31	0.01
823	XLPE		TS	1	3.8	1.15	0	0.04	0.70	0.30	0.00	0.00
824	EPR	CSPE	TS	1	5.1	1.42	1.13	0.08	0.34	0.46	0.20	0.00

4 CONE CALORIMETER MEASUREMENTS

4.1 Description

The cone calorimeter is a widely-used device in fire protection engineering for measuring the heat release rate of a material sample under a constant imposed heat flux. In Phase 1 of the CHRISTIFIRE program, 12 cable samples were tested at 3 different heat fluxes (25 kW/m^2, 50 kW/m^2, and 75 kW/m^2) to determine at which flux the burning rate of cables best matched that measured at larger scale. The results indicated that an imposed heat flux of 25 kW/m^2 was too low to produce heat release rates consistent with larger scale experiments; thus, for Phase 2, it was decided to only test the cables at 50 kW/m^2 and 75 kW/m^2.

The cone calorimeter measurements were performed at NIST in early 2012. The experiments were conducted using the standardized procedure for cables, ASTM D 6113-03, "Standard Test Method for Using a Cone Calorimeter to Determine Fire-Test-Response Characteristics of Insulating Materials Contained in Electrical or Optical Fiber Cables." Preparation for all cable samples followed the procedure outlined in Sections 8.1.2 and 8.1.4 of the standard, with some modifications as described in the procedure below.

Step 1. Cable samples were cut into 10 cm (4 in) segments and placed within a shallow tray formed with aluminum foil, shiny side up (Figure 4-1).

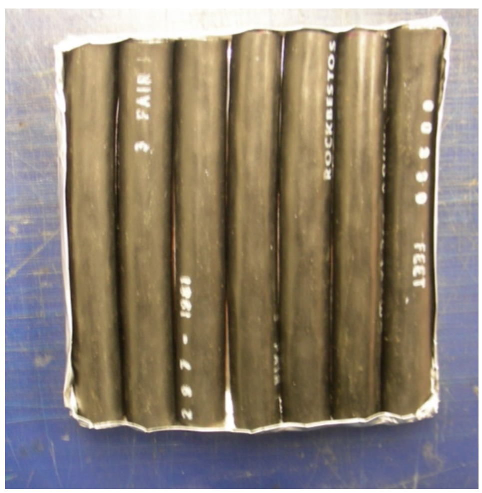


Figure 4-1. Typical cable sample for cone calorimeter.

Step 2. The sample holder was assembled from its components: frame bottom, several layers of mineral wool to ensure a tight fit, cables, wire grid, and frame top (Figure 4-2). The area of the cover opening was 88.4 cm^2 ± 0.9 cm^2 (13.7 in^2 ± 0.1 in^2). Two pins were used to hold the frame bottom and top together. The wire grid is designed to prevent the cables from bowing upwards when heated. The entire assembly is shown in Figure 4-3.

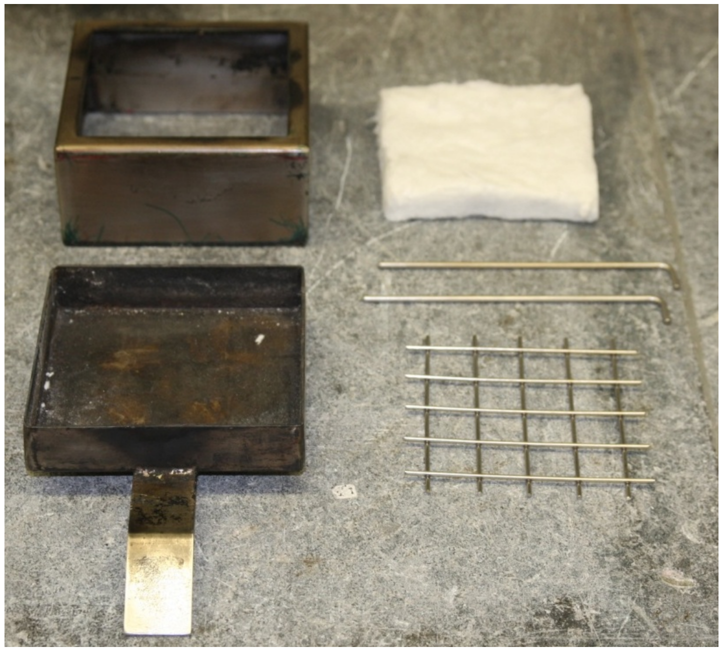


Figure 4-2. Components of the cone calorimeter sample holder.

Figure 4-3. The completed specimen assembly for the cone calorimeter.

4.2 Uncertainty

The uncertainty in the heat release rate measurement is a combination of the systematic uncertainty associated with the various measurements and assumptions underlying the calculation of the heat release rate; and the random uncertainty associated with the construction of the specimen holder and conduct of the experiment.

Enright and Fleischmann (1999) conducted an analysis of the calculation method used in most cone calorimeter standards, including the one used here. They report that for a sample whose exact chemical composition is unknown, the relative standard uncertainty is approximately 6 % during the period of time in which the bulk of the sample is consumed. The key component of this estimate is the assumption that the heat of combustion based on oxygen consumption is 13,100 kJ/kg of oxygen consumed. This value has an estimated standard relative uncertainty of ±5 %. The remaining uncertainty is due mainly to the measurement of oxygen consumption and a stoichiometric expansion factor.

To quantify the random uncertainty, three replicate measurements were made for each cable sample at each imposed heat flux value. The relative standard deviation for repeatability (RSD_r) of the heat release rate measurements was 5.6 %.

Following the recommended guidelines for evaluating and expressing the uncertainty of NIST measurements (Taylor and Kuyatt 1994), the systematic and random uncertainty values are combined via quadrature resulting in a *combined relative standard uncertainty* of 8 %. To be consistent with current international practice, NIST recommends that a coverage factor of 2 be applied to this value, yielding an *expanded relative uncertainty* of 16 %. This is also referred to as the 95 % confidence interval.

4.3 Results

The following pages contain a brief description of each set of cone calorimeter measurements, along with the measured heat release rates for the cable samples at the two heat flux exposures. As part of the analysis, an effective heat release rate per unit area (HRRPUA) is calculated. Figure 4-4 displays the heat release rate per unit area as a function of time for three replicate experiments. The solid curves indicate the actual test data. The dashed lines display a simplified time history of the data that is useful for modeling. The flat part of the simplified function is taken as the average HRR. To compute it, first define the total heat released per unit area, Q'', by integrating the heat release rate per unit area, $\dot{q}''$, over the duration of the experiment:

$$Q'' = \int_0^\infty \dot{q}''(t)\, dt \tag{4-1}$$

Next, define the points in time, t_1 and t_2, before which 10 % of the total energy has been released and after which 90 % of the energy has been released, respectively:

$$0.1\, Q'' = \int_0^{t_1} \dot{q}''(t)\, dt \quad ; \quad 0.1\, Q'' = \int_{t_2}^{\infty} \dot{q}''(t)\, dt \tag{4-2}$$

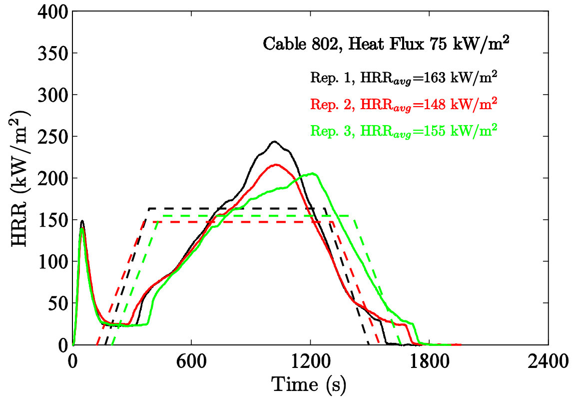


Figure 4-4. Sample output from cone calorimeter.

The average heat release rate per unit area is defined as the heat release rate during the time period between t_1 and t_2 over which 80 % of the total energy has been released:

$$\overline{\dot{q}''} = \frac{\int_{t_1}^{t_2} \dot{q}''\,dt}{t_2 - t_1} \tag{4-3}$$

Note that the duration of the linear ramp up is $(t_2 - t_1)/6$. The linear ramp down period is also this same duration. Note also that the simplified heat release rate curve does not account for the actual ignition time.

4.3.1 Cable 800

The cables ignited in approximately 33 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 19 s when exposed to 75 kW/m^2. They burned steadily for the duration of the test. The tests were terminated following approximately 1 min of non-flaming. Figure 4-5 displays the cable cross section and post-burn debris. Figure 4-6 displays the heat release rate per unit area for the two imposed heat flux values.

Figure 4-5. Cross section of Cable 800 and photograph of burn residue.

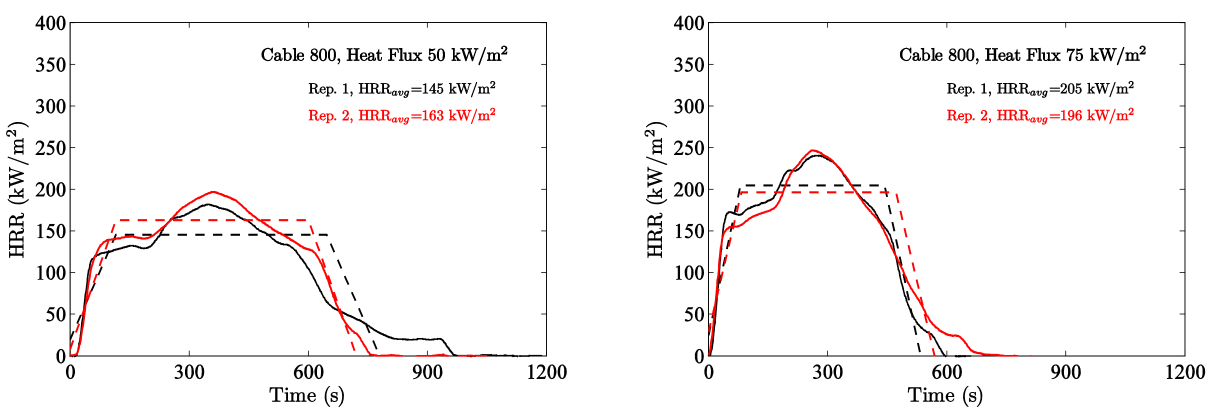


Figure 4-6. Results of cone calorimeter experiments, Cable 800.

4.3.2 Cable 801

The cables ignited in approximately 32 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 15 s when exposed to 75 kW/m^2. They burned steadily for the duration of the tests. The tests were terminated following approximately 1 min of non-flaming. Figure 4-7 displays the cable cross section and post-burn debris. Figure 4-8 displays the heat release rate per unit area for the two imposed heat flux values.

Figure 4-7. Cross section of Cable 801 and photograph of burn residue.

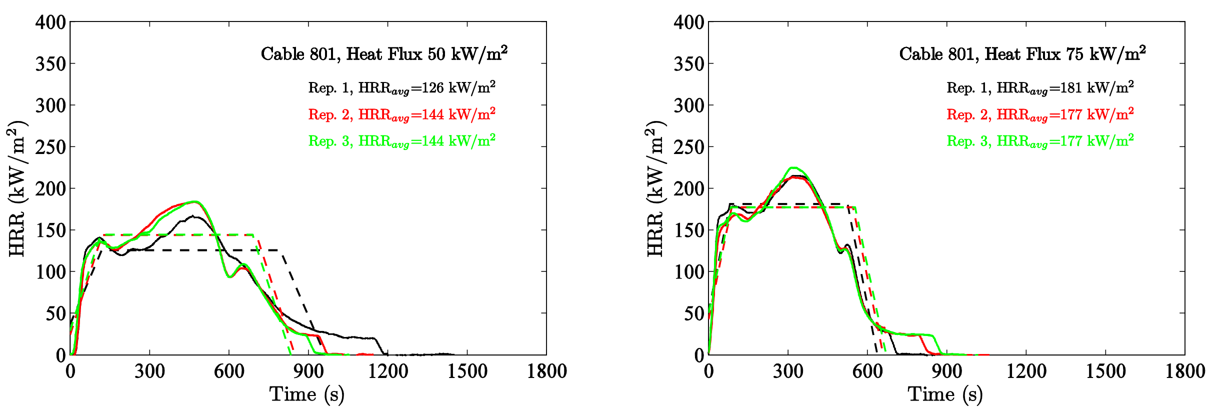


Figure 4-8. Results of cone calorimeter experiments, Cable 801.

4.3.3 Cable 802

The cables ignited in approximately 42 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 22 s when exposed to 75 kW/m^2. However, the flames extinguished after a few minutes in each case. The pilot igniter was then re-positioned and eventually the cables re-ignited and burned steadily. Small beads of jacketing material were observed being expelled from the specimen holder. The tests were terminated following approximately 1 min of non-flaming. Figure 4-9 displays the cable cross section and post-burn debris. Figure 4-10 displays the heat release rate per unit area for the two imposed heat flux values.

Figure 4-9. Cross section of Cable 802 and photograph of burn residue.

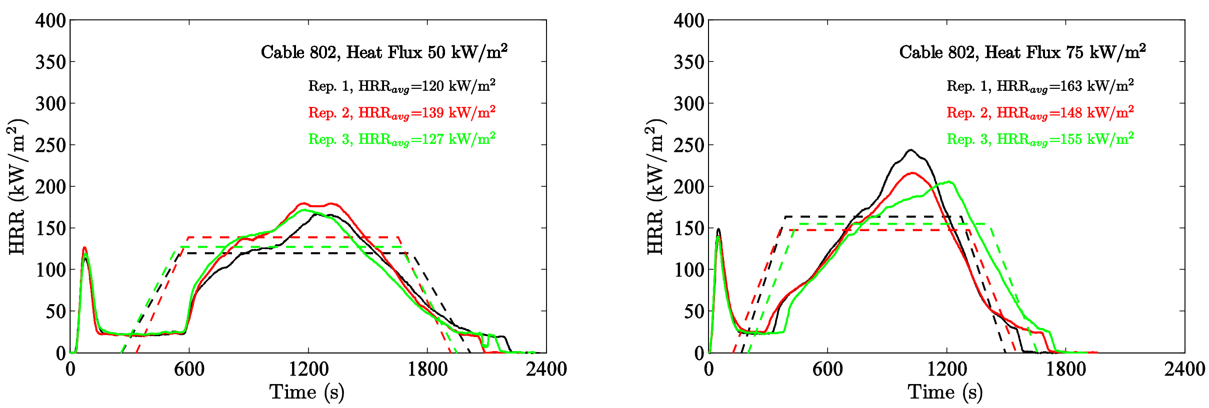


Figure 4-10. Results of cone calorimeter experiments, Cable 802.

4.3.4 Cable 803

The cables ignited in approximately 60 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 29 s when exposed to 75 kW/m^2. However, the flames extinguished after a few minutes in both cases. The pilot igniter was then re-positioned and eventually the cables re-ignited and burned steadily. Liquid was observed dripping from the bottom of the sample holder, along with an occasional flame. Small beads of jacketing material were observed being expelled from the specimen holder. The tests were terminated following approximately 1 min of non-flaming. Figure 4-11 displays the cable cross section and post-burn debris. Figure 4-12 displays the heat release rate per unit area for the two imposed heat flux values.

Figure 4-11. Cross section of Cable 803 and photograph of burn residue.

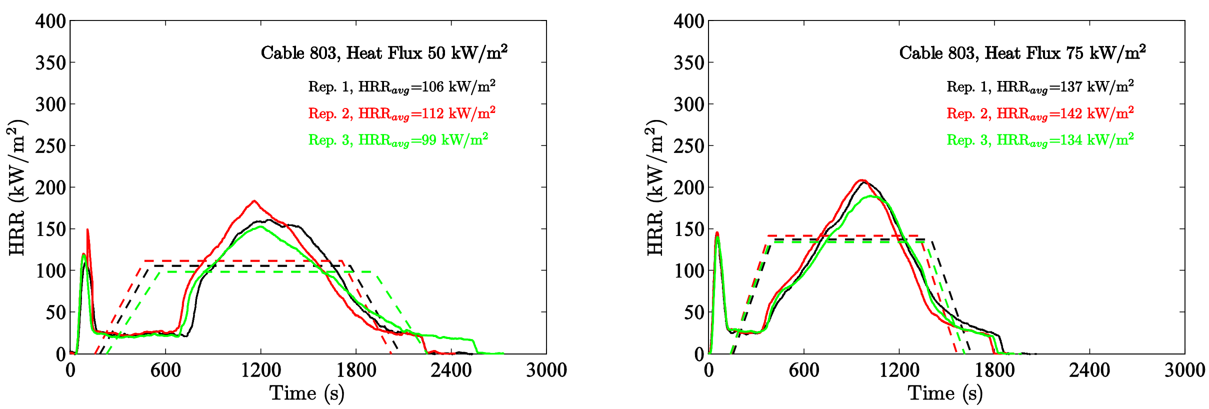


Figure 4-12. Results of cone calorimeter experiments, Cable 803.

4.3.5 Cable 804

The cables ignited in approximately 36 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 20 s when exposed to 75 kW/m^2. They burned steadily for the duration of the tests. The tests were terminated after approximately 1 min of non-flaming. Figure 4-13 displays the cable cross section and post-burn debris. Figure 4-14 displays the heat release rate per unit area for the two imposed heat flux values.

Figure 4-13. Cross section of Cable 804 and photograph of burn residue.

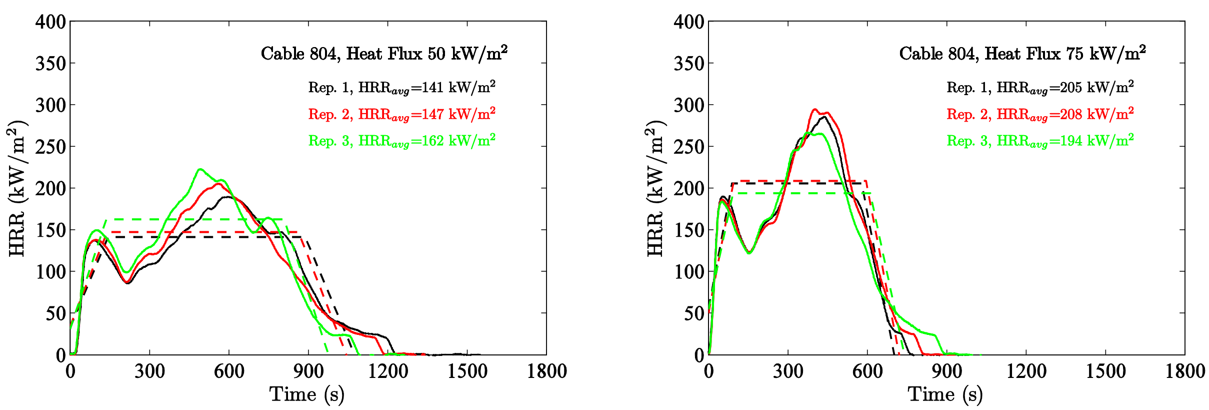


Figure 4-14. Results of cone calorimeter experiments, Cable 804.

4.3.6 Cable 805

The cables ignited in approximately 241 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 81 s when exposed to 75 kW/m^2. They burned steadily for the duration of the tests. The tests were terminated following approximately 1 min of non-flaming. Figure 4-15 displays the cable cross section and post-burn debris. Figure 4-16 displays the heat release rate per unit area for the two imposed heat flux values.

Figure 4-15. Cross section of Cable 805 and photograph of burn residue.

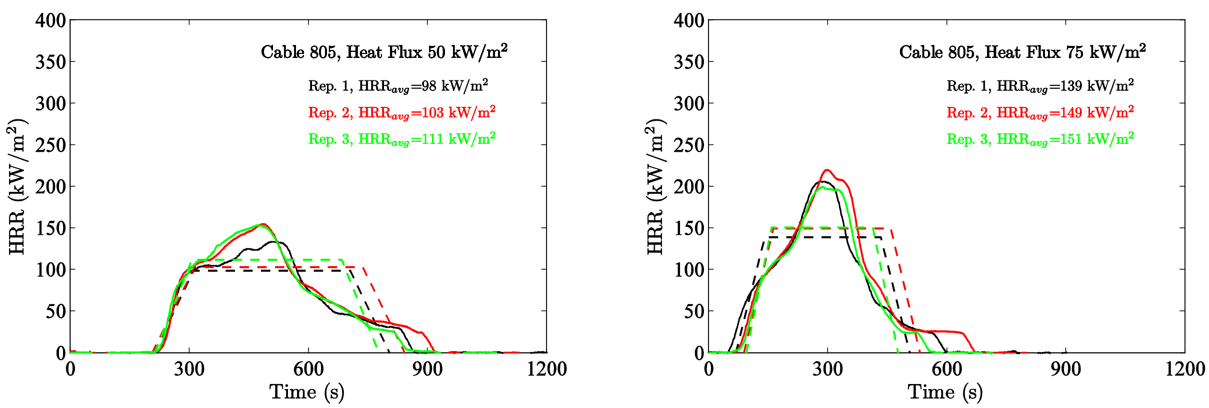


Figure 4-16. Results of cone calorimeter experiments, Cable 805.

4.3.7 Cable 806

The cables ignited in approximately 121 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 40 s when exposed to 75 kW/m^2. They burned steadily for the duration of the tests. The tests were terminated after approximately 1 min of non-flaming. Figure 4-17 displays the cable cross section and post-burn debris. Figure 4-18 displays the heat release rate per unit area for the two imposed heat flux values.

Figure 4-17. Cross section of Cable 806 and photograph of burn residue.

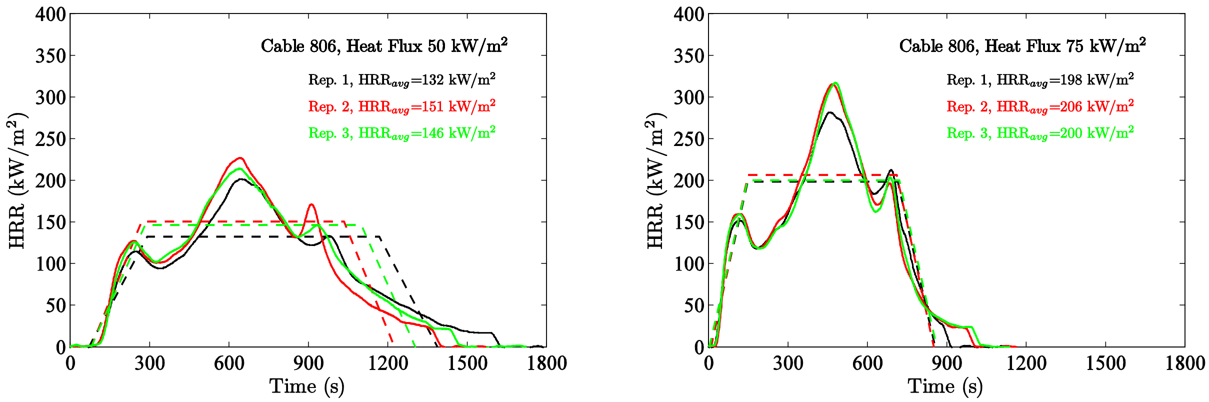


Figure 4-18. Results of cone calorimeter experiments, Cable 806.

4.3.8 Cable 807

The cables ignited in approximately 35 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 20 s when exposed to 75 kW/m^2. They burned steadily for the duration of the tests. The tests were terminated after approximately 1 min of non-flaming. The jacket material was observed to expand beyond the restraining grid. Figure 4-19 displays the cable cross section and post-burn debris. Figure 4-20 displays the heat release rate per unit area for the two imposed heat flux values.

Figure 4-19. Cross section of Cable 807 and photograph of burn residue.

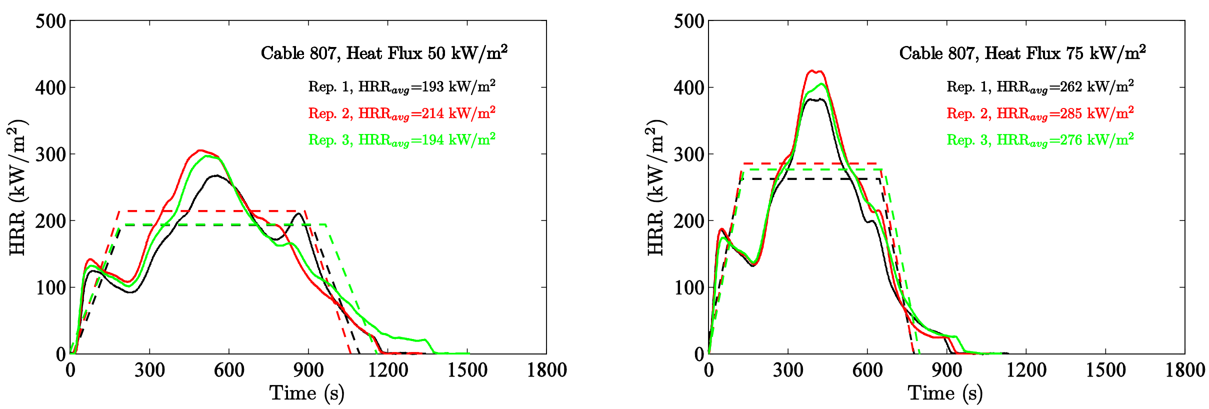


Figure 4-20. Results of cone calorimeter experiments, Cable 807.

4.3.9 Cable 808

The cables ignited in approximately 87 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 46 s when exposed to 75 kW/m^2. They burned steadily at a relatively low rate for the duration of the tests. The tests were terminated after approximately 1 min of non-flaming. A white residue coated the sample holder after the tests. Figure 4-21 displays the cable cross section and post-burn debris. Figure 4-22 displays the heat release rate per unit area for the two imposed heat flux values.

Figure 4-21. Cross section of Cable 808 and photograph of burn residue.

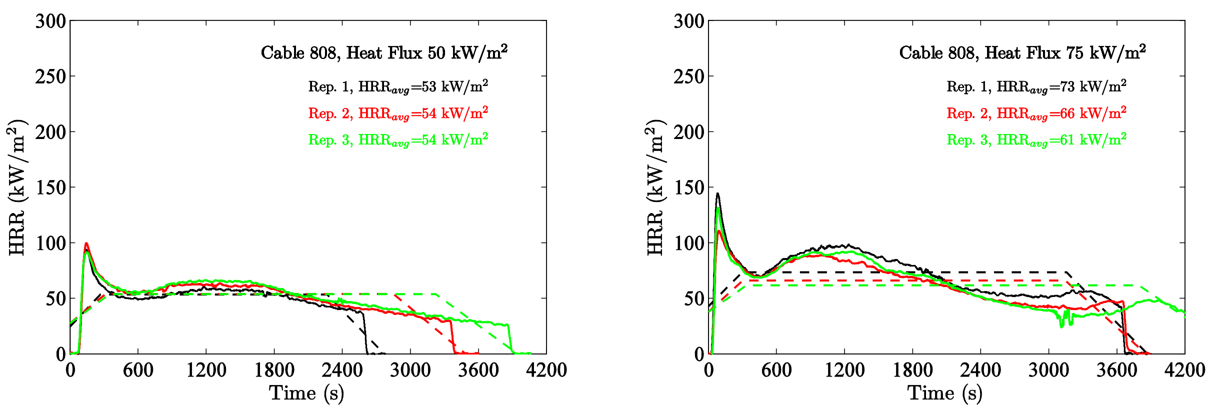


Figure 4-22. Results of cone calorimeter experiments, Cable 808.

4.3.10 Cable 809

The cables ignited in approximately 22 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 11 s when exposed to 75 kW/m^2. However, at 50 kW/m^2 the igniter was required to relight the sample after a few minutes of burning. The tests were terminated after approximately 1 min of non-flaming. A white residue coated the sample holder after the tests, similar to Cable 808. The aramid braid material covering the jacket was more or less intact following each test. Figure 4-23 displays the cable cross section and post-burn debris. Figure 4-24 displays the heat release rate per unit area for the two imposed heat flux values.

Figure 4-23. Cross section of Cable 809 and photograph of burn residue.

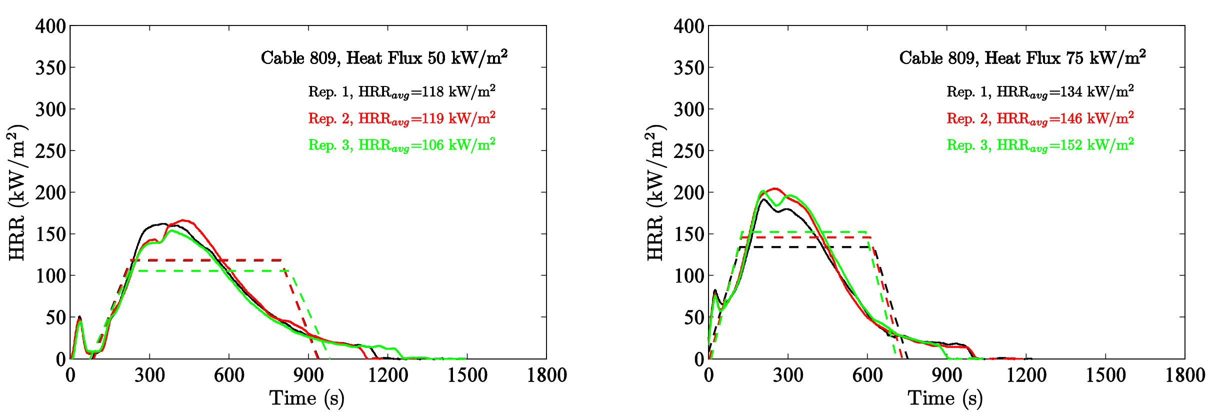


Figure 4-24. Results of cone calorimeter experiments, Cable 809.

4.3.11 Cable 810

The cables ignited in approximately 35 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 15 s when exposed to 75 kW/m^2. The cables burned steadily over the course of each test. The tests were terminated after approximately 1 min of non-flaming. The jacketing material was observed to expand beyond the restraining grill. Figure 4-25 displays the cable cross section and the sample holder at the end of the experiment. Figure 4-26 displays the heat release rate per unit area for the two imposed heat flux values.

Figure 4-25. Cross section of Cable 810 and photograph of burn residue.

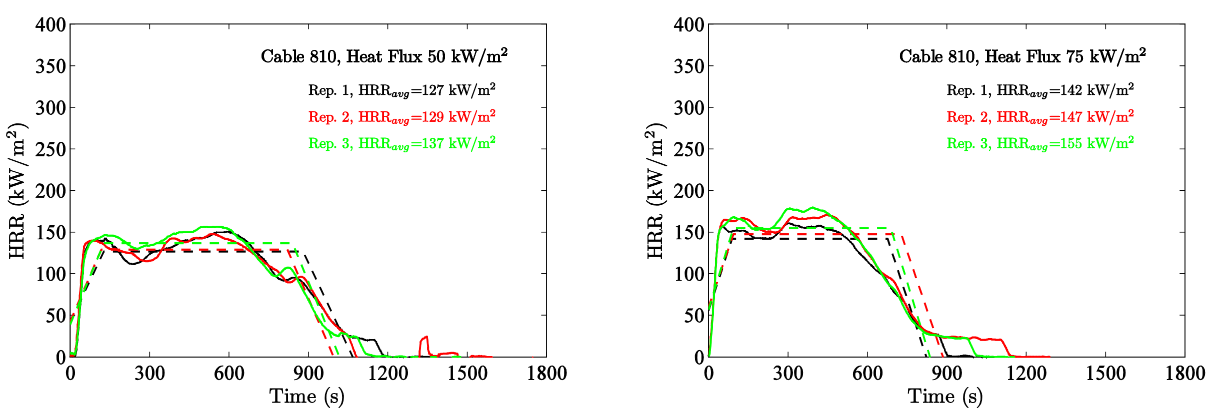
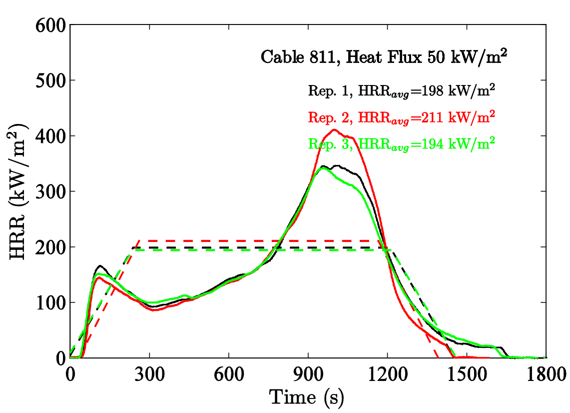


Figure 4-26. Results of cone calorimeter experiments, Cable 810.

4.3.12 Cable 811

The cables ignited in approximately 58 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 21 s when exposed to 75 kW/m^2. The burning rate increased steadily over the course of each test, peaking at relatively high values. Liquid was observed dripping from the bottom of the sample holder, along with an occasional flame. The tests were terminated after approximately 1 min of non-flaming. The jacketing material was observed to expand beyond the restraining screen. Figure 4-27 displays the cable cross section and post-burn debris. Figure 4-28 displays the heat release rate per unit area for the two imposed heat flux values.

Figure 4-27. Cross section of Cable 811 and photograph of burn residue.



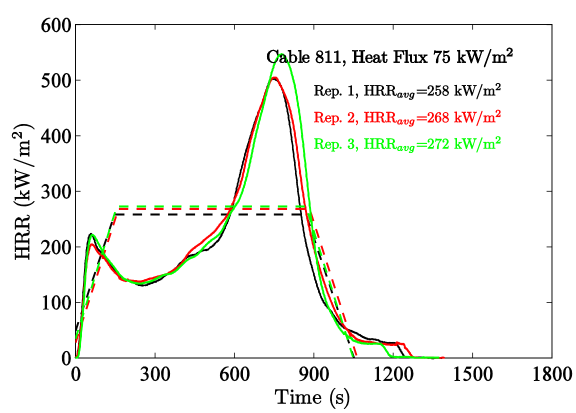


Figure 4-28. Results of cone calorimeter experiments, Cable 811.

4.3.13 Cable 812

The cables ignited in approximately 51 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 25 s when exposed to 75 kW/m^2. However the fires extinguished after several minutes and were re-ignited. A second re-ignition was required for both exposures. Liquid was observed dripping from the bottom of the sample holder, along with an occasional flame. Figure 4-29 displays the cable cross section and post-burn debris. Figure 4-30 displays the heat release rate per unit area for the two imposed heat flux values.

Figure 4-29. Cross section of Cable 812 and photograph of burn residue.

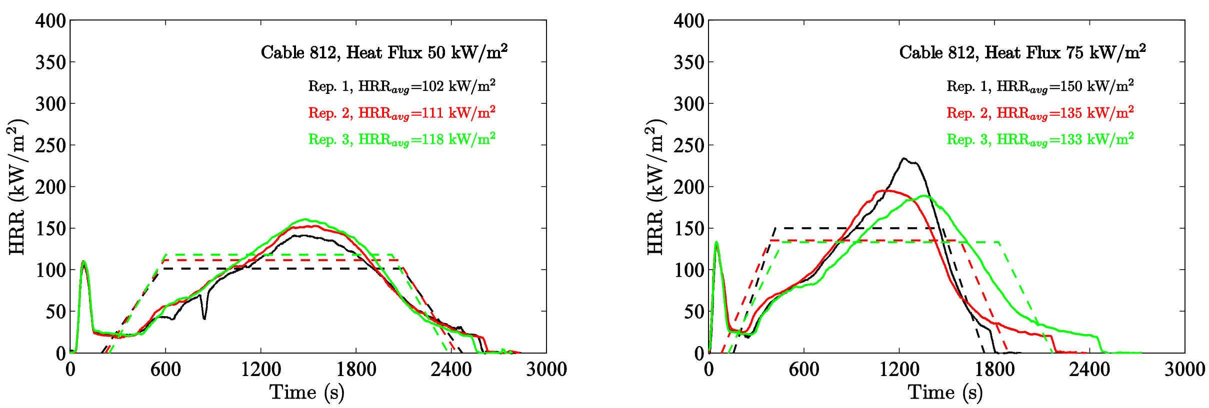


Figure 4-30. Results of cone calorimeter experiments, Cable 812.

4.3.14 Cable 813

The cables ignited in approximately 40 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 18 s when exposed to 75 kW/m^2. However the fires extinguished after several minutes and were re-ignited. Liquid was observed dripping from the bottom of the sample holder, along with an occasional flame. Small beads of jacketing material were expelled from the sample holder. Figure 4-31 displays the cable cross section and post-burn debris. Figure 4-32 displays the heat release rate per unit area for the two imposed heat flux values.

Figure 4-31. Cross section of Cable 813 and photograph of burn residue.

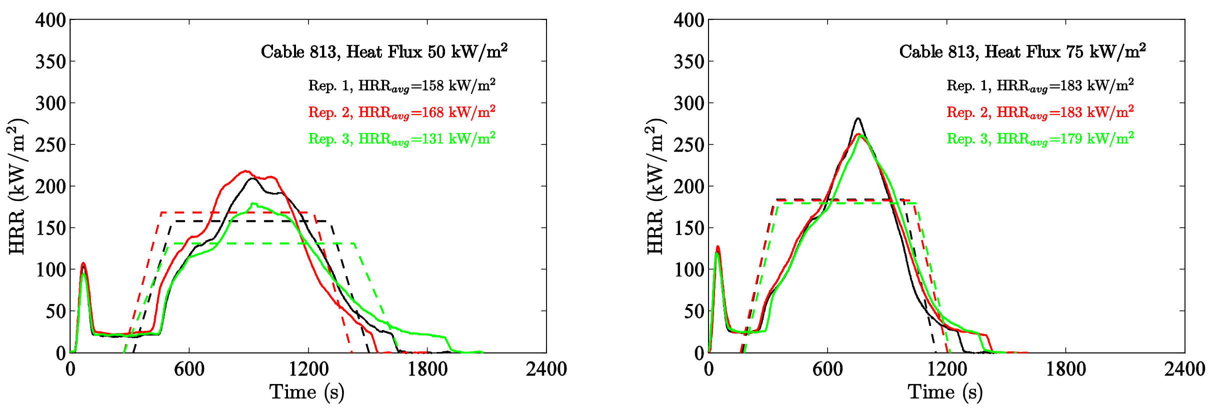


Figure 4-32. Results of cone calorimeter experiments, Cable 813.

4.3.15 Cable 814

The cables ignited in approximately 34 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 15 s when exposed to 75 kW/m^2. The fires burned relatively steadily for duration of the tests. Figure 4-33 displays the cable cross section and post-burn debris. Figure 4-34 displays the heat release rate per unit area for the two imposed heat flux values.

Figure 4-33. Cross section of Cable 814 and photograph of burn residue.

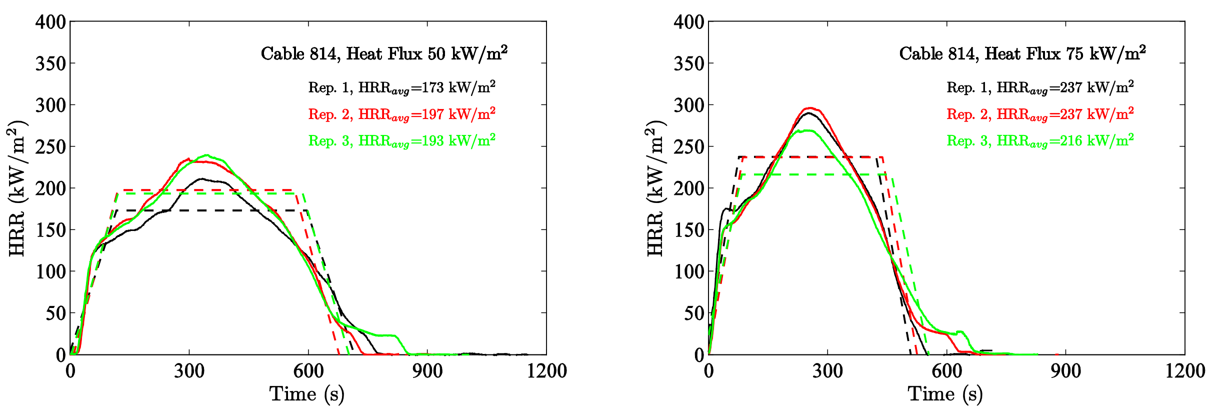


Figure 4-34. Results of cone calorimeter experiments, Cable 814.

4.3.16 Cable 815

The cables ignited in approximately 32 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 12 s when exposed to 75 kW/m^2. The fires burned relatively steadily for duration of the tests. Figure 4-35 displays the cable cross section and post-burn debris. Figure 4-36 displays the heat release rate per unit area for the two imposed heat flux values.

Figure 4-35. Cross section of Cable 815 and photograph of burn residue.

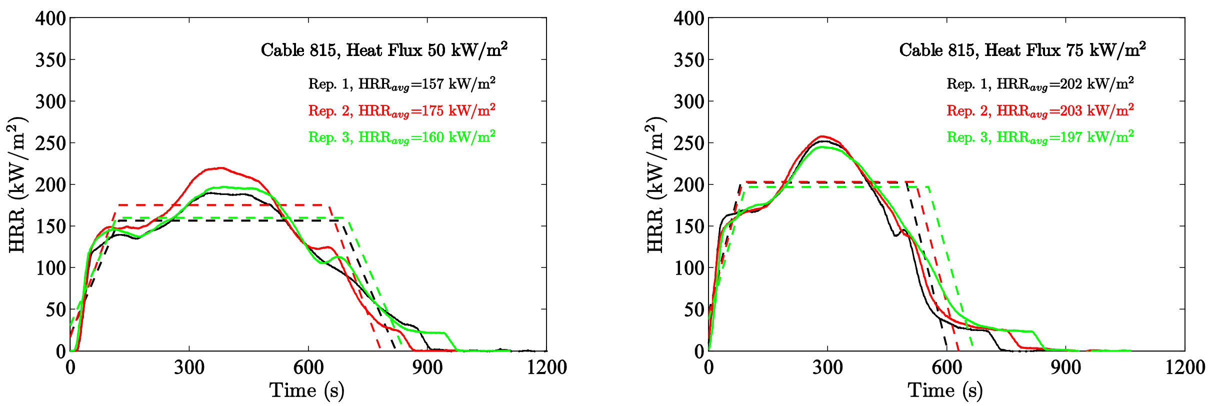


Figure 4-36. Results of cone calorimeter experiments, Cable 815.

4.3.17 Cable 816

The cables ignited in approximately 61 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 26 s when exposed to 75 kW/m^2. However the fires extinguished after several minutes and were re-ignited. Liquid was observed dripping from the bottom of the sample holder. Small beads of jacketing material were expelled from the sample holder. Figure 4-37 displays the cable cross section and post-burn debris. Figure 4-38 displays the heat release rate per unit area for the two imposed heat flux values.

Figure 4-37. Cross section of Cable 816 and photograph of burn residue.

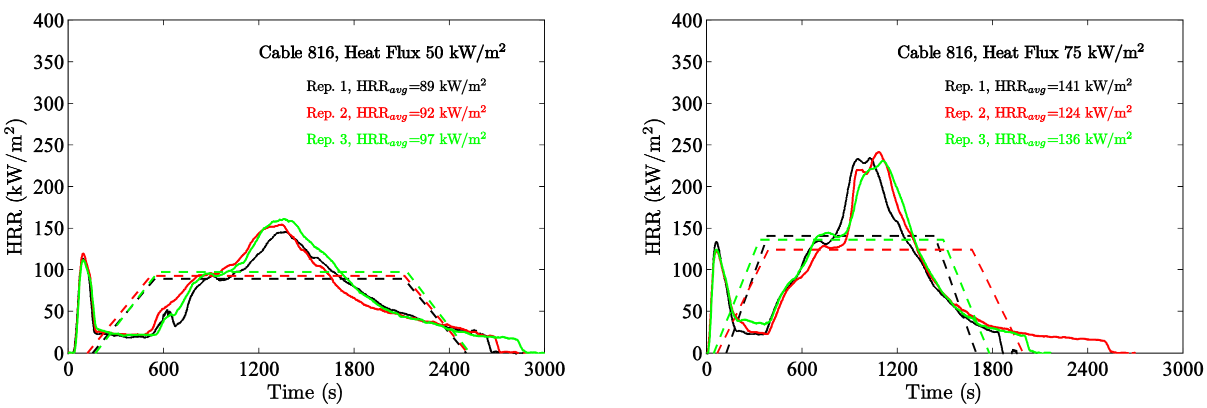


Figure 4-38. Results of cone calorimeter experiments, Cable 816.

4.3.18 Cable 817

The cables ignited in approximately 77 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 31 s when exposed to 75 kW/m^2. However the fires at 50 kW/m^2 extinguished after several minutes and were re-ignited. Liquid was observed dripping from the bottom of the sample holder. Small beads of jacketing material were expelled from the sample holder. Figure 4-39 displays the cable cross section and post-burn debris. Figure 4-40 displays the heat release rate per unit area for the two imposed heat flux values.

Figure 4-39. Cross section of Cable 817 and photograph of burn residue.

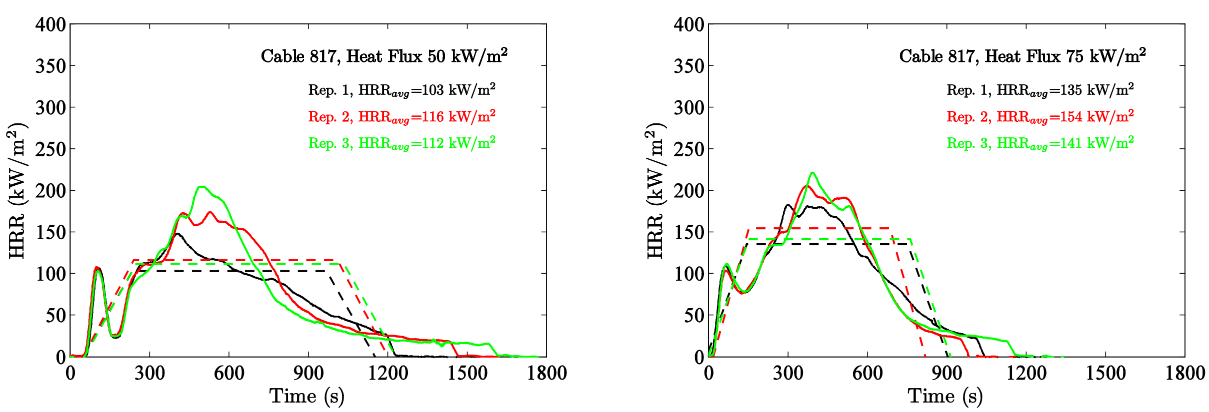


Figure 4-40. Results of cone calorimeter experiments, Cable 817.

4.3.19 Cable 818

The cables ignited in approximately 64 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 22 s when exposed to 75 kW/m^2. After the tests, the only materials that remained were the cable conductor and metal mesh shielding. Figure 4-41 displays the cable cross section and post-burn debris. Figure 4-42 displays the heat release rate per unit area for the two imposed heat flux values.

Figure 4-41. Cross section of Cable 818 and photograph of burn residue.

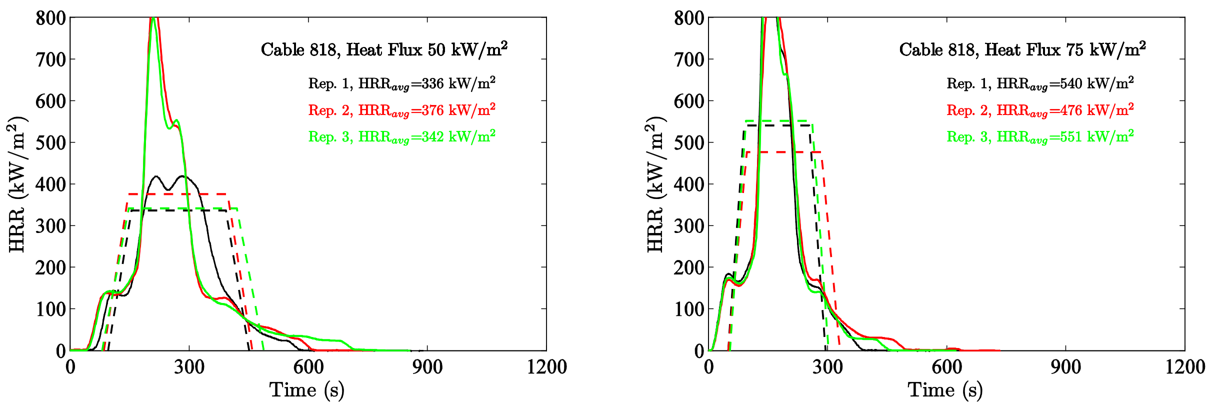


Figure 4-42. Results of cone calorimeter experiments, Cable 818.

4.3.20 Cable 819

The cables ignited in approximately 38 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 16 s when exposed to 75 kW/m^2. In all six tests, a white crust formed above the specimen holder. This white crust appeared to force the effluent out the bottom of the sample holder. Following the tests, the cables appeared to be relatively intact. Figure 4-43 displays the cable cross section and post-burn debris. Figure 4-44 displays the heat release rate per unit area for the two imposed heat flux values. Figure 4-45 shows additional photographs of this experiment.

Figure 4-43. Cross section of Cable 819 and photograph of burn residue.

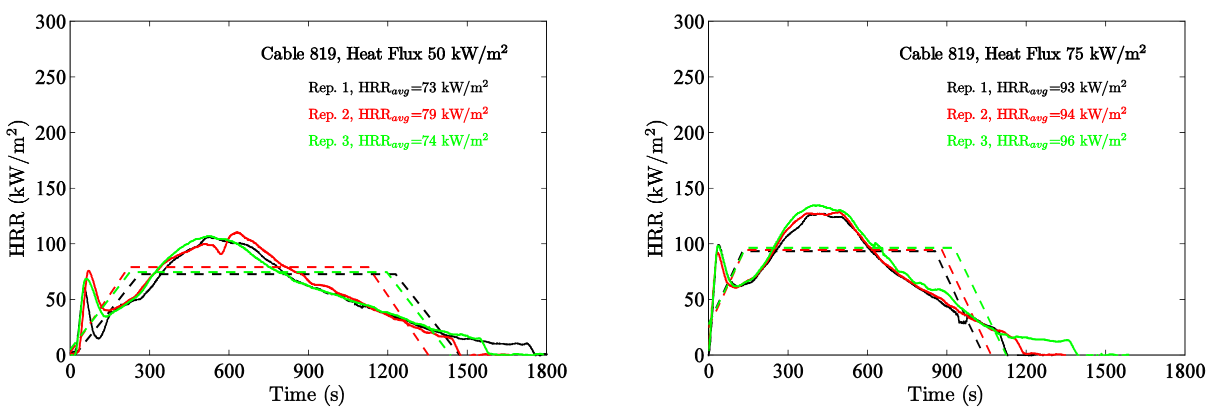


Figure 4-44. Results of cone calorimeter experiments, Cable 819.

Figure 4-45. Additional photographs of Cable 819.

4.3.21 Cable 822

The cables ignited in approximately 75 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 41 s when exposed to 75 kW/m^2. In all six tests, a white crust formed above the specimen holder. This white crust appeared to force the effluent out the bottom of the sample holder. Liquid dripped from the bottom as well, sometimes igniting. Following the tests, the cable casing remained relatively intact, but the insulation was completely consumed. Figure 4-46 displays the cable cross section and post-burn debris. Figure 4-47 displays the heat release rate per unit area for the two imposed heat flux values.

Figure 4-46. Cross section of Cable 822 and photograph of burn residue.

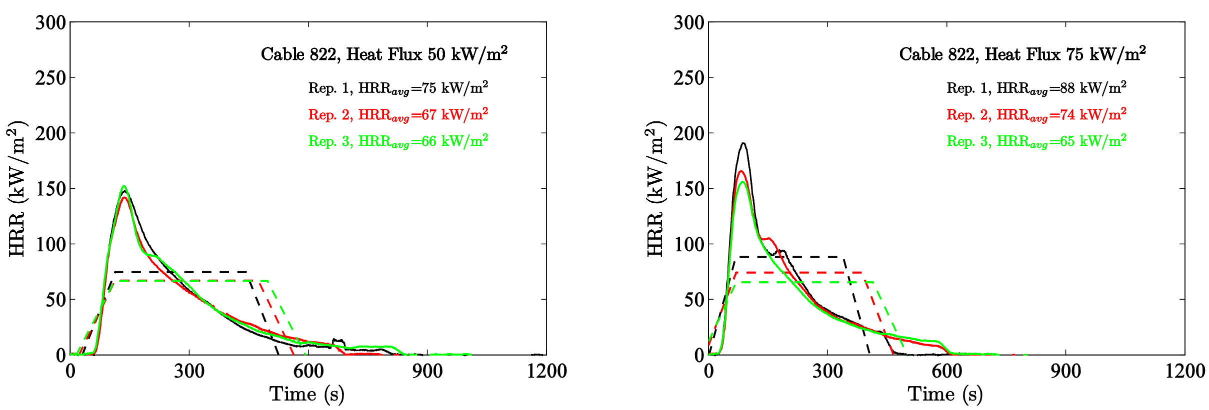


Figure 4-47. Results of cone calorimeter experiments, Cable 822.

4.3.22 Cable 823

The cables ignited in approximately 94 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 42 s when exposed to 75 kW/m^2. This relatively thin, single conductor cable burned relatively quickly and left little residue. Figure 4-48 displays the cable cross section and post-burn debris. Figure 4-49 displays the heat release rate per unit area for the two imposed heat flux values.

Figure 4-48. Cross section of Cable 823 and photograph of burn residue.

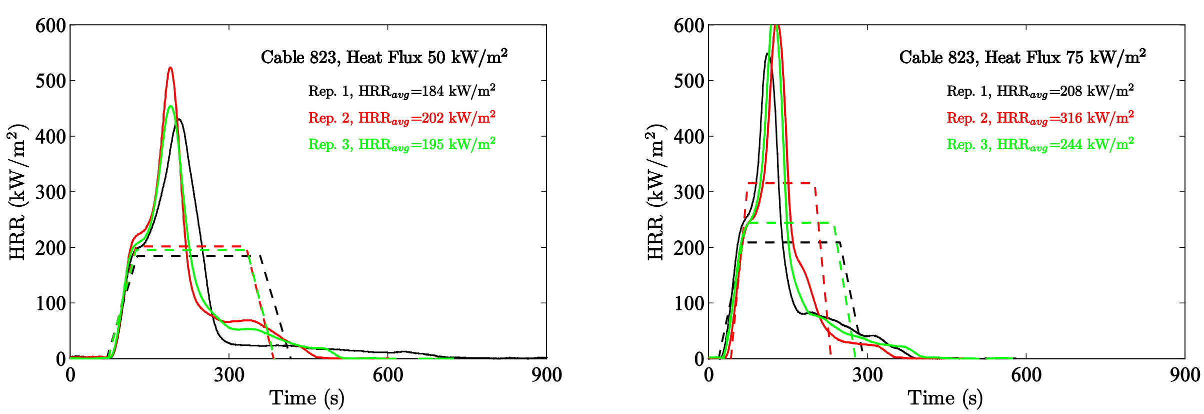


Figure 4-49. Results of cone calorimeter experiments, Cable 823.

4.3.23 Cable 824

The cables ignited in approximately 39 s following their exposure to an imposed heat flux of 50 kW/m^2. They ignited in approximately 17 s when exposed to 75 kW/m^2. In the tests conducted with an imposed heat flux of 50 kW/m^2, the fire was re-ignited after several minutes of burning. The tests at 75 kW/m^2 did not require re-ignition. Small beads of jacket material were expelled from the top of the sample holder. Figure 4-50 displays the cable cross section and post-burn debris. Figure 4-51 displays the heat release rate per unit area for the two imposed heat flux values.

Figure 4-50. Cross section of Cable 824 and photograph of burn residue.

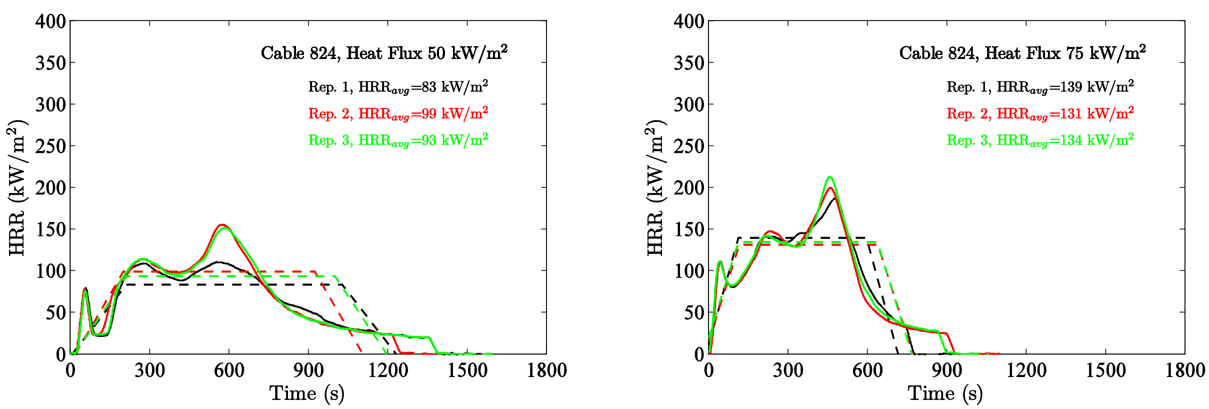


Figure 4-51. Results of cone calorimeter experiments, Cable 824.

4.4 Summary

Table 4-1 presents the results of the cone calorimeter measurements. The Heat Release Rate for each imposed heat flux is an average of three replicate experiments[2]. The Heat of Combustion, the energy released per unit mass of fuel consumed, for each cable is the average of its values at both imposed heat fluxes (six in total). It is calculated by measuring the total oxygen consumed by the fire, Δm_{O_2}, and multiplying it by the amount of energy released per unit mass of oxygen consumed, ΔH_{O_2}, and dividing this product by the total change in mass of the sample, Δm_s:

$$\Delta H = \frac{\Delta m_{O_2}\, \Delta H_{O_2}}{\Delta m_s} \tag{4-4}$$

The assumed value of ΔH_{O_2} is 13.1 MJ/kg (SFPE, 2008). The uncertainty in the Heat of Combustion is due mainly to this assumption. According to Janssens (SFPE, 2008, chapter "Calorimetry"), the value of ΔH_{O_2} for polymeric materials ranges from approximately 12.5 MJ/kg to 13.7 MJ/kg. The value of 13.1 MJ/kg is merely an average over a large number of combustible materials. The exact chemical composition of each cable is unknown, which is why this nominal value is used.

The Residue Fraction is the fraction of the non-metallic material that is not consumed by the fire. Note that Cables 808, 809, 819, and 822 have relatively high residue fractions. Cable 808 is the VITALink® TC/NCC Fire Resistive Control/Power Cable. Cables 809, 819, and 822 each have a substantial amount of silicone rubber and are wrapped in sleeves made of aramid braid or glass fiber. For each of these cables, a white crust formed early in the test creating a barrier that trapped the effluent.

Table 4-2 shows the average heat release rates and residue fractions for the TP and TS cables. The HRR for the TS cables is approximately 35 % lower than that of the TP cables, and the residue fraction of the TS cables is approximately twice that of the TP cables.

Table 4-3 compares the heat release rates of four types of cables that were manufactured in 2006 with comparable cables manufactured in 2010/2011. For example, Cable 800 was manufactured in 2006 while Cable 801 was manufactured in 2011. Both are nominally the same cable with the same part number (Cable 801 has an additional layer of nylon around the insulation material). The newer cables all have lower heat release rates, but there is no discernible property that would explain why.

[2] The relative standard deviation for repeatability (RSD_r) of the heat release rate measurements was 5.6 %.

Table 4-1. Summary of cone calorimeter measurements.

Cable No.	Insulation Material	Jacket Material	Diam. (mm)	Class	Time to Ignition (s) Imposed Heat Flux 50	Time to Ignition (s) Imposed Heat Flux 75	Average Heat Release Rate (kW/m^2) Imposed Heat Flux 50	Average Heat Release Rate (kW/m^2) Imposed Heat Flux 75	Heat of Combustion (MJ/kg)	Residue Fraction
800	PVC		12.4	TP	33	19	154	200	12.3	0.24
801	PVC/Nylon	PVC	12.5	TP	32	15	138	179	13.8	0.26
802	XLPE	CSPE	15.0	TS	42	22	129	155	17.8	0.42
803	XLPE	CSPE	15.0	TS	60	29	105	138	17.8	0.42
804	XLPE	PVC	15.1	Mix	36	20	150	203	14.4	0.33
805	Tefzel®		10.2	TP	241	81	105	147	7.1	0.17
806	XLPE	XLPO	12.2	TS	121	40	143	202	20.4	0.32
807	PE	PVC	15.0	TP	35	20	200	275	17.5	0.18
808	VITA-LINK		19.6	TS	87	46	54	67	24.9	0.61*
809	SR	Aramid Braid	14.5	TS	22	11	114	144	22.0	0.65*
810	PVC/Nylon	PVC	15.2	TP	35	15	130	148	13.4	0.25
811	XLPE	CSPE	16.3	TS	58	21	201	266	22.5	0.22
812	XLPE	CSPE	16.3	TS	51	25	110	139	20.0	0.43
813	XLPE	CSPE	12.7	TS	40	18	152	182	17.5	0.39
814	PVC		11.3	TP	34	15	188	230	12.5	0.05
815	PVC/Nylon	PVC	11.3	TP	32	12	164	201	13.9	0.05
816	XLPE	CSPE	16.7	TS	61	26	93	134	17.7	0.52
817	XLPE	CSPE	7.8	TS	77	31	111	144	17.1	0.49
818	PE	PVC	16.3	TP	64	22	352	525	21.2	0.18
819	SR	Glass Braid	15.0	TS	38	16	75	95	24.1	0.77*
822	SR	Glass Braid	3.7	TS	75	41	69	77	24.0	0.69*
823	XLPE		3.8	TS	94	42	196	259	15.9	0.13
824	EPR	CSPE	5.1	TS	39	17	92	135	17.9	0.43

* Cables 808, 809, 819, and 822 formed a hard crust that partially sealed the opening of the sample holder.

Table 4-2. Average heat release rates and residue fractions for TS and TP cables.

Class	Average Residue Fraction	Average Heat Release Rate (kW/m^2)	
		50	75
TP	0.17	179	238
TS	0.38	117	153

Table 4-3. Heat release rates of similar cables.

Cable No.	Type	Insulation/Jacket	Part No.	Year	Avg. Heat Release Rate (kW/m^2) Imposed Heat Flux (kW/m^2)	
					50	75
800	TP	PVC/PVC	234620	2006	154	200
801		PVC/Nylon/PVC		2011	138	179
814	TP	PVC/PVC	236120	2006	188	230
815		PVC/Nylon/PVC		2011	164	201
802	TS	XLPE/CSPE	C52-0070	2006	129	155
803				2011	105	138
811	TS	XLPE/CSPE	P62-0084	2006	201	266
812				2012	110	139

5 VERTICAL TRAY (VT) EXPERIMENTS

5.1 Overview

The objective of the Vertical Tray (VT) Experiments was to measure the heat release and spread rates of fires originating at the base of a pair of vertical cable trays. Because typical qualification tests involve a single vertical tray of cables in a relatively open configuration, the purpose of these experiments was to assess the effect of multiple trays side-by-side and the effect of a relatively confined vertical shaft on the spread rate.

5.2 Experimental Design

The test rig is shown in Figure 5-1 and Figure 5-2. The apparatus was designed to hold four 0.45 m (18 in) wide ladder back cable trays simultaneously. Two of the trays were mounted inside of a 1.2 m (4 ft) wide, 0.6 m (2 ft) deep, 3.6 m (12 ft) tall vertical shaft. One of these trays was mounted directly to a sheet of concrete board, and the other tray was suspended using steel struts at a distance that varied from 15 cm to 30 cm (6 in to 12 in). Two trays were mounted in a similar fashion outside of the shaft (Figure 5-2). This allowed for replicate experiments to be conducted in which the same tray configuration could be studied inside and outside of the vertical shaft. The shaft was built to test the hypothesis that the heat trapped by the walls might enhance the radiative feedback to the fire; and, thus, increase its spread rate.

The entire assembly was mounted on a steel rack that allowed for it to be rotated 90° to make installation and clean-up of the cables easier and safer. The rotating pins are shown in the top sketch of Figure 5-2. Typically, a fire test of the exterior cables was performed in the morning, followed by the interior cables in the afternoon. The type and quantity of cables was the same – the only difference being the position inside or outside of the vertical shaft.

The heat release rate of the fire was determined via oxygen consumption calorimetry. Details are provided in Volume 1 (McGrattan et al. 2012).

5.3 Procedure

The experiments were conducted in pairs. In the first experiment, two cable trays mounted on the exterior of the vertical shaft were burned. In the second, two trays containing the same amount of cable and mounted the same way inside the shaft were burned. The intent was to determine what effect the shaft might have on the vertical spread rate.

The cables were exposed to a 20 kW sand burner. The burner was 30 cm (1 ft) square and supplied with natural gas. It was positioned at the base of the cable trays. At the beginning of the test series, the burner was positioned against the same wall as that to which one of the trays was mounted. However, in later tests, the burner was positioned midway between the trays. Table 5-1 refers to the **Burner Position** as “Wall” and “Centered”. Details are given in the description of each experiment.

In some experiments, the fire spread upwards for several meters, but did not spread all the way to the top of the 3.6 m (12 ft) trays. In these cases, the HRR of the sand burner was increased to determine if the additional heating would cause further spread. The intent was to establish whether the given configuration would support steady-state flame spread indefinitely, regardless of the exact nature of the ignition source.

5.4 Results

The results of the experiments are summarized in Table 5-1. The primary purpose of the experiments was to measure the vertical flame spread rate. In cases where the fire did not spread to the top of the shaft, an estimate was made of the height to which the fire spread (**Spread Distance** in Table 5-1). In cases where the fire spread to the top of the tray, the spread rate was determined by dividing the length of the tray by the time interval between the time the cables ignited and the time of peak HRR. The uncertainty of this estimate is approximately 5 m/h owing mainly to the determination of the time for the fire to reach the top of the tray. Note that the 3.6 m (12 ft) tray is probably not tall enough to determine if the vertical flame spread rate is truly constant, but it is adequate to assess fire spread rates from one level of a plant to another.

Following the summary table, the individual experiments are discussed and the heat release rate measurements presented. Videos of the experiments are included on the DVD that accompanies this report.

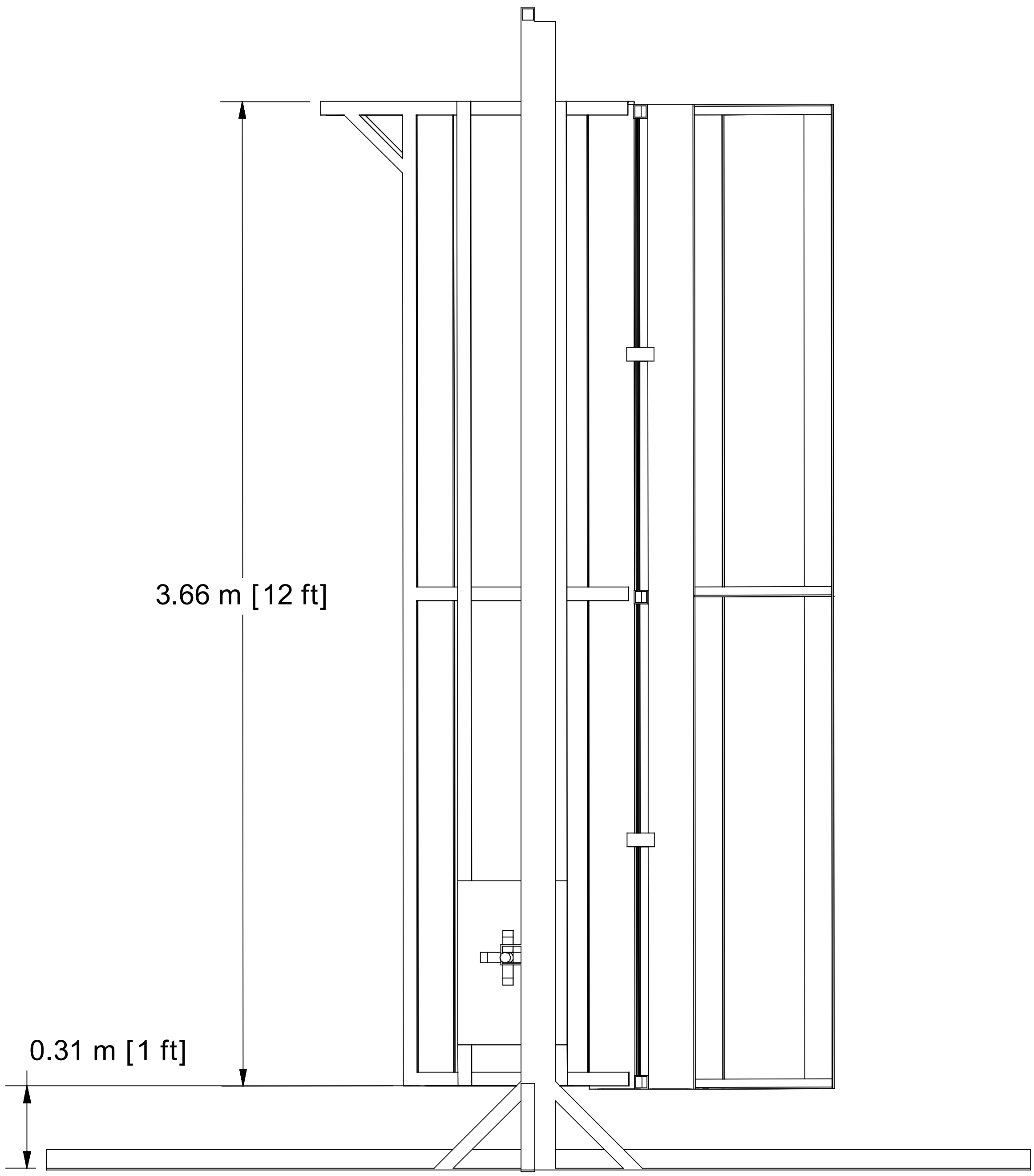


Figure 5-1. Side view of the Vertical Tray Apparatus.

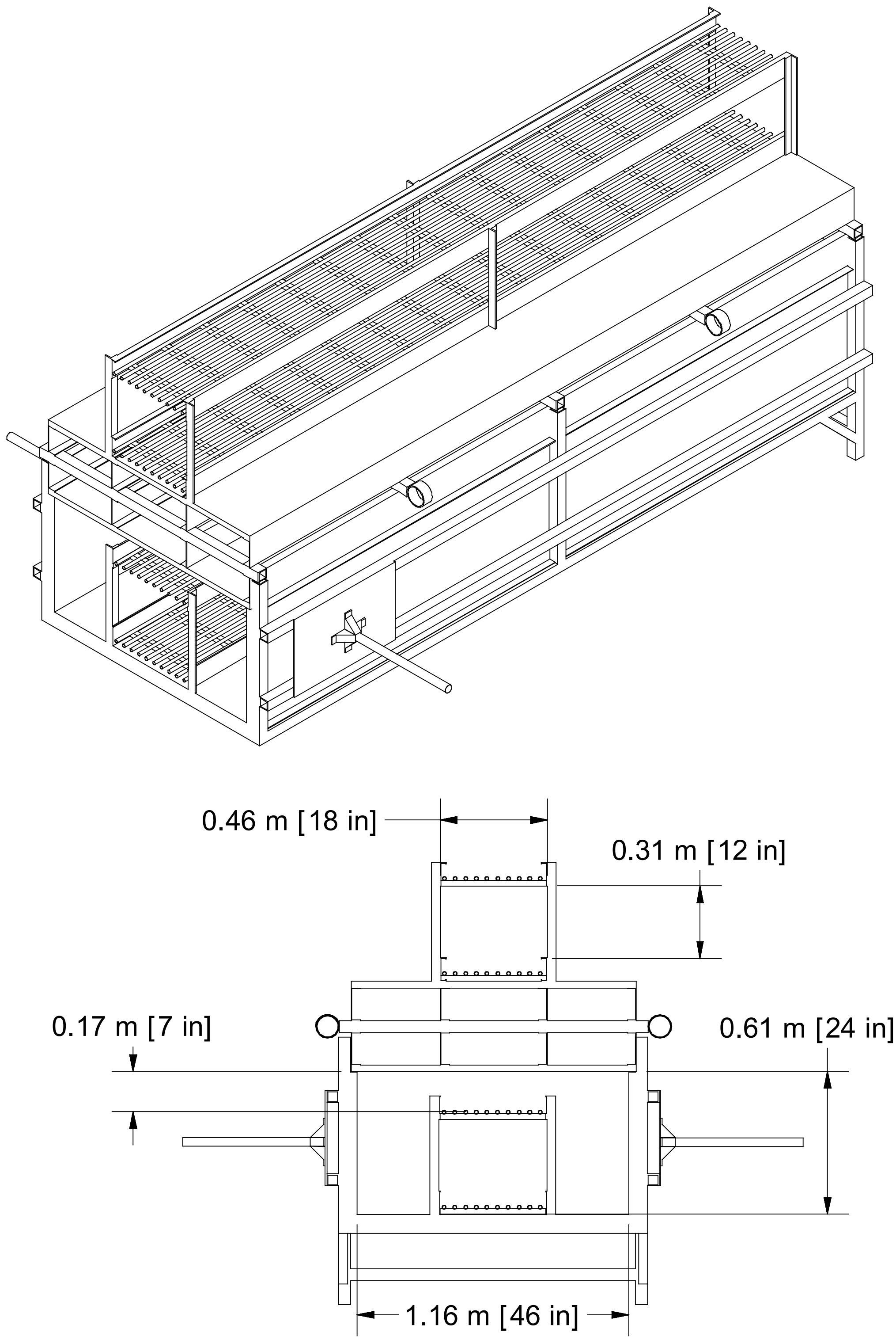


Figure 5-2. Perspective and plan view of the Vertical Tray Apparatus.

Table 5-1. Summary of the Vertical Tray Experiments.

Test No.	Item No.	Cable Type	No. of Cables Per Tray	Percent of NEC Fill Limit*	Horizontal Tray Spacing cm (in)	Interior	Burner Position	Peak HRR kW	Spread Distance m	Spread Rate	
										m/h	ft/min
VT-1	803	TS	20	25	30 (12)	No	Wall	64	1	No Continuous Spread**	
VT-2	803	TS	20	25	30 (12)	Yes	Wall	90	1	No Continuous Spread**	
VT-3	803	TS	40, 20	50, 25	30 (12)	No	Wall	87	2	No Continuous Spread**	
VT-4	800	TP	28	25	30 (12)	No	Wall	77	1	No Continuous Spread**	
VT-5	800	TP	28	25	30 (12)	Yes	Wall	63	0.5	No Continuous Spread**	
VT-6	801	TP	56, 28	50, 25	30 (12)	No	Wall	594	Tray Top	25	1.4
VT-7	801	TP	56, 28	50, 25	30 (12)	Yes	Centered	512	Tray Top	25	1.4
VT-8	802	TS	20	25	15 (6)	No	Centered	140	2	No Continuous Spread**	
VT-9	802	TS	20	25	15 (6)	Yes	Centered	254	2	No Continuous Spread**	
VT-10	815	TP	34	25	15 (6)	No	Centered	977	Tray Top	50	2.7
VT-11	815	TP	34	25	15 (6)	Yes	Centered	1072	Tray Top	50	2.7
VT-12	816	TS	16	25	15 (6)	No	Centered	269	2.5	No Continuous Spread**	
VT-13	816	TS	16	25	15 (6)	Yes	Centered	140	3	No Continuous Spread**	
VT-14	810	TP	19	25	30 (12)	No	Centered	571	Tray Top	25	1.4
VT-15	810	TP	19	25	30 (12)	Yes	Centered	95	2	No Continuous Spread**	
VT-16	812	TS	17	25	30 (12)	No	Centered	224	1.5	No Continuous Spread**	
VT-17	812	TS	17	25	30 (12)	Yes	Centered	412	2	No Continuous Spread**	

* The National Electric Code requires that the total cross sectional area of cables not exceed 40 % of the cross sectional area of tray.
** The fire did not spread to the top of the tray.

5.4.1 Vertical Tray Experiments VT-1, VT-2, and VT-3

For Experiment VT-1, two trays were positioned on the outside of the vertical shaft and separated by 30 cm (12 in). The burner was positioned at the wall, directly under one of the trays. The fire spread approximately 1 m (3 ft), but did not continue to the top. For VT-2, the same tray and burner configuration were replicated inside the vertical shaft, but the results were similar to VT-1. For VT-3, the amount of cable in the primary tray was doubled to 50 % of the NEC limit, but the fire still did not spread to the top. Figure 5-3 displays the HRR for the three experiments. Figure 5-4 displays photographs of VT-1 and VT-3.

For all three experiments, increasing the heat release rate of the burner (solid black line in Figure 5-3) from 20 kW to 50 kW did not cause the fire to spread higher.

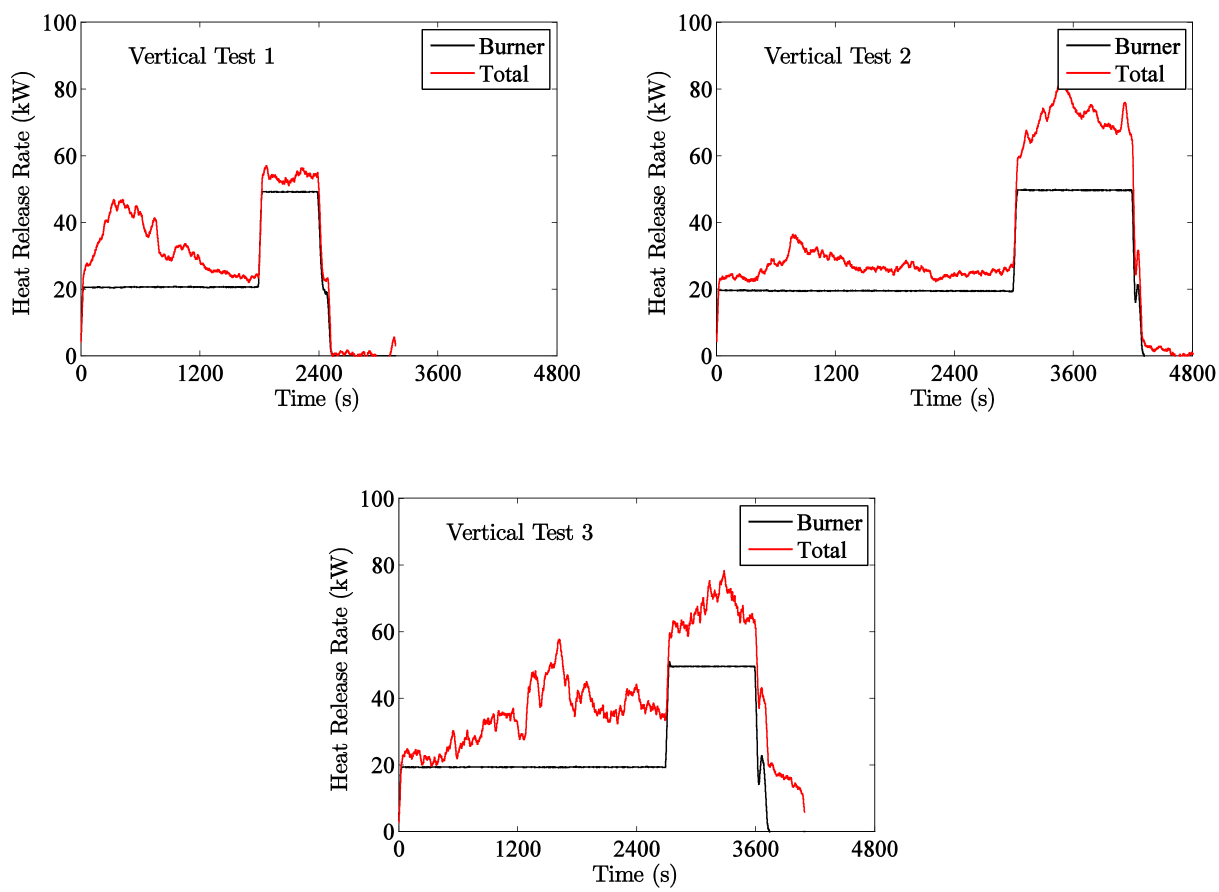


Figure 5-3. Heat release rates for Vertical Tests VT-1, VT-2, and VT-3.

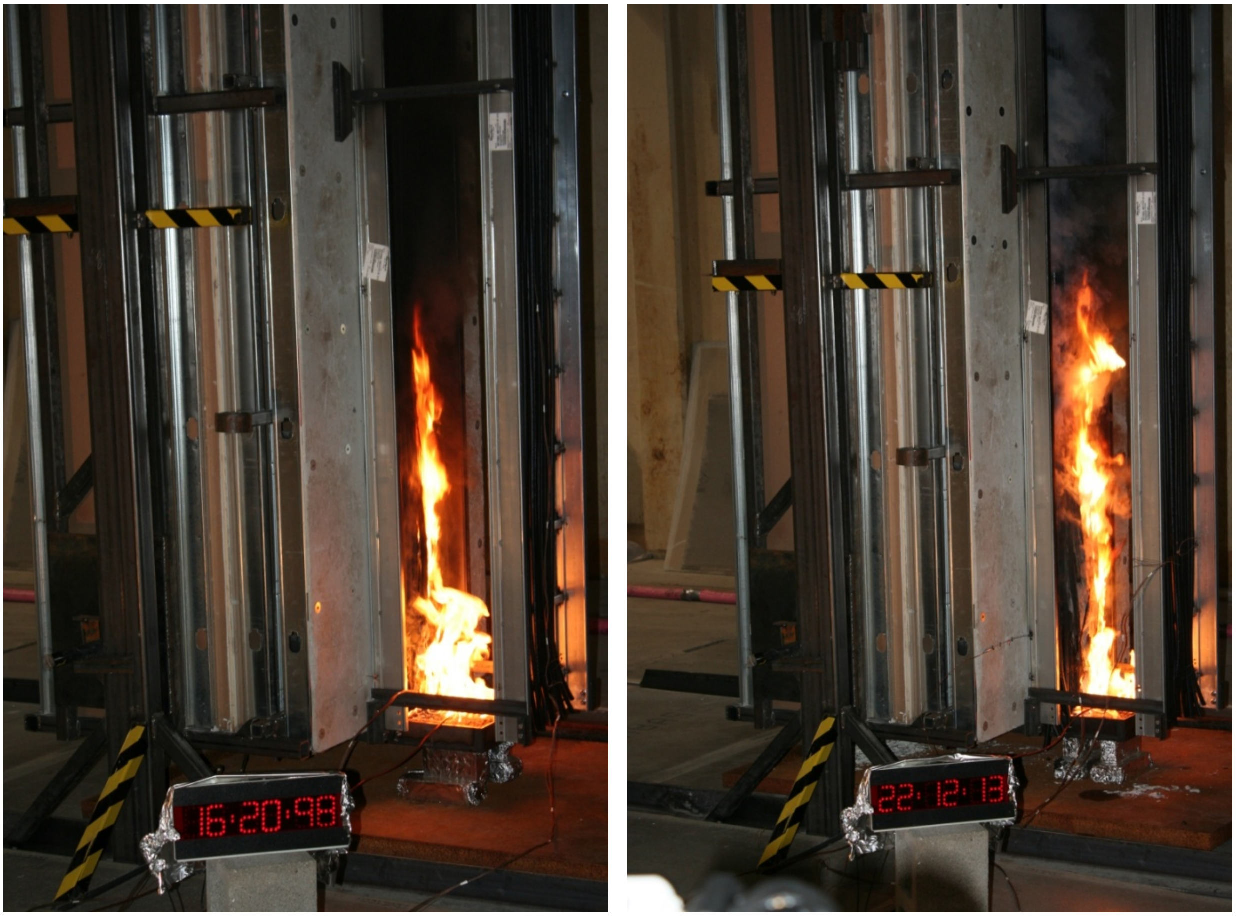


Figure 5-4. Photographs of Vertical Tests VT-1 (left) and VT-3 (right)

5.4.2 Vertical Tray Experiments VT-4 and VT-5

Experiments VT-4 and VT-5 were conducted in a similar fashion to VT-1 and VT-2, except a thermoplastic cable was used instead of a thermoset cable. VT-4 is an exterior test; VT-5 is interior. The results (Figure 5-5) were similar; the fire only spread on the primary tray to a height of approximately 1 m (3 ft). Figure 5-6 displays a photograph of VT-4.

For both experiments, increasing the heat release rate of the burner (solid black line in Figure 5-5) from 20 kW to 50 kW did not cause the fire to spread higher.

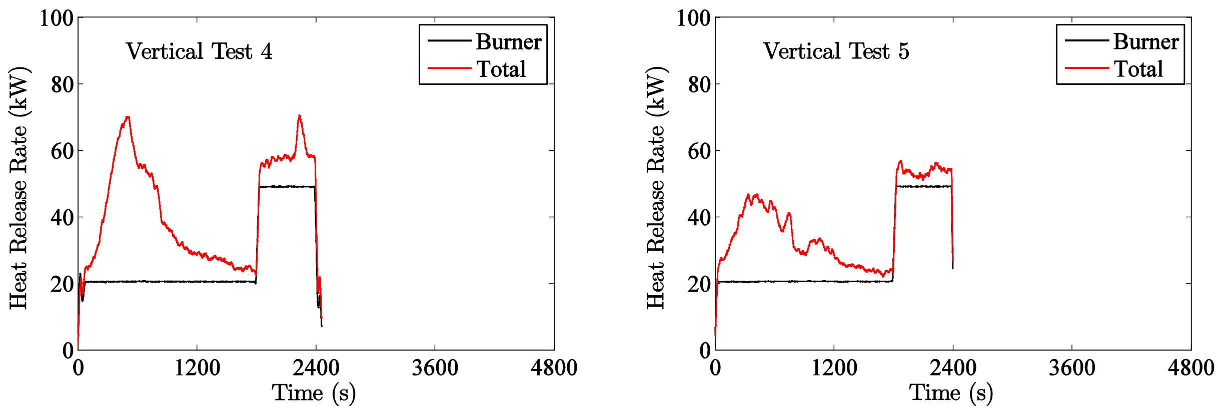


Figure 5-5. Heat release rates for Vertical Tests VT-4 and VT-5.

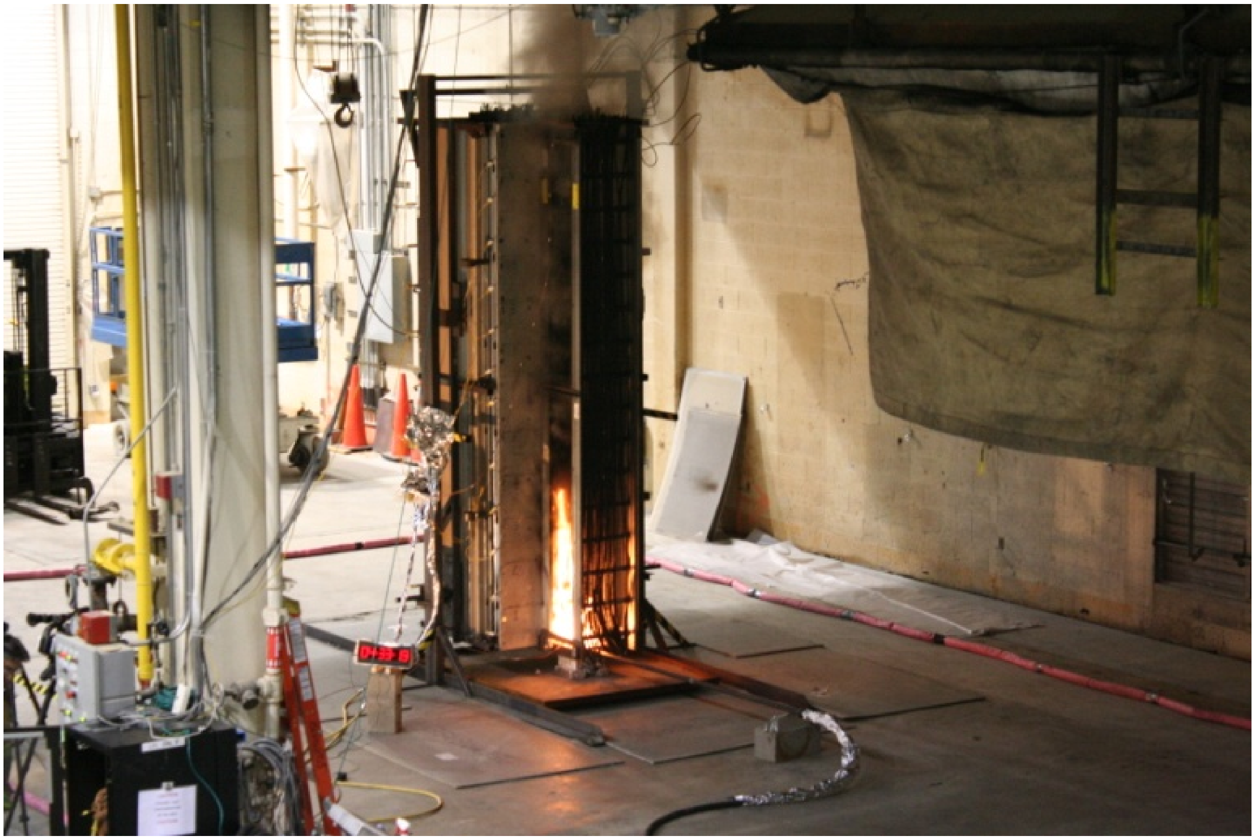


Figure 5-6. Photograph of Vertical Test VT-4.

5.4.3 Vertical Tray Experiments VT-6 and VT-7

The set-up of experiments VT-6 (exterior) and VT-7 (interior) was similar to VT-4 and VT-5, only that the number of thermoplastic cables was doubled to 50 % of the NEC limit. In both experiments, the 20 kW burner ignited the cables in the primary tray, and the fire spread approximately 1.5 m high and stopped. However, after the burner was increased to 50 kW, the cables in the secondary tray ignited, and the fire spread fairly rapidly to the top. Figure 5-7 shows the HRR of VT-6 and VT-7, and Figure 5-8 displays a few photographs of VT-6.

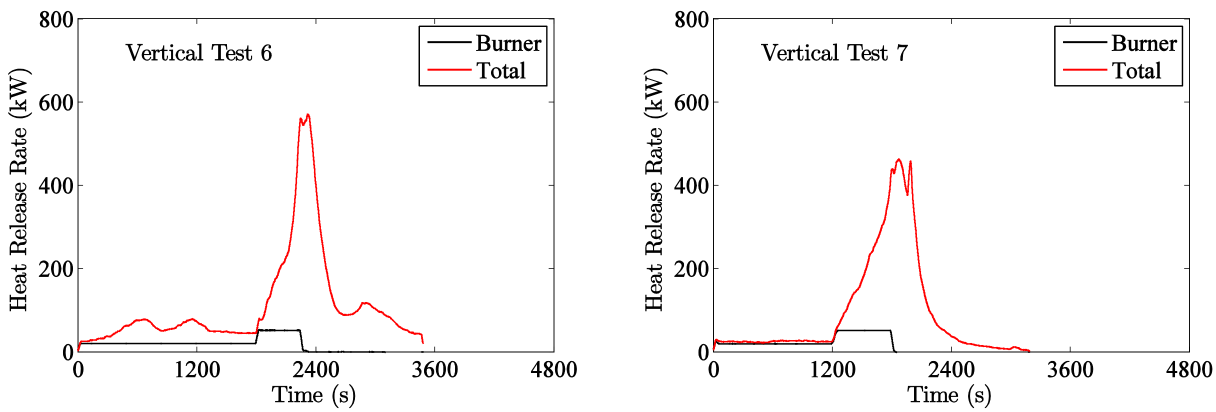


Figure 5-7. Heat release rates for Vertical Tests VT-6 and VT-7.

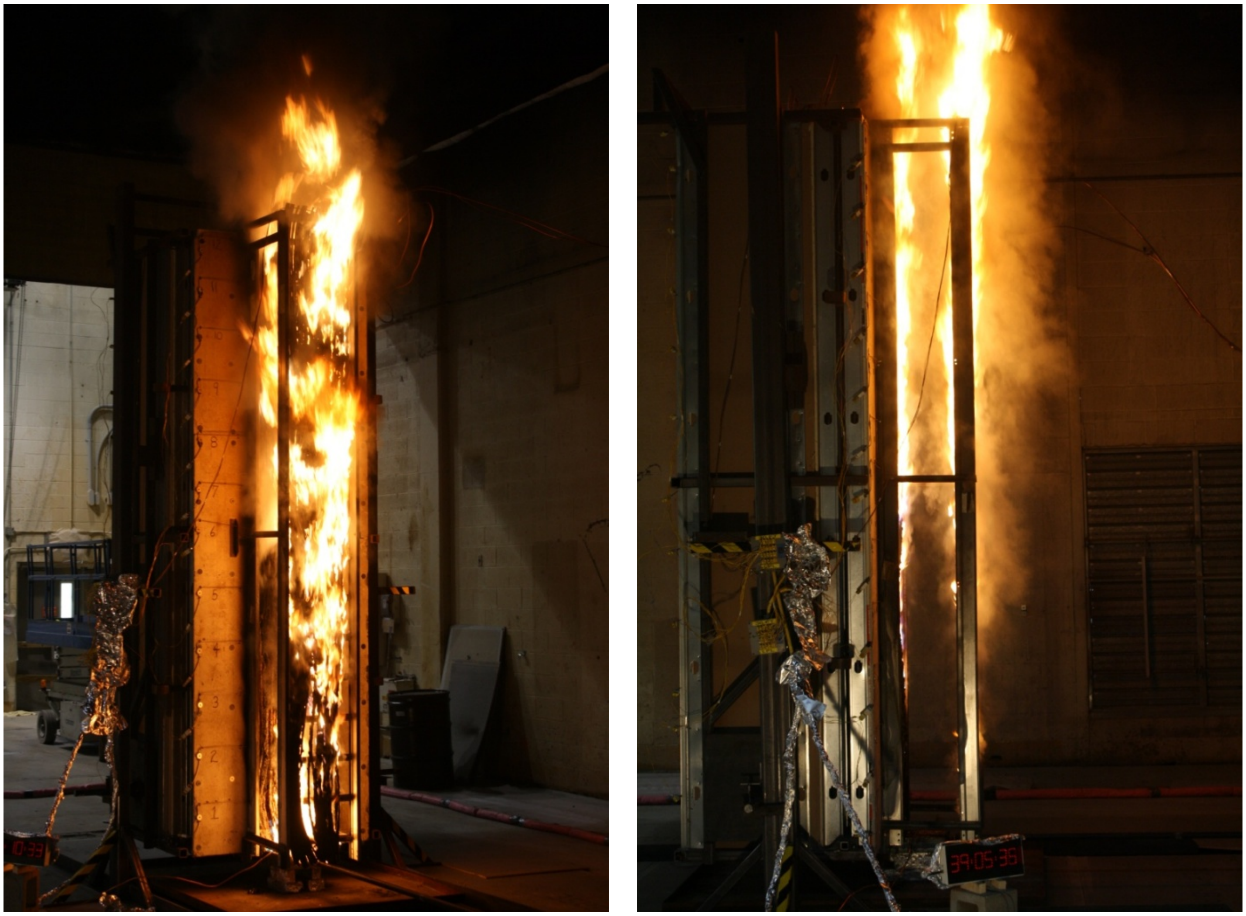


Figure 5-8. Photographs of Vertical Test VT-6.

5.4.4 Vertical Tray Experiments VT-8 and VT-9

For these experiments, the tray spacing was reduced from 30 cm (1 ft) to 15 cm (6 in). It was observed in the previous experiments that vertical spread was achieved by the ignition of both trays; thus, it was decided to move the trays closer together to ensure that both trays would ignite. However, the fires in experiments VT-8 (exterior) and VT-9 (interior) did not spread to the top, even though both trays were ignited by the burner. Increasing the HRR of the burner in Test 9 did not cause the fire to spread higher.

The HRR for both experiments is shown in Figure 5-9. A few photographs of VT-8 are shown in Figure 5-10.

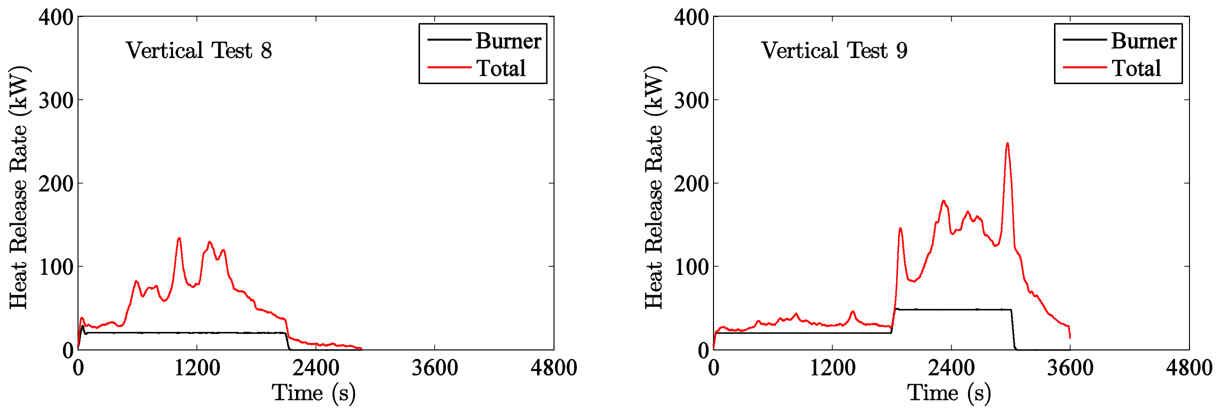
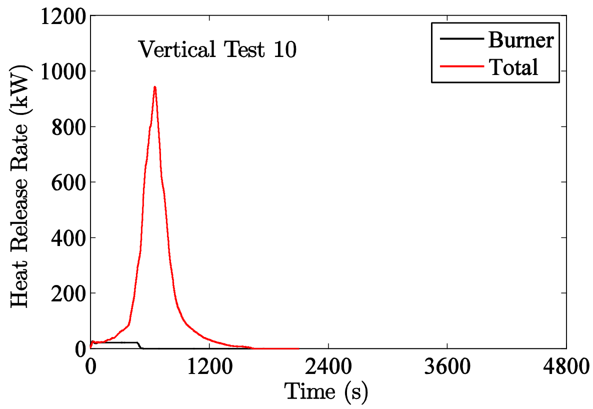


Figure 5-9. Heat release rates for Vertical Tests VT-8 and VT-9.

Figure 5-10. Photographs of Vertical Test VT-8.

5.4.5 Vertical Tray Experiments VT-10 and VT-11

Experiments VT-10 (exterior) and VT-11 (interior) were similar to the two previous experiments, except that thermoplastic cables were used in lieu of thermosets. Both trays of cable ignited readily with the 20 kW burner and both fires spread rapidly to the top of the tray. The HRR for both experiments is shown in Figure 5-11, and photographs of VT-10 are shown in Figure 5-12.



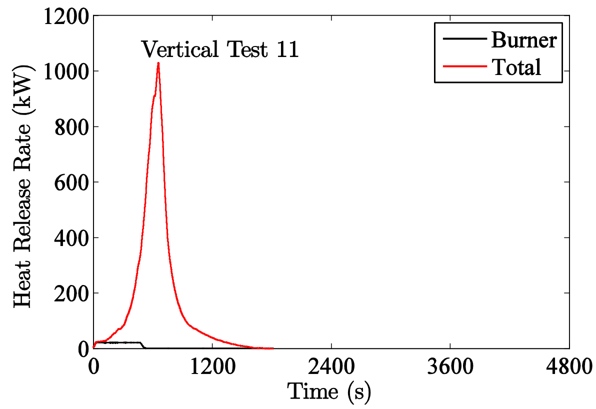


Figure 5-11. Heat release rates for Vertical Tests VT-10 and VT-11.

Figure 5-12. Photographs of Vertical Test VT-10.

5.4.6 Vertical Tray Experiments VT-12 and VT-13

VT-12 (exterior) and VT-13 (interior) were similar in design to VT-8 and VT-9. The trays were loaded with thermoset cables to 25 % of the NEC limit. The 15 cm (6 in) tray spacing ensured that both trays ignited, and the reciprocating heat flux did cause the fire to spread higher and produce more heat than the earlier experiments with a 30 cm (1 ft) tray spacing. However, the fire still could not be sustained long enough to spread to the top, and eventually the lower section of the trays simply ran out of fuel. The HRR curves are shown in Figure 5-13. The photographs in Figure 5-14 shows that flames extended to the top of the tray, but the actual cable damage was limited to approximately 2.5 m (8 ft).

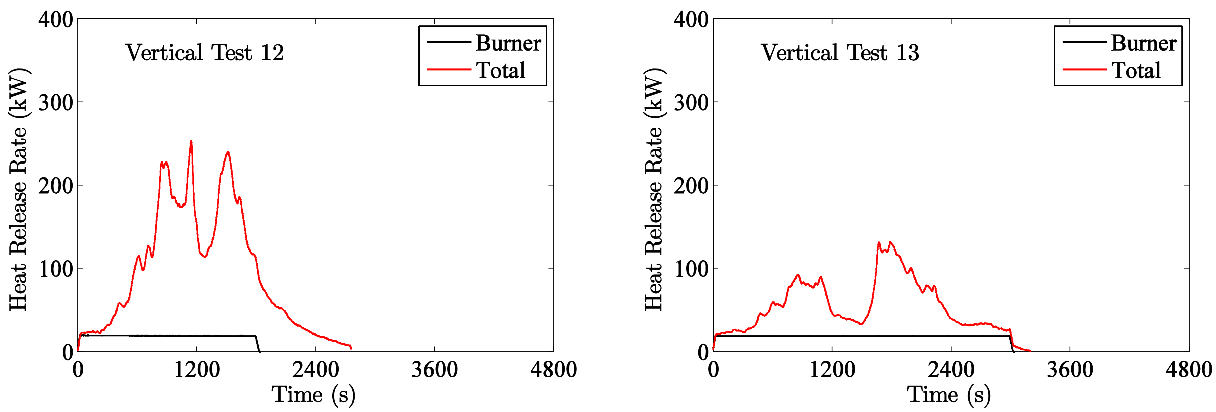


Figure 5-13. Heat release rates for Vertical Tests VT-12 and VT-13.

Figure 5-14. Photographs of Vertical Test VT-12.

5.4.7 Vertical Tray Experiments VT-14 and VT-15

In these experiments, the tray spacing was returned to 30 cm (1 ft) and the burner was centered between the two. Both trays were loaded with thermoplastic cables at 25 % of the NEC limit. For VT-14, the exterior test, the 20 kW fire did not ignite either tray, but when the HRR was increased to 50 kW, both trays ignited and the fire spread to the top. For the interior test, VT-15, the fire did not spread to the top. The HRR is shown in Figure 5-15, and a few photographs of VT-14 are shown in Figure 5-16.

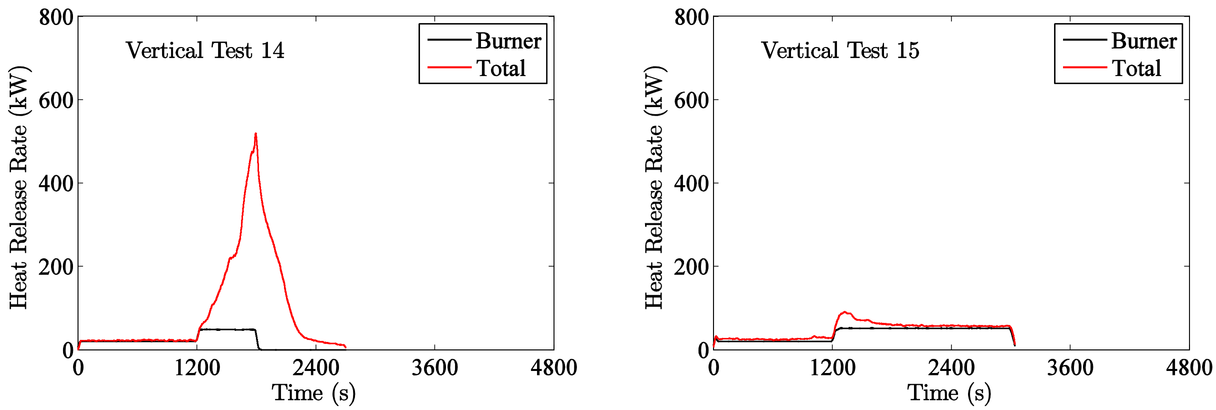
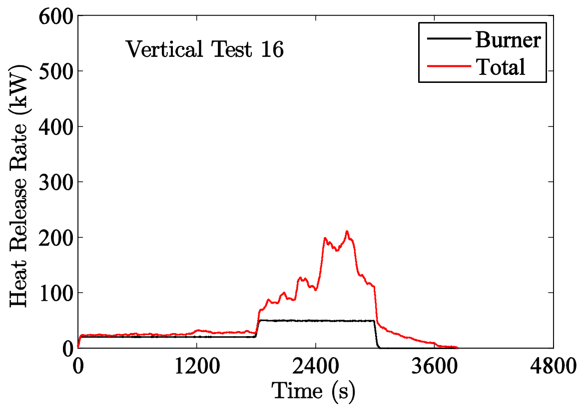


Figure 5-15. Heat release rates for Vertical Tests VT-14 and VT-15.

Figure 5-16. Photographs of Vertical Test VT-14.

5.4.8 Vertical Tray Experiments VT-16 and VT-17

For VT-16 (exterior) and VT-17 (interior), the trays were loaded with thermoset cables at 25 % of the NEC limit. In neither test did the fire spread significantly. For VT-17, the initial burner HRR was 50 kW, which was increased to 100 kW, but the fire did not spread to the top. The HRR curves are shown in Figure 5-17 and a few photographs of VT-16 are shown in Figure 5-18.



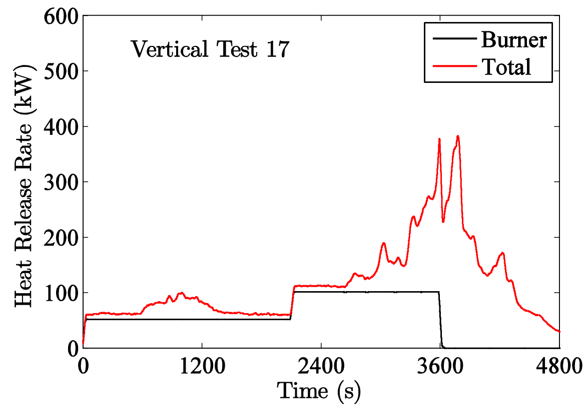


Figure 5-17. Heat release rates for Vertical Tests VT-16 and VT-17.

Figure 5-18. Photographs of Vertical Test VT-16.

5.5 Summary

All of the cables burned in the vertical experiments reportedly passed the IEEE 383 Vertical Tray Flame Test, which consists of a 20 kW, 20 min heat exposure and a single 2.4 m (8 ft) vertical tray. The experiments described in this chapter were not intended to replicate IEEE 383. In fact, the primary intent was to determine if either multiple trays or an enclosure would increase the likelihood of spread. The results of the experiments confirm that a single tray of IEEE 383 qualified cable is unlikely to spread a fire significantly further than its ignition point. However, it has been demonstrated that two trays of thermoplastic cables, positioned within 30 cm (1 ft) of each other, can spread upward, potentially without limit.

The 1.2 m by 0.6 m (4 ft by 2 ft) vertical shaft did not increase the spread or burning rates of the cables in any of the experiments. The shaft was built to test the hypothesis that the heat trapped by the walls might enhance the radiative feedback to the fire and thus increase its spread rate. If anything, the shaft potentially limited the air supply to the burning cables, inhibiting its growth and spread.

6 CORRIDOR EXPERIMENTS

6.1 Overview

The objective of the Corridor Experiments was to measure the heat release and spread rates of fires within horizontal cable trays positioned near the ceiling of a relatively long enclosure. During Phase 1 of CHRISTIFIRE, a series of experiments was conducted to measure the heat release and spread rates of fires burning within stacks of horizontal cable trays in the open; that is, outside of an enclosure.

6.2 Experimental Design

The corridor (Figure 6-1) was nominally 7.3 m (24 ft) long, 2.3 m (7.7 ft) wide, and 2.4 m (8 ft) high. These dimensions were chosen for ease of construction because typical wall materials in the U.S. are sold in 8 ft by 4 ft sheets. The corridor was framed with wood studs and lined with one layer of 1.6 cm (5/8 in) gypsum board. An extra layer of concrete board with the same nominal thickness was added on top of the gypsum board to provide a thermal boundary similar to the concrete walls of a typical power plant. Both ends of the corridor were open; thus, the fire scenarios should be considered well-ventilated. No experiments were conducted in an under-ventilated compartment.

The cables were arranged in ladder back trays with 10 cm (4 in) rails that were mounted on a set of two rolling steel racks, each approximately 3.6 m (12 ft) long. The uppermost trays were 0.3 m (1 ft) from the ceiling. The second and third tiers were separated (rail top to rail top) by the same amount. The distance between the wall and the trays nearest the wall was approximately 5 cm (2 in). The uppermost tray nearest the wall is designated Position 1. The trays below it are Positions 2 and 3. The uppermost tray on the opposite side of the rack is designated Position 4. No trays were positioned below it.

The racks were rolled in and out of the compartment via steel rails placed on top of a single layer of concrete board lying atop the concrete floor of the testing laboratory. The burner was positioned approximately 20 cm (8 in) below the lowest tray containing cables, and approximately 40 cm (16 in) from the corridor entrance.

A steel pipe was positioned along the centerline of the top of the rack to serve as a dry pipe sprinkler system. This system was added for safety reasons. During portions of Test 5 and Test 9, the sprinkler system was activated because the fire threatened the integrity of the compartment.

A 0.3 m (1 ft) deep plenum space was created to trap some of the heat within the corridor. A 0.3 m (1 ft) square sand burner was mounted on a cart and positioned at one end of the corridor below the lowermost tray containing cables.

6.3 Results

A summary of the Corridor Experiments is provided in Table 6-1. Videos of the experiments are included on the DVD that accompanies this report.

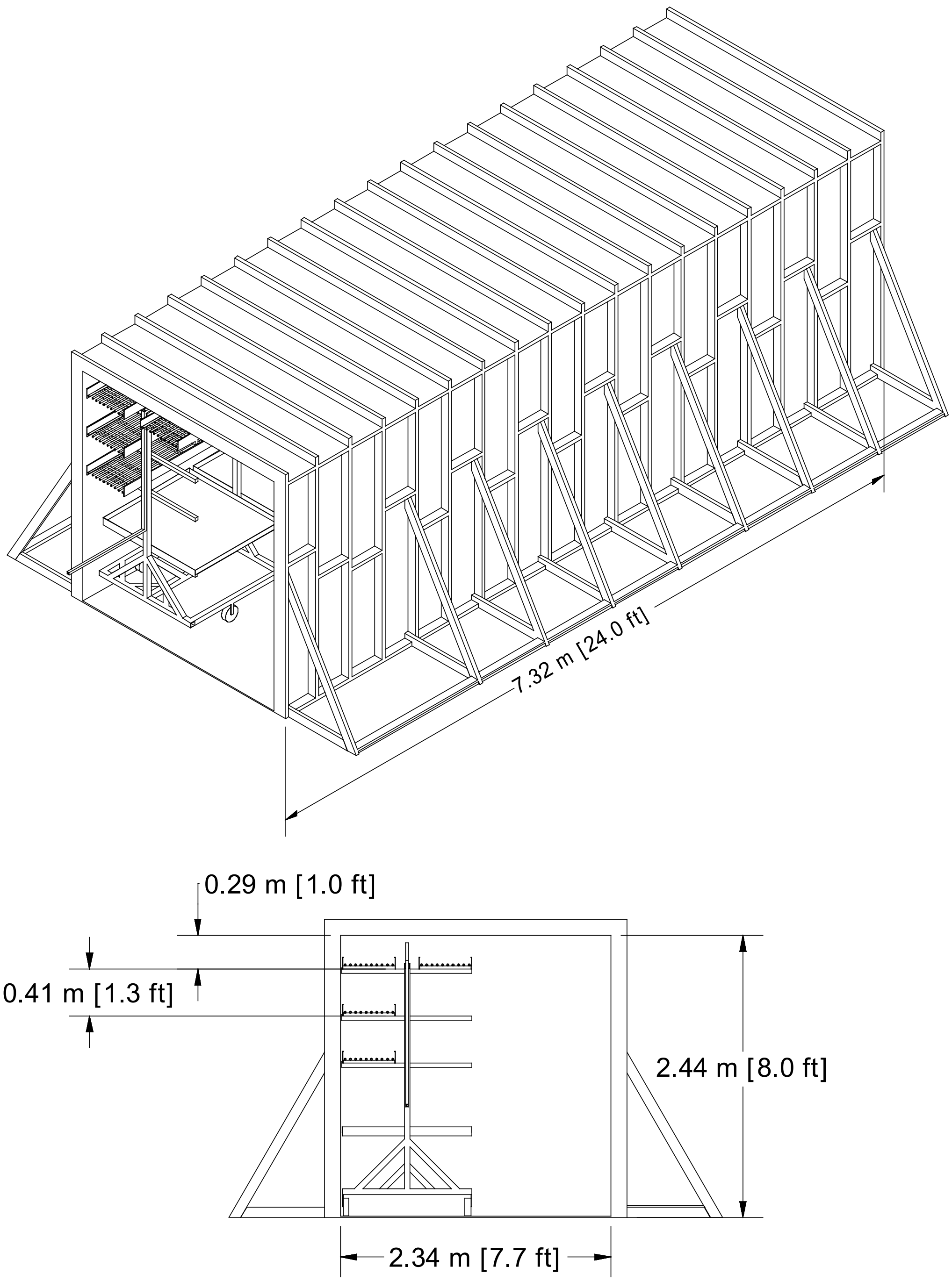


Figure 6-1. Corridor assembly.

Table 6-1. Summary of Corridor Experiments.

Test No.	Cable No.	Cable Type	No. of Trays	Cables per Tray	Load (%)	HGL Temp. (°C)	Peak HRR (kW)	Spread Rate (m/h)	Notes
HW-0	800	TP	1	56	50	100-200	204	--	Single tray extending only halfway down corridor. The fire did not reach the end of the tray.
HW-1	800	TP	2	56	50	200-250	432	Tray 1: 11 Tray 2: 7	Upper tray fire spreads in 40 min; lower tray 60 min.
HW-2	802 803	TS	2	40	50	200-300	602	Tray 1: 9 Tray 2: 7	30 #802; 10 #803 per tray
HW-3	802	TS	2	20	25	150-250	338	--	Upper tray fire spreads just past halfway mark. No spread in lower.
HW-4	800	TP	2	28	25	300	450	Tray 1: 21 Tray 2: --	Fire in lower tray spreads only 2 m
HW-5	815 802	TP TS	2 1	66 19	49 24	400+	1245	Tray 1: 18 Tray 2: --	Extra target tray in Position 4. Water suppression required. No spread in lower tray.
HW-6	816	TS	2	32	45	350	755	Tray 1: 17 Tray 2: 13	Fire in lower tray ignited by falling embers from upper tray.
HW-7	812	TS	3	10	21	350	605	Tray 1: 10 Tray 2: 9	Upper tray fire spreads in 44 min; second tray 50 min. No spread in lowest tray.
HW-8	810	TP	3	20	26	400+	837	Tray 1: 36 Tray 2: 31	Upper tray fire spreads in 12 min; second tray 14 min. No spread in lowest tray.
HW-9	824	TS	2	103	31	400+	1170	Tray 1: 31 Tray 2: 22	Water suppression required.
HW-10	803 802	TS	2	40	50	350	521	Tray 1: 14 Tray 2: 7	No soffit Tray 1 contained 40 #803 cables Tray 2 contained 40 #802 cables

6.3.1 Corridor Test HW-0

This experiment was intended as a shakedown test, which is why it is labeled "Test HW-0." It involved only a single tray of a thermoplastic control cable (#800). The cable was placed in only a single 3.6 m (12 ft) long tray. The fire spread a distance of approximately 3 m (10 ft), just short of the end of the cable. Based on this result, all subsequent experiments were performed with at least two trays. The HRR and near-ceiling temperature measurements are shown in Figure 6-2. Photographs are shown in Figure 6-3 and Figure 6-4.

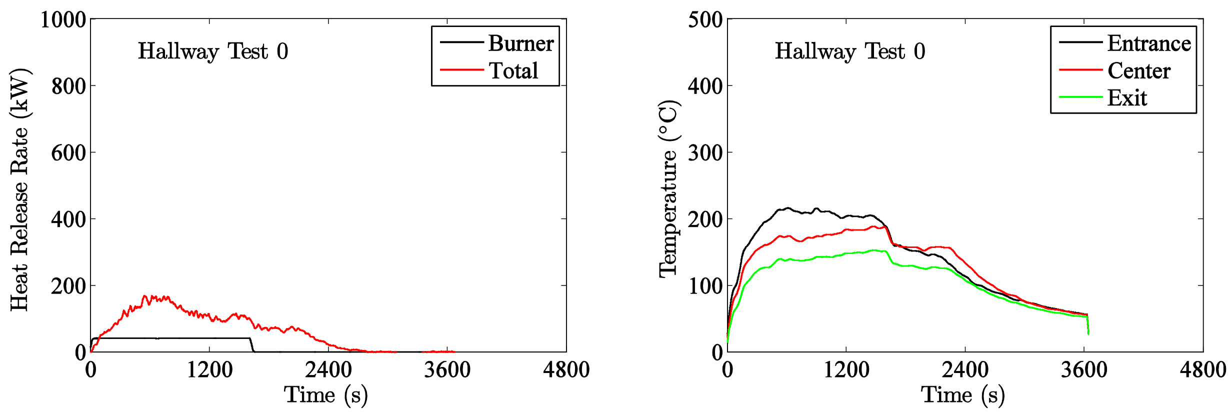


Figure 6-2. Heat release rate and HGL temperatures of Corridor Test HW-0.

Figure 6-3. Photograph of Test HW-0 a few minutes after ignition.

Figure 6-4. Photograph of Test HW-0. Shown are the burner and the lower tray.

6.3.2 Corridor Test HW-1

This experiment involved two trays containing a 50 % load of thermoplastic control cable. The fire in the upper tray spread to the end of the corridor in 40 min, followed by the fire in the lower tray in 60 min. The burner was extinguished after 25 min. The last flames were observed at approximately 66 min. The HRR and near-ceiling temperature measurements are shown in Figure 6-5. Photographs are shown in Figure 6-6 and Figure 6-7.

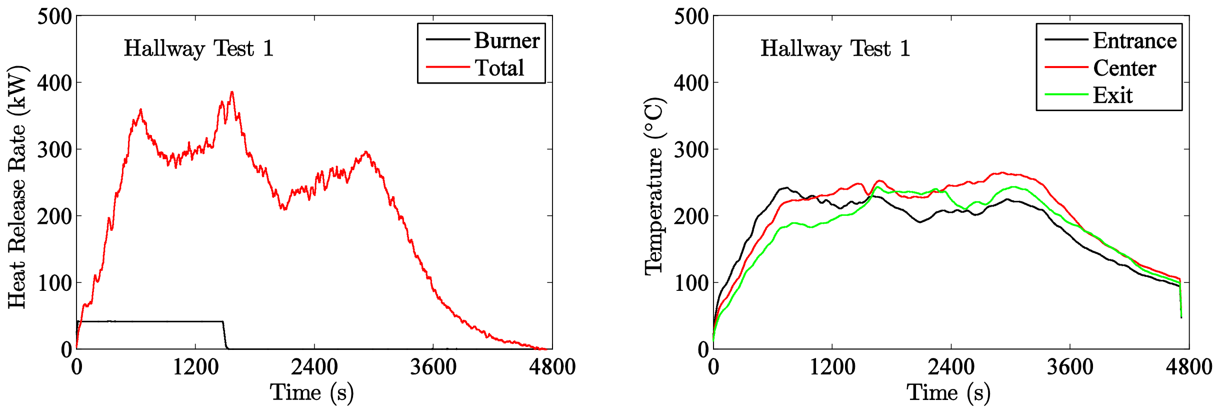


Figure 6-5. Heat release rate and HGL temperatures of Corridor Test HW-1.

Figure 6-6. Photograph of Test HW-1 from the burner side of the corridor.

Figure 6-7. Photograph of Test HW-1 from the exit side of the corridor.

6.3.3 Corridor Test HW-2

This experiment involved two trays containing a 50 % load of thermoset control cable. The fire in the upper tray spread to the end of the corridor in 51 min, followed by the fire in the lower tray in 61 min. The burner was extinguished after 38 min. The last flames were observed at approximately 87 min. The HRR and near-ceiling temperature measurements are shown in Figure 6-8. Photographs are shown in Figure 6-9 and Figure 6-10.

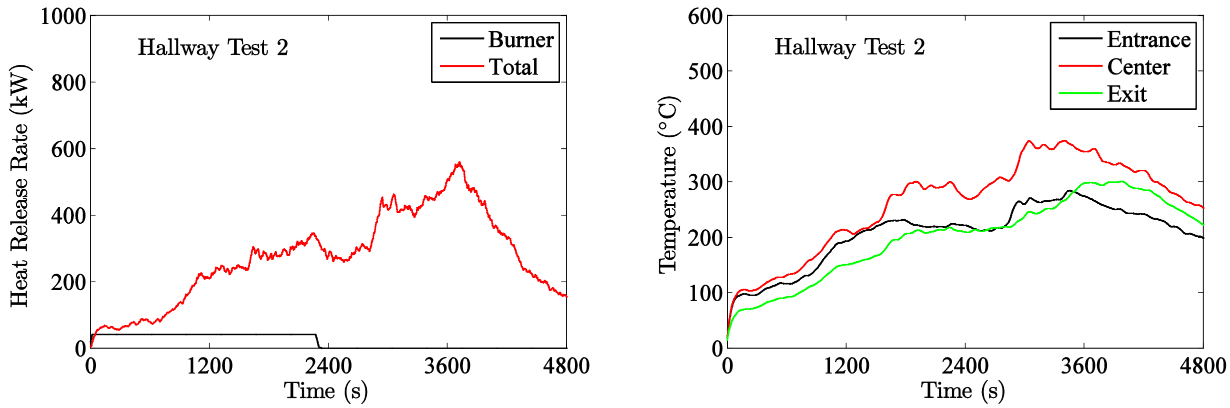


Figure 6-8. Heat release rate and HGL temperatures of Corridor Test HW-2.

Figure 6-9. Photograph of Test HW-2, from the burner side.

Figure 6-10. Photograph of Test HW-2, from the exit side.

6.3.4 Corridor Test HW-3

This experiment was similar to HW-2, except that the cable loading was reduced to 25 %. As in HW-2, the burner was extinguished in 38 min, but the fires did not spread to the end of the corridor. The extent of the spread in the upper tray was approximately 4.5 m (15 ft). The fire in the lower tray did not spread beyond the vicinity of the burner. The HRR and near-ceiling temperature measurements are shown in Figure 6-11. Photographs are shown in Figure 6-12 and Figure 6-13.

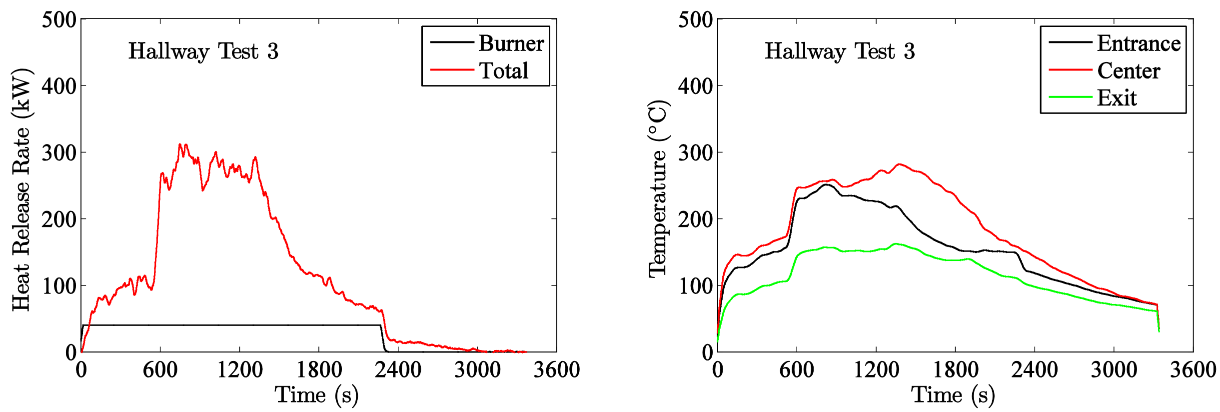


Figure 6-11. Heat release rate and HGL temperatures of Corridor Test HW-3.

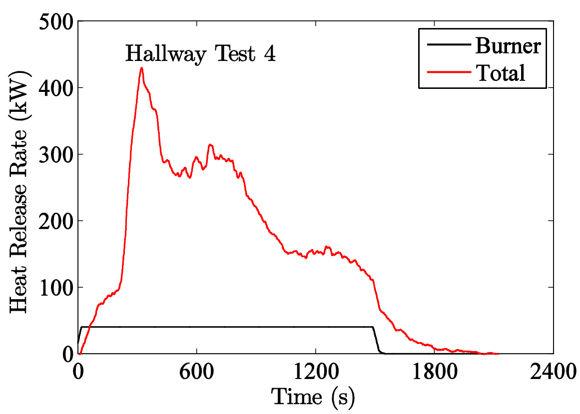
Figure 6-12. Photograph of corridor entrance, HW-3.

Figure 6-13. Photograph of corridor entrance, HW-3.

6.3.5 Corridor Test HW-4

This experiment was similar to HW-1, except it involved two trays of relatively lightly loaded (25 %) thermoplastic control cable. The fire in the upper tray spread to the end of the corridor in 21 min. The burner was extinguished at 25 min, but the fire in the second tray did not spread beyond approximately 2 m (6 ft) from the corridor entrance. The cable jackets in the second tray exhibited some melting, but the fire did not spread across it. The HRR and near-ceiling temperature measurements are shown in Figure 6-14. Photographs are shown in Figure 6-15 and Figure 6-16.

It is interesting to note that the fire in this experiment spread down the corridor at a rate that was approximately twice that of HW-1, where the trays contained twice as many cables. The peak HRR in HW-4 was slightly greater than that of HW-1, but the fire did not last as long.



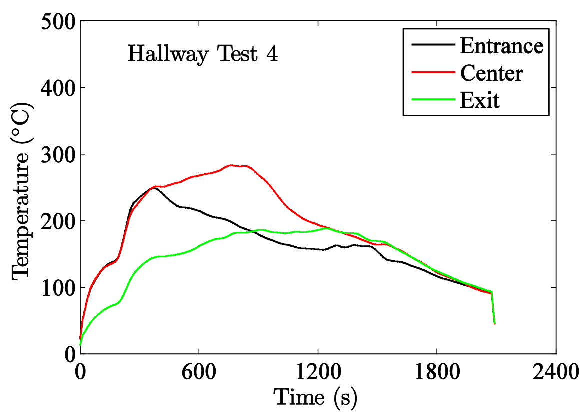


Figure 6-14. Heat release rate and HGL temperatures of Corridor Test HW-4.

Figure 6-15. Photograph of corridor entrance, HW-4.

Figure 6-16. Photograph of corridor exit, HW-4.

6.3.6 Corridor Test HW-5

This experiment involved two trays in Positions 1 and 2 containing a thermoplastic instrumentation cable. The loading was 49 %. A third tray with a 24 % load of thermoset control cable was placed at Position 4. The HRR and near-ceiling temperature measurements are shown in Figure 6-17. Photographs are shown in Figure 6-18 and Figure 6-19.

Because the HRR and temperature increased at a relatively high rate during the early stages of the fire, a decision was made to activate the sprinkler system within the corridor at approximately 19 min past ignition for 1 min, 30 s. The HRR decreased by over 50 % during the period of water application. The decision to suppress the fire was made to prevent excessive damage to the test compartment.

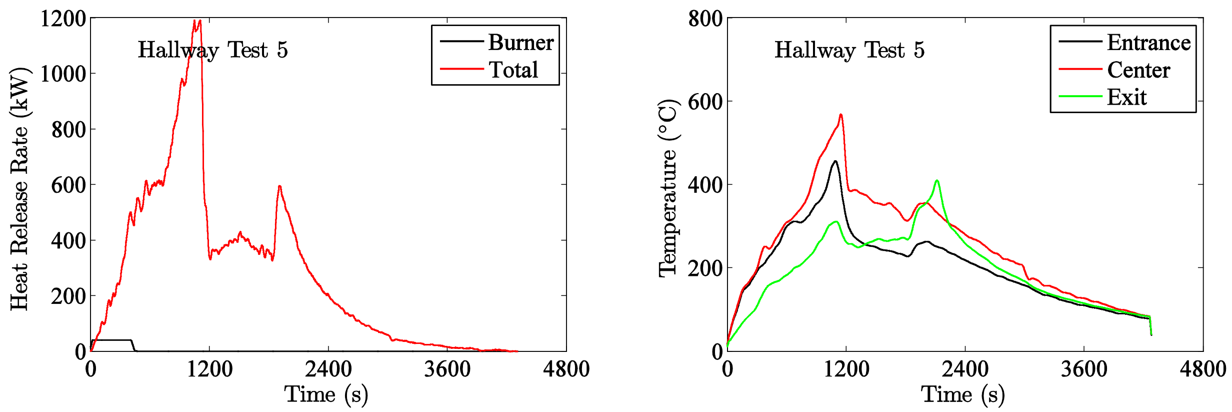


Figure 6-17. Heat release rate and HGL temperatures of Corridor Test HW-5.

Figure 6-18. Photograph of corridor entrance, HW-5.

Figure 6-19. Photograph of corridor exit, HW-5.

6.3.7 Corridor Test HW-6

This experiment involved two trays containing thermoset (XLPE/CSPE, 4/C) cables filled to 45 % of the NEC limit. The fire in the upper tray reached the end of the corridor in 26 min, and the fire in the lower tray reached the end in 35 min. However, the fire in the lower tray did not spread continuously from one end of the corridor to the other, but rather was ignited at various points by flaming debris from the cables overhead. This caused the lower tray to burn along its entire length simultaneously, and consequently the HRR increased fairly rapidly after approximately 30 min. To prevent excessive damage to the compartment, it was decided to activate the suppression system at 38 min. The HRR and near-ceiling temperature measurements are shown in Figure 6-20. Photographs are shown in Figure 6-21 and Figure 6-22.

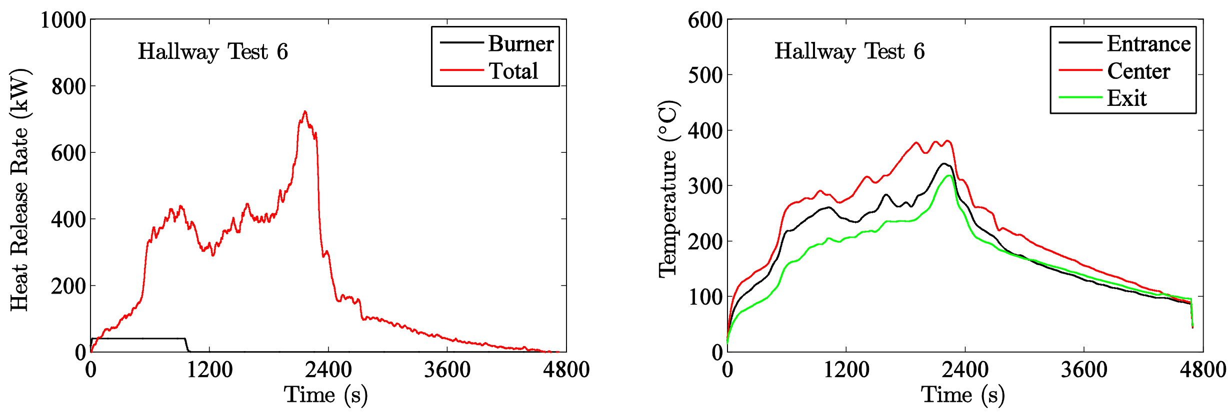


Figure 6-20. Heat release rate and HGL temperatures of Corridor Test HW-6.

Figure 6-21. Photograph of corridor entrance, HW-6.

Figure 6-22. Flames at the end of the corridor, HW-6.

6.3.8 Corridor Test HW-7

This experiment involved three trays containing a fairly light load (21 % NEC limit) of thermoset cables (XLPE/CSPE, 3/C). The 40 kW burner ignited the cables in the bottom tray, but the fire did not spread beyond the vicinity of the burner, and the HGL temperature in the corridor did not increase above 100 °C. After 30 min, it was decided to increase the burner HRR to 100 kW, causing the HGL temperature to rise and the fire to spread. The burner was extinguished at 37 min, and the fire in the uppermost tray reached the end of the corridor at 44 min. The fire in the second tray reached the end at 50 min. The cables in the third (lowest) tray were relatively undamaged except in the vicinity of the burner. The HRR and near-ceiling temperature measurements are shown in Figure 6-23. Photographs are shown in Figure 6-24 and Figure 6-25.

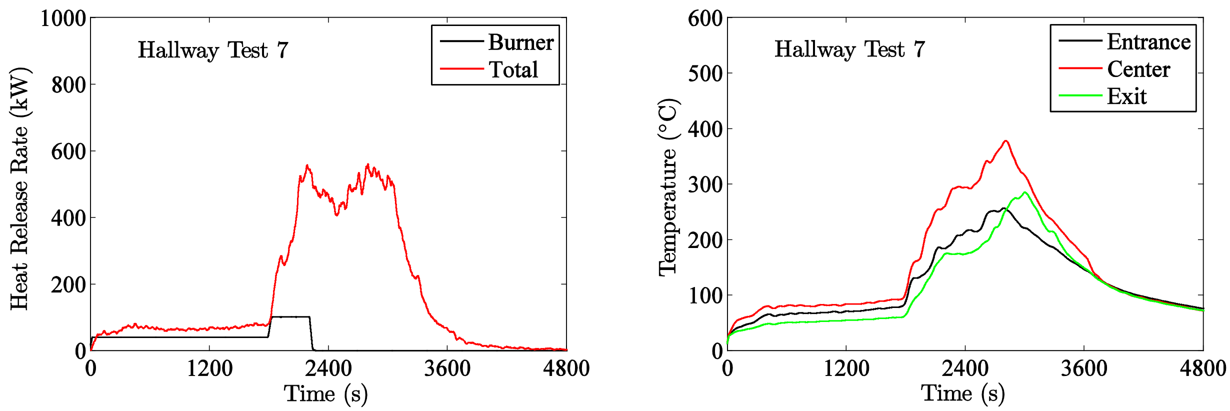


Figure 6-23. Heat release rate and HGL temperatures of Corridor Test HW-7.

Figure 6-24. Photograph of corridor entrance, HW-7.

Figure 6-25. Photograph of corridor exit, HW-7.

6.3.9 Corridor Test HW-8

This experiment involved three trays containing a fairly light load (26 % NEC limit) of thermoplastic cables (PVC/Nylon/PVC, 3/C). The fire in the uppermost tray reached the end of the corridor in approximately 12 min, followed a short time later by the fire in the second tray at 14 min. The HRR and near-ceiling temperature measurements are shown in Figure 6-26. Photographs are shown in Figure 6-27 and Figure 6-28.

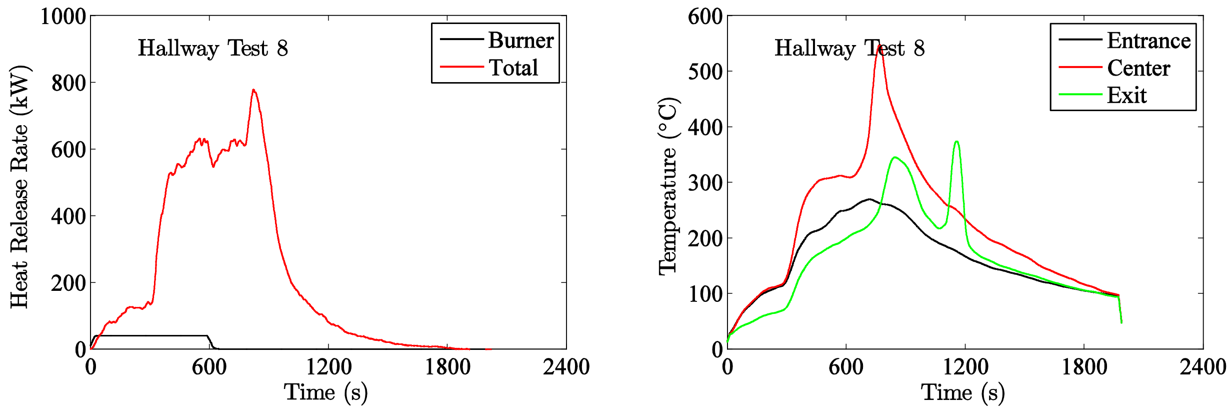


Figure 6-26. Heat release rate and HGL temperatures of Corridor Test HW-8.

Figure 6-27. Photograph of corridor entrance, HW-8.

Figure 6-28. Photograph of corridor exit, HW-8.

6.3.10 Corridor Test HW-9

This experiment involved two trays, each containing 103 relatively thin cables (31 % NEC load, Kerite, 1/C). The fire spread rapidly. The burner was extinguished after only 6 min. The fire in the upper tray spread to the end of the corridor in 14 min; the fire in the lower tray spread in 20 min. The HRR and near-ceiling temperature measurements are shown in Figure 6-29. Photographs are shown in Figure 6-30 and Figure 6-31.

The sprinkler system was activated at 22 min to prevent excessive damage to the compartment. Following several minutes of water flow, the system was shut off and the fire was allowed to resume. By this point, much of the combustible mass had been consumed and the HRR decayed to zero over the following 30 min.

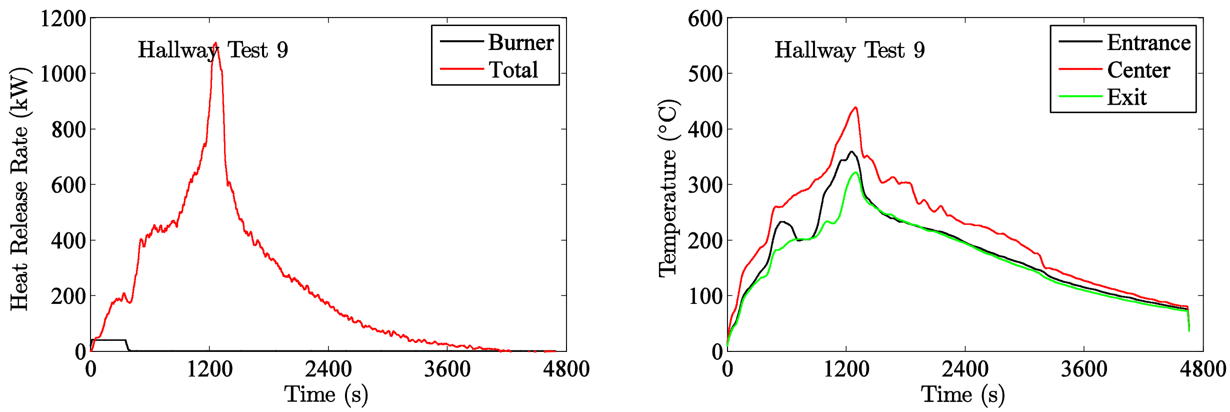


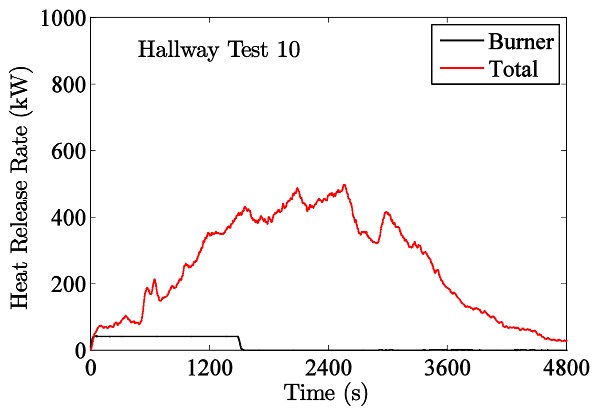
Figure 6-29. Heat release rate and HGL temperatures of Corridor Test HW-9.

Figure 6-30. Photograph of corridor entrance, HW-9.

Figure 6-31. Photograph of corridor exit, HW-9.

6.3.11 Corridor Test HW-10

This experiment was similar to HW-2, except that the 0.3 m (1 ft) soffit was removed. The fire in the upper tray spread to the end of the corridor in 33 min; the fire in the lower tray in 60 min. Even though the cable composition was not exactly the same, the removal of the soffit did not appear to significantly affect the outcome. The HRR and near-ceiling temperature measurements are shown in Figure 6-32. Photographs are shown in Figure 6-33 and Figure 6-34.



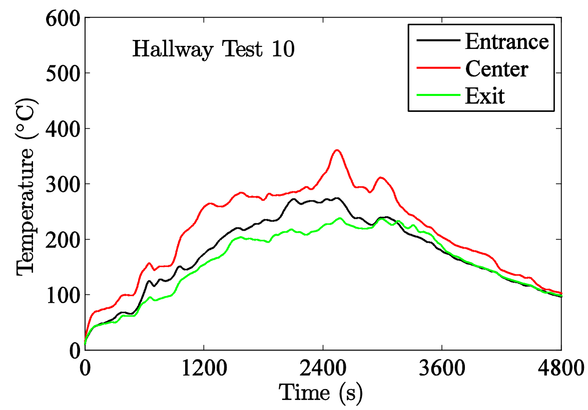


Figure 6-32. Heat release rate and HGL temperatures of Corridor Test HW-10.

Figure 6-33. Photograph of corridor entrance, HW-10.

Figure 6-34. Photograph of corridor exit, HW-10.

6.4 Summary

The primary purpose of the Corridor Experiments was to quantify the increased spread rate of a fire within a horizontal cable tray near to a ceiling. Ten experiments were conducted within a 2.4 m by 2.4 m by 7.3 m (8 ft by 8 ft by 24 ft) corridor, in which cable trays were positioned horizontally 30 cm (1 ft) below the ceiling. The formation of a hot gas layer pre-heated the cables in front of the spreading fire; and, thus, spread rates were up to 10 times greater than those observed in experiments conducted outside of a compartment.

In 8 of the 10 experiments, the fire in the tray 30 cm (1 ft) below the upper tray spread through the corridor at a lower rate than the fire in the upper tray, but this rate was still greater than that observed in experiments conducted outside of a compartment. Determining the spread rate in the lower tray was complicated by the fact that flaming debris from the upper tray sometimes ignited fires within the lower tray, hastening the spread through the corridor.

7 MODELING IMPLICATIONS

In Phase 1 of the CHRISTIFIRE project, a model was developed to estimate the heat release rate of a fire within an array of horizontal, ladder-back cable trays. In this chapter, the model is extended to address cable trays within enclosures and vertical tray configurations.

7.1 Extending the FLASH-CAT to Enclosures and Vertical Trays

The FLASH-CAT (Flame Spread in Horizontal Cable Trays) model is based on the assumption that the cable trays are not directly under a ceiling or confined within a relatively narrow corridor or shaft. The experiments that were used to validate the model consisted of arrays of trays that were set under a large calorimeter with no involvement of walls or ceilings. In this configuration, the lateral flame spread rates were limited to approximately 3 m/h for thermoplastic cables and 1 m/h for thermoset cables. However, the corridor experiments described in the previous chapter have shown that flame spread rates for cable trays close to the ceiling can be as much as 10 times greater than these limits. To better understand why, consider the analytical result stating that the flame spread rate, v, over a solid surface is proportional to the following expression (Hasemi, 2008):

$$v \propto \frac{(\dot{q}_{\mathrm{f}}'')^2 \, \delta_{\mathrm{f}}}{\pi \, (k\rho c) \, \left(T_{\mathrm{ign}} - T_{\infty}\right)^2} \tag{7-1}$$

where $\dot{q}_{\mathrm{f}}''$ is the heat flux from the flame, δ_{f} is a preheating distance, k is the thermal conductivity, ρ is the solid density, c is the specific heat of the solid, T_{ign} is the ignition temperature, and T_{∞} is the ambient temperature. This result is difficult to apply in practice because the proportionality constant is configuration dependent and the various terms are not readily quantified or even well-defined. For example, the heat flux from the flame is not a constant but rather a continuous function that decreases with the distance from the flame front. Nevertheless, this formula can be used to better understand the enhancement of the flame spread rate caused by positioning the cables near the ceiling. The ceiling heats up above the fire, adding to the heat flux term, $\dot{q}_{\mathrm{f}}''$. The ceiling also traps and extends the flame, increasing the pre-heat distance, δ_{f}. Finally, the ceiling (and walls) form a hot gas layer (HGL) that effectively increase the ambient temperature,T_{∞}, of the cables far from the fire source. While it is difficult to quantify exactly how each term is affected by the ceiling, it is certainly easy to understand how the flame speed could be increased by a factor of 10. Consider the measured HGL temperatures in the corridor experiments described in the previous chapter. Given that the cable ignition temperature is approximately 400 °C (752 °F), and normally the ambient temperature is approximately 20 °C (68 °F), an HGL temperature of 280 °C (536 °F) can theoretically increase the flame speed by a factor of 10, all other factors remaining the same:

$$\frac{v_2}{v_1} = \left(\frac{T_{\mathrm{ign}} - T_{\infty}}{T_{\mathrm{ign}} - T_{\mathrm{HGL}}}\right)^2 = \left(\frac{400 - 20}{400 - 280}\right)^2 \cong 10 \tag{7-2}$$

Obviously, as the HGL temperature approaches the cable ignition temperature, the possibility exists that the entire tray could ignite fairly quickly in a process that is referred to as "flashover."

For cable tray fires that are not affected by the ceiling or HGL, the FLASH-CAT model takes as input a fixed value of the fire spread rate; namely 3.2 m/h (10 ft/h) for thermoplastic cables and 1.1 m/h (4 ft/h) for thermoset cables. However, if the cables are within the HGL, the fire's spread rate will be increased due to the pre-heating of the cables. The increased spread rate in turn increases the heat release rate of the fire and consequently the HGL temperature. To better understand the relationship, consider a fire spreading along a single tray. The length of tray that is burning at a given instant in time, L, is given by

$$L = v\,\tau \tag{7-3}$$

where v is the spread rate and τ is the burnout time of the cables. The combustible load in the tray determines the burn out time; that is, the more cables in the tray, the longer the fire will burn at a given point along the tray. For this very simple scenario, the HRR, $\dot{Q}$, can be estimated by multiplying the average burning rate per unit area, $\dot{q}''_{\mathrm{avg}}$, by the area of burning cables, $L\,W$:

$$\dot{Q} = L\,W\,\dot{q}''_{\mathrm{avg}} = v\,\tau\,W\,\dot{q}''_{\mathrm{avg}} \tag{7-4}$$

The spread rate is dependent on the HGL temperature, and the HGL temperature is dependent on the HRR. Thus, the HRR, spread rate, and HGL temperature are interdependent and it is difficult to predict the increase in the spread rate without doing a compartment fire calculation to estimate the increase in the HGL temperature. Nevertheless, based on the Corridor Experiments, an estimate for the increased spread rate is:

$$v = 10\,v_0 \tag{7-5}$$

where v_0 is the fire spread rate for the cables if they were outside of the HGL (3.2 m/h for TP and 1.1 m/h for TS).

The factor of 10 increase in the fire spread rate is based solely on a single set of experiments that were conducted within a single enclosure. It provides an upper bound on the spread rate when the cables are located within an HGL where the average gas temperature approaches or surpasses the ignition temperature of the cables. However, for some fire scenarios, even though the cables might be located in the HGL, the HGL temperature may not rise high enough to significantly affect the spread rate. For example, the volume of the HGL may be very large, or very deep. In the Corridor Experiments, the HGL temperature, as determined from the three near-ceiling thermocouple measurements, was at least 200 °C (392 °F) in all tests except Test 0, in which case the fire did not spread to the end of the corridor. Based on this evidence, it is recommended that the increased spread rate calculated in Eq. (7-5) only be used in fire scenarios where the HGL temperature is expected to exceed 200 °C (392 °F).

7.2 Predictions of the Corridor Experiments

Figure 7-1 and Figure 7-2 display comparisons of FLASH-CAT predictions with the measured HRR of the Corridor Experiments. The input parameters for the model are listed in Table 7-1.

Table 7-1. Input parameters for the FLASH-CAT Model.

Test #	Cable ID	No. cables	No. trays	Tray Spacing	Tray Length	Tray Width	Mass/Length	Plastic Mass Fraction	Char Yield	HRRPUA	Heat of Combustion	Burner Length	Burner Width	Burner HRR	Burner Duration	Burner Offset	Spread Rate
				m	m	m	kg/m	kg/kg	kg/kg	kW/m^2	kJ/kg	m	m	kW	s	m	m/h
HW-1	800	56	2	0.3	6.8	0.45	0.310	0.34	0.	250	16000	0.3	0.3	40	900	0.2	32
HW-2	802	40	2	0.3	6.8	0.45	0.42	0.5	0.25	150	16000	0.3	0.3	40	900	0.2	11
HW-3	802	20	2	0.3	6.8	0.45	0.42	0.5	0.25	150	16000	0.3	0.3	40	900	0.2	11
HW-4	800	28	2	0.3	6.8	0.45	0.31	0.34	0	250	16000	0.3	0.3	40	900	0.2	32
HW-5	815	66	2	0.3	6.8	0.45	0.19	0.41	0	250	16000	0.3	0.3	40	900	0.2	32
HW-6	816	32	2	0.3	6.8	0.45	0.42	0.32	0.25	150	16000	0.3	0.3	40	900	0.2	11
HW-7	812	10	3	0.3	6.8	0.45	0.54	0.47	0.25	150	16000	0.3	0.3	40	900	0.2	11
HW-8	810	20	3	0.3	6.8	0.45	0.43	0.37	0	250	16000	0.3	0.3	40	900	0.2	32
HW-9	824	103	2	0.3	6.8	0.45	0.08	0.66	0.25	150	16000	0.3	0.3	40	900	0.2	32*
HW-10	803	40	2	0.3	6.8	0.45	0.44	0.52	0.25	150	16000	0.3	0.3	40	900	0.2	11
VT-06	801	84	1	0.3	3.4	0.45	0.31	0.34	0.26	300	16000	0.3	0.3	20	900	0.2	50
VT-07	801	84	1	0.3	3.4	0.45	0.31	0.34	0.26	300	16000	0.3	0.3	20	900	0.2	50
VT-10	815	68	1	0.3	3.4	0.45	0.19	0.41	0.05	500	16000	0.3	0.3	20	900	0.2	50
VT-11	815	68	1	0.3	3.4	0.45	0.19	0.41	0.05	500	16000	0.3	0.3	20	900	0.2	50
VT-14	810	38	1	0.3	3.4	0.45	0.43	0.37	0.25	500	16000	0.3	0.3	20	900	0.2	50
VT-15	810	38	1	0.3	3.4	0.45	0.43	0.37	0.25	500	16000	0.3	0.3	20	900	0.2	50

* Note that the diameter of Cable #824 used in Test HW-9 is 5 mm (0.2 in) and heats relatively quickly. For this reason, it has been assigned the spread rate of a thermoplastic cable, even though it is constructed of thermoset materials.

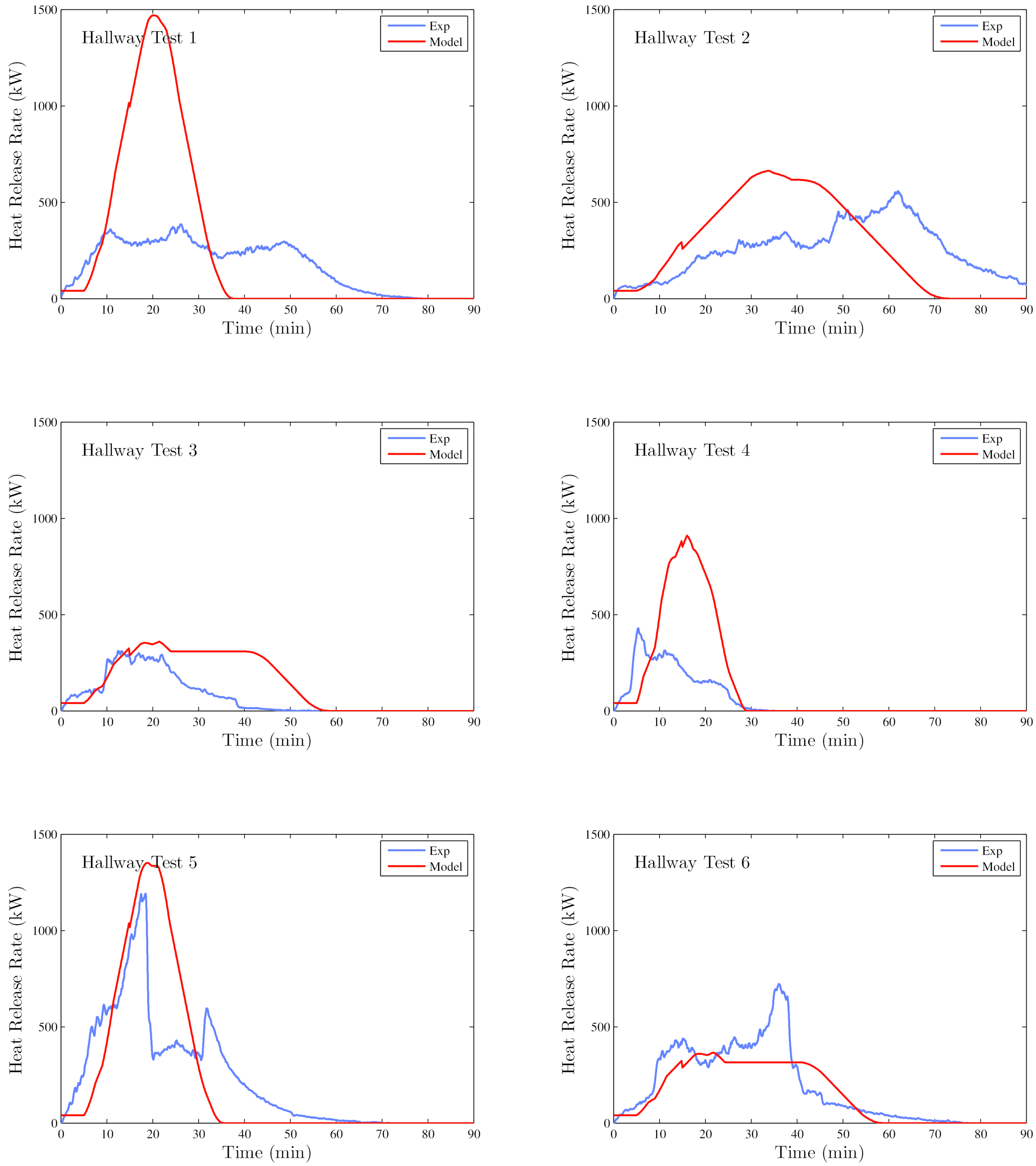


Figure 7-1. FLASH-CAT model predictions, Corridor Tests 1-6.

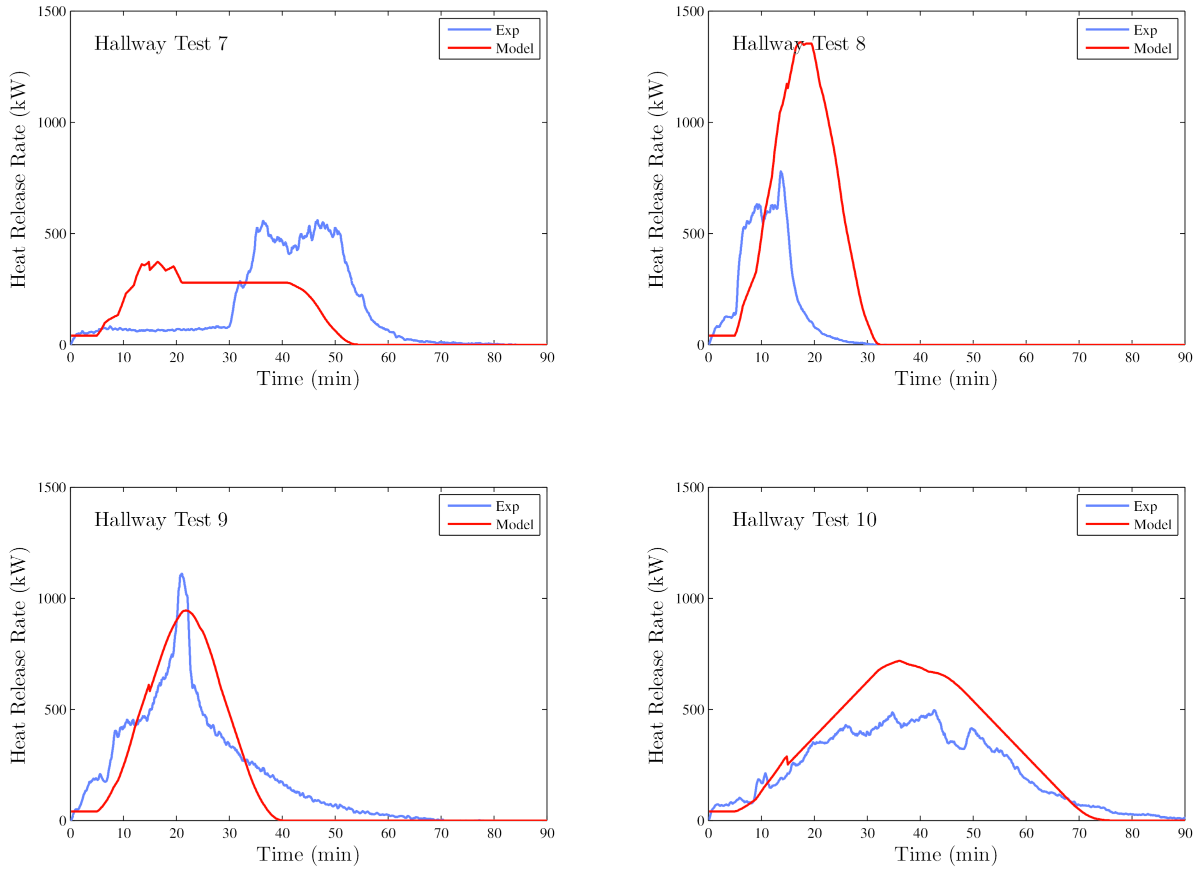


Figure 7-2. FLASH-CAT model predictions, Corridor Tests 7-10.

The following is a brief description of each prediction:

<u>Corridor Test 1</u>: In the experiment, the measured spread rates were 11 m/h (36 ft/h) for the upper tray and 7 m/h for the lower tray. In the model, however, the spread rate is specified to be 31 m/h (102 ft/h), based on the fact that the cable is thermoplastic and the spread rate is assumed to be 10 times the base spread rate of 3.1 m/h (10 ft/h). The comparison of the predicted and measured HRR shown in Figure 7-1 indicates that the over-predicted spread rate leads to an over-predicted peak HRR and shorter duration fire.

<u>Corridor Test 2</u>: The measured spread rate was 9 m/h (30 ft/h) and 7 m/h (23 ft/h) for the upper and lower trays, respectively. The model spread rate is 11 m/h (1.1 m/h × 10) for both trays. The result of this assumption is that the model fire lasts about 70 min whereas the actual fire lasted about 100 min.

<u>Corridor Test 3</u>: In the experiment, the fire spread only halfway down the corridor in the upper tray, and did not spread beyond the vicinity of the burner in the lower tray. The model fire, however, consumes all of the combustible material in both trays, which explains why the model fire lasts longer than the actual fire.

Corridor Test 4: In the experiment, the fire spread at a rate of 21 m/h (69 ft/h) in the upper tray, and it did not spread in the lower. The model fire spreads in both trays at a rate of 31 m/h (102 ft/h). Roughly twice as much energy is released in the model owing to the assumption that the fire spreads in both trays.

Corridor Test 5: In the experiment, the fire spread at a rate of 18 m/h (59 ft/h) and it was decided to partially suppress the fire with water at approximately 19 min to limit the rise in compartment temperature. There is no accounting for suppression in the model, but up to the time of suppression, the model and measured HRR rise at a comparable rate.

Corridor Test 6: In this case, the measured spread rate of the fire on the thermoset cables was 17 m/h whereas the specified rate in the model is only 11 m/h (36 ft/h). For this reason, the measured peak HRR exceeds that which is predicted by the model. Also, there is no mechanism in the model that can explain the observed rise in HRR towards the end of the experiment.

Corridor Test 7: In the experiment, the fire did not spread beyond the vicinity of the ignition burner for 30 min, at which point the HRR of the burner was increased causing the fire to spread fairly rapidly down the corridor. The measured spread rate was 10 m/h (33 ft/h), but this was calculated based on the time of ignition, not the delay time of 30 min. In fact, the fire spread three times more rapidly because it was delayed by 30 min. The model does not account for a delay in the spread and the resulting pre-heating of the unburned cables. As a result, the model prediction yields a lower peak HRR and a longer duration than the actual fire.

Corridor Test 8: The actual and model spread rates are comparable (36 m/h (118 ft/h) in the experiment; 31 m/h (102 ft/h) in the model). However, the model spreads the fire over three trays, whereas in the experiment, the fire only spread over two of the three trays. Consequently, the total energy released (the area under the HRR curve) is less in the experiment.

Corridor Test 9: The model predicts the actual HRR curve reasonably well. However, even though the cable is thermoset, it is assigned the spread rate of a thermoplastic cable because of its relatively small diameter (5.1 mm). The rate of spread of a cable fire is a function of its burning rate and its thermal inertia. A relatively thin cable will heat up relatively quickly, which in turn increases the spread rate.

Corridor Test 10: The model predicts the HRR reasonably well in this case. The measured spread rates in the upper and lower trays were 14 m/h and 7 m/h, respectively. The model spread is 11 m/h (36 ft/h) for both; thus, on average the fire growth rate is comparable.

7.3 Predictions of the Vertical Tray Experiments

The "H" in FLASH-CAT stands for Horizontal. However, there is no reason why the simple empirical methodology should not work for vertical tray configurations, assuming that the vertical spread rate is specified. The reason is that the FLASH-CAT model does not explicitly involve gravity, but rather makes use of a specified, empirically determined fire spread rate.

To circumvent the ignition delay sequence developed for a stack of horizontal cable trays, all of the cables are concentrated into a single tray, and the value of HRRPUA is increased accordingly. In the case of two trays, the HRRPUA is doubled to account for the fact that in reality, two trays would burn at twice the rate of one. Because the cables are concentrated in one tray, the combustible mass is conserved.

Table 7-1 lists the input parameters and Figure 7-3 displays the results of the modified FLASH-CAT model for the five Vertical Tray Experiments for which the fire spread to the top of the tray. A single case is also included (VT-15) to demonstrate that the model has no validity in cases where the fire does not spread beyond the vicinity of the ignition source. Note that the spread rate is 50 m/h for all cases where it is expected that the fire will spread upwards indefinitely. This figure is based solely on five experiments where the fire was observed to spread to the top of the tray. In each case, the fire burned along both vertical trays. In no case did the fire spread to the top on just a single tray.

The following is a brief discussion of the outcome of the model predictions:

<u>Corridor Test 6 and 7</u>: In the model, the fire begins to spread upwards after 5 min. This delay time is purely empirical. In the actual experiments, upward spread did not occur until the ignition burner's HRR was increased from 20 kW to 50 kW which caused the cables in the adjacent tray to ignite. Once both trays of cables had ignited, the fire spread upwards at a rate that was estimated to be about half of the rate specified in the model. The peak HRR is predicted fairly well, but the total energy released, represented by the area under the HRR curve, is over-predicted.

<u>Corridor Test 10 and 11</u>: The model predicts the measured HRR well in both cases. The measured and specified spread rates are equal.

<u>Corridor Test 14 and 15</u>: Test 14 is similar in outcome to Tests 6 and 7. However, the fire inside the vertical shaft in Test 15 did not spread upwards. The model cannot predict this – it always predicts upward spread at 50 m/h for cables placed in adjacent vertical trays.

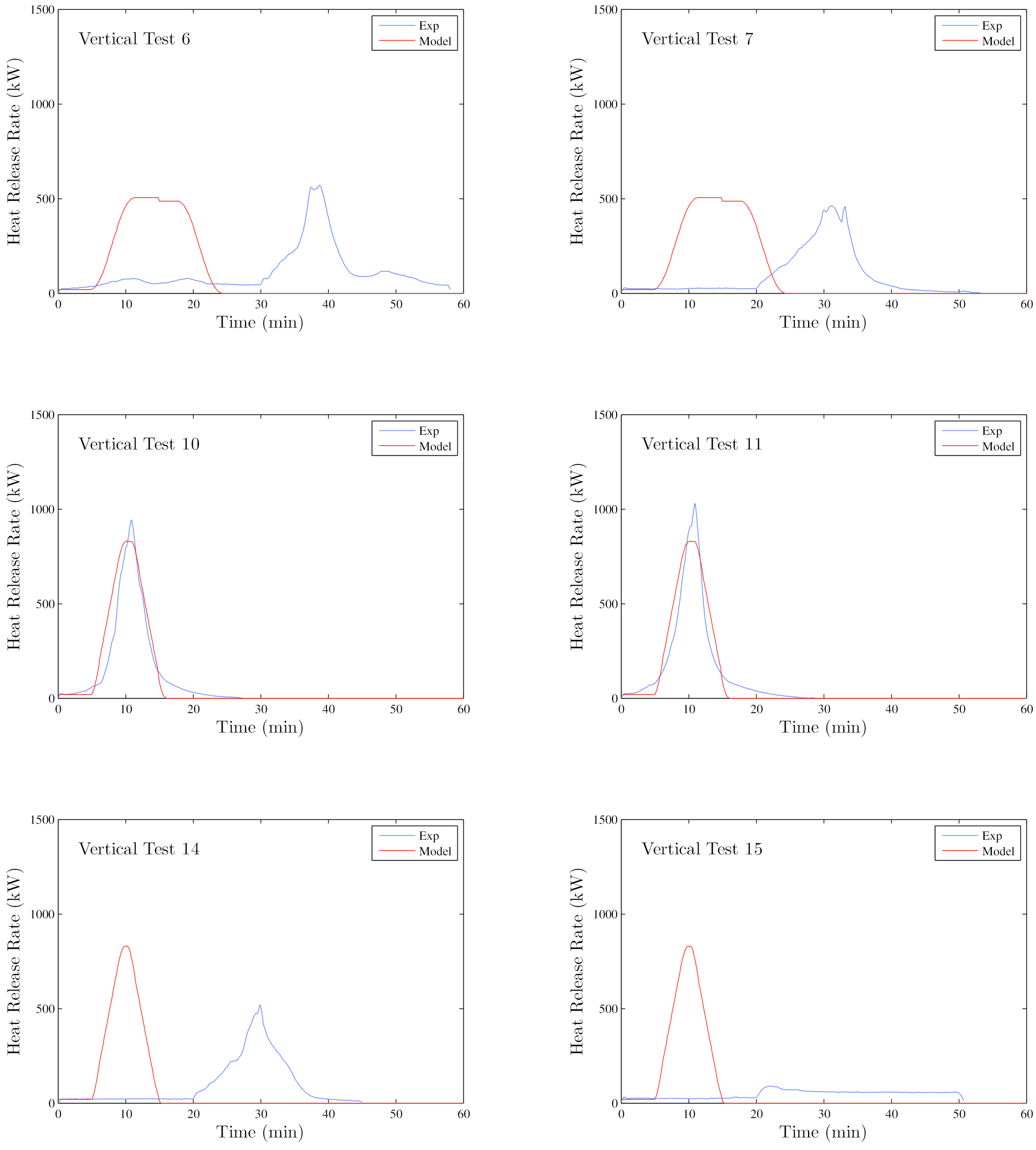


Figure 7-3. FLASH-CAT model predictions, Vertical Tray Tests.

8 CONCLUSIONS AND FUTURE WORK

Phase 2 of the CHRISTIFIRE program has extended the experimentation and modeling of fires within cable trays to include vertical configurations and enclosure effects. In addition, bench-scale calorimetry of cables manufactured within the time frame of 2006 through 2011 shows similar burning rates for thermoset and thermoplastic cables as was observed for cables manufactured in the early 1980's. Some of the noteworthy aspects of Phase 2 include:

Cone calorimeter measurements of a variety of cables manufactured in the early 1980's yielded average heat release rates per unit area (HRRPUA) of approximately 150 kW/m^2 for thermoset cables and 250 kW/m^2 for thermoplastic cables. Similar types of cables manufactured between 2006 and 2011 yielded similar values. This finding suggests that the recommended values of HRRPUA for the simple FLASH-CAT (Flame Spread over Horizontal Cable Trays) model are fairly robust over a wide range of cable types and ages.

Seventeen experiments were conducted involving pairs of vertically aligned cable trays. In experiments where only one of the trays was ignited at the base, the fire did not spread to the top of the 3.6 m (12 ft) tray. However, in some experiments where both trays were ignited at their base, the fire did spread to the top. This finding is not inconsistent with the fact that the cables had all passed the IEEE 383 Vertical Tray Flame Test (or similar standard test) because these standard tests do not include multiple trays. The fires spread vertically in two trays that were spaced either 0.15 m or 0.30 m (6 in or 12 in) apart because the thermal radiation from one tray pre-heated the other. This is a similar spread mechanism to that of multiple horizontal trays that were studied in Phase 1 of CHRISTIFIRE. The Phase 2 Vertical Tray Experiments suggest that fires are unlikely to spread upwards indefinitely on a single tray of qualified cables, but this cannot be said of multiple trays of qualified cables.

Ten experiments were conducted within a 2.4 m by 2.4 m by 7.3 m (8 ft by 8 ft by 24 ft) corridor, in which cable trays were positioned horizontally just below the ceiling. The formation of a hot gas layer pre-heated the cables in front of the spreading fire; and, thus, spread rates were up to 10 times greater than those observed in experiments conducted outside of a compartment. Both ends of the corridor were open; thus, the fire scenarios should be considered well-ventilated. No experiments were conducted in an under-ventilated compartment.

Based on the results of the Vertical Tray and Corridor Experiments, the FLASH-CAT model was extended to include scenarios where the cables are vertically oriented or within a hot gas layer. However, it is difficult to predict the enhanced spread rate of the fire because the spread rate, hot gas layer temperature, and the fire's heat release rate are interdependent. Nevertheless, a simple formula to approximate the enhanced fire spread rate has been put forth and tested in the FLASH-CAT model. The predicted heat release rates for the fires have a considerable amount of uncertainty, and it is suggested that modelers of these types of fire scenarios consider a range of spread rates to determine the peak heat release rate and duration of a hypothetical fire within cable trays inside of a compartment.

9 REFERENCES

ASTM D 6113-03 (2003) Standard Test Method for Using a Cone Calorimeter to Determine Fire-Test-Response Characteristics of Insulating Materials Contained in Electrical or Optical Fiber Cables. ASTM International, West Conshohocken, Pennsylvania.

ASTM E 1354-09 (2000) Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter. ASTM International, West Conshohocken, Pennsylvania.

Bryant, R.A. *et al*. (2004) *NIST 3 Megawatt Quantitative Heat Release Rate Facility: Description and Procedures*. NISTIR 7052, National Institute of Standards and Technology, Gaithersburg, Maryland.

Enright, P.A. and C.M. Fleischmann (1999) "Uncertainty of Heat Release Rate Calculation of the ISO5660-1 Cone Calorimeter Standard Test Method," *Fire Technology*, Vol. 5, No. 2, pp. 155-169.

Grayson, S.J., P. Van Hees, U. Vercellotti, H. Breulet and A. Green (2000). *Fire Performance of Electric Cables (FIPEC), Final Report on the European SMT Programme Sponsored Research Project SMT 4-CT96-2059*, Interscience Communications Limited, Greenwich, UK.

Hasemi, Y. (2008) "Surface Flame Spread," in *SFPE Handbook of Fire Protection Engineering,* 4th ed., National Fire Protection Association, Quincy, Massachusetts.

IEEE Standard 384 (2008) *IEEE Standard Criteria for Independence of Class 1E Equipment and Circuits.* IEEE Power & Energy Society, New York, New York.

Iqbal, N. and M. Salley (2004) *Fire Dynamics Tools*, NUREG-1805, U.S. Nuclear Regulatory Commission, Washington, DC.

Klamerus, L.J. (1977) *A Preliminary Report on Fire Protection Research Program (July 6, 1977 Test)*, SAND77-1424, Sandia Laboratories, Albuquerque, New Mexico.

Mangs, J. and O. Keski-Rahkonen (1997) "Full-scale fire experiments on vertical and horizontal cable trays," VTT Publication 324, 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.

NFPA 70 (2008) *National Electric Code®*, National Fire Protection Association, Quincy, Massachusetts.

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.

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

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

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

Van Hees, P. and P. Thureson (1996). *Burning Behaviour of Cables – Modelling of Flame Spread*, BRANDFORSK Project 725-942, SP Report 1996:30, Swedish National Testing and Research Institute, Borås, Sweden.

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D.W. Stroup, NRC Project Manager

11. ABSTRACT (200 words or less)

This report documents the second phase of a multi-year program called CHRISTIFIRE (Cable Heat Release, Ignition, and Spread in Tray Installations during Fire). The overall goal of the program is to quantify the burning characteristics of grouped electrical cables. This second phase of the program involved bench-scale and large-scale experiments. Bench-scale experiments were performed using a cone calorimeter in which 10 cm (4 in) by 10 cm (4 in) cable segments were exposed to a relatively high heat flux to determine their burning rate, heat of combustion, and other properties. The large scale experiments consisted of loaded cable trays situated in vertical and horizontal configurations. For the vertical experiments, two cable trays were positioned either in the open air, or in a vertical shaft that was open at the top and bottom. For the horizontal experiments, from one to four loaded cable trays were positioned horizontally with a 30 cm (1 ft) separation from the ceiling and tray to tray. The purpose of both sets of full-scale experiments was to determine the heat release and spread rates of burning cables in a variety of realistic configurations.

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