

Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE)

Volume 1: Horizontal Trays

Draft Report for Comment

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Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE)

Volume 1: Horizontal Trays

Draft Report for Comment

Manuscript Completed: September 2010
Date Published: October 2010

Prepared by
¹ K. McGrattan, ¹ A. Lock, ¹ N. Marsh, ¹ M. Nyden,
¹ M. Price (Summer Undergraduate Research Fellow)

² A.B. Morgan, ² M. Galaska, ² K. Schenck

¹ National Institute of Standards and Technology
Building and Fire Research Laboratory
Gaithersburg, MD 20899-8663

² University of Dayton Research Institute
Multi-Scale Composites and Polymers Division
Dayton, OH 45469-0160

D. Stroup, NRC Project Manager

NRC Job Code N6549

Office of Nuclear Regulatory Research

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For any questions about the material in this report, please contact:

David Stroup
CSB-4C07M
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
Phone: 301-251-7609
E-mail: david.stroup@nrc.gov

ABSTRACT

This report documents the first 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. The first phase of the program focuses on horizontal tray configurations. The experiments conducted range from micro-scale, in which very small (5 mg) samples of cable materials were burned in a calorimeter to determine their heat of combustion and other properties; to full-scale, in which horizontal, ladder-back trays loaded with varying amounts of cable were burned under a large oxygen-depletion calorimeter. Other experiments include cone calorimetry, smoke and effluent characterization in a small test furnace, and intermediate-scale calorimetry involving a single tray of cables underneath a bank of radiant panels. The results of the small-scale experiments are to serve as input data for fire models; while the results of the full-scale experiments are to serve as validation data for the models.

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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: for instance, the 1975 Browns Ferry fire demonstrated the vulnerability of electrical cables to fire-induced temperatures. The behavior of cables in a fire depends on a number of factors, including their constituent materials, construction, 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 behavior, it is still a considerable challenge to predict the actual heat release rate 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 (HRR) 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 1 of the CHRISTIFIRE (Cable Heat Release, Ignition and Spread in Tray Installations during FIRE) testing program conducted by the National Institute of Standards and Technology (NIST). The overall goal of this multiyear program is to quantify the burning characteristics of grouped electrical cables installed in cable trays. This first phase of the program focuses on horizontal tray configurations.

CHRISTIFIRE addresses the burning behavior of a cable 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 conducted range from bench-scale measurements of the effluent from small samples of burning cables to full-scale 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. The results of the small-scale experiments can serve as input data for fire models; while the results of the full-scale experiments are valuable as validation data for the models. Follow on phases of the CHRISTIFIRE program will address additional variables such as vertical tray configurations, cable fire retardant coatings, and other variables.

The CHRISTIFIRE Phase 1 experiments and modeling efforts are summarized as follows:

Micro-Scale Calorimetry: Following the procedure set forth in ASTM D 7309, small (5 mg) samples of cable jackets and insulation were burned within a small calorimeter to measure the heat of combustion, pyrolysis temperature, heat release capacity, and residue yield. The results of these experiments provide direct input for a variety of fire models. Simple models can use the heat of combustion, pyrolysis temperature, and residue yield to estimate how much of a given cable can be burned, at what temperature, and the amount of heat released.

More detailed models can use the kinetic parameters (pre-exponential factor and activation energy) that can be extracted from the measurement. These parameters describe the multiple reaction

decomposition of the material into fuel gas and residue/char. In light of the results of the larger-scale experiments, it was found that the pyrolysis temperature is the most important result of the MCC experiments. The cable with the lowest measured pyrolysis temperature was found to burn most readily at all the scales tested.

Bench-Scale Effluent Characterization: Following the procedure set forth in ISO/TS 19700, meter-long cable segments were slowly fed through a small furnace, referred to as the Tube Furnace, and the effluent was captured and measured via a variety of spectrometric techniques. The gases analyzed included CO₂, CO, HCl, H₂O, and soot particulate. The purpose of these experiments was to provide models with the production rates of various exhaust gases that are of interest in fire hazard analyses. Several cables were found to contain significant amounts of chlorine that formed HCl upon burning, a leading cause of corrosion in industrial settings.

Bench-Scale Calorimetry: Following the procedure set forth in ASTM D 6113, the standard Cone Calorimeter test was modified to accommodate electrical cables. In the experiment, 10 cm (4 in) by 10 cm (4 in) cable arrays were exposed to heat fluxes of 25 kW/m², 50 kW/m², and 75 kW/m², and the heat release rate per unit area (HRRPUA) was measured. The objective of these experiments was to determine whether the measured HRRPUA was comparable to what was measured using intermediate- and full-scale calorimetry. It was found that thermoset cables typically burn between 100 kW/m² and 200 kW/m², while thermoplastic cables typically burn in the range 200 kW/m² to 300 kW/m². These measurements are consistent with similar measurements made at intermediate- and full- scale.

Intermediate-Scale Calorimetry: The Radiant Panel (RP) Apparatus is a specially-designed device for measuring the burning rate of cables at a larger scale than the Cone Calorimeter. It consists of a single horizontal ladder-back cable tray, 1.2 m (4 ft) long, 0.45 m (18 in) wide, containing varying numbers of cables that are exposed to an array of radiant panels positioned overhead. The objective of these experiments was to compile a table of heat release rates per unit area (HRRPUA) for a variety of heat flux levels and tray fill levels. It was found that the values of HRRPUA measured in the Radiant Panel Apparatus were consistent with the burning rates at bench-scale (Cone Calorimeter) and full-scale (Multiple Tray Experiments).

Full-Scale Calorimetry: The Multiple Tray (MT) Experiments were composed of vertical stacks of three to seven cable trays. There were 26 experiments which were divided into two series. Series 1 addresses a fairly common tray configuration where 0.45 m (18 in)-wide horizontal, ladder-back trays are stacked over top of each other with 0.3 m (1 ft) spacing. The types and amount of cables in each tray were varied, although the cables in a given tray (or often for a given experiment) were typically of a single type. The aim was to perform a full-scale test on the cables that were tested in the Radiant Panel Apparatus and in the Cone Calorimeter to determine whether the burning rate data collected at bench and intermediate-scales could be applied to the full-scale experiments.

Series 2 involved mixtures of cables that were not tested under the Radiant Panel Apparatus or the Cone Calorimeter. This series was designed to assess the effect of changing the vertical tray spacing, tray width, and tray fill. As with Series 1, these tests also provided experimental data for model validation.

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. 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 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 26 Multiple Tray Experiments, and it was observed that the predicted HRR was comparable to or greater than the measured values. These experiments thus provide experimental validation of the calculation methods set forth in NUREG/CR-6850.

ACKNOWLEDGEMENTS

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. Jason Dreisbach and Mark 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 experiments described in this report were conducted primarily at NIST in the Large Fire Laboratory. Matthew Bundy is the laboratory supervisor and 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.

The cables used in the experiments were purchased by US NRC for the purpose of experimental measurements conducted at Brookhaven National Laboratory. Anthony Hamins and Jay McElroy of NIST arranged for the transfer of the cables to the NIST campus in Gaithersburg, Maryland and assembled an inventory list of the cables.

ABBREVIATIONS

ASTM	American Society for Testing and Materials
AWG	American Wire Gauge
CAROLFIRE	Cable Response to Live Fire
CHRISTIFIRE	Cable Heat Release, Ignition, and Spread in Tray Installations
CPE	Chlorinated Polyethylene
CSPE	Chloro-Sulfanated Polyethylene
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
FTIR	Fourier Transform Infrared Spectroscopy
HRR	Heat Release Rate
HRRPUA	Heat Release Rate Per Unit Area
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
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
PCFC	Pyrolysis Combustion Flow Calorimeter
PE	Polyethylene
PRA	Probabilistic Risk Assessment
PVC	Poly-vinyl Chloride
RES	NRC Office of Nuclear Regulatory Research
RP	Radiant Panel
SNL	Sandia National Laboratories
SP	Swedish National Testing and Research Institute
SR	Silicone Rubber
TC	Thermocouple
THIEF	Thermally-Induced Electrical Failure
TP	Thermoplastic
TS	Thermoset
UL	Underwriters Laboratories

VTT
XLPE or XPE
XLPO

Valtion Teknillinen Tutkimuskeskus (Technical Research Centre, Finland)
Cross-Linked Polyethylene
Cross-Linked Polyolefin

1 BACKGROUND

1.1 Introduction

Electrical cables perform numerous functions in nuclear power plants (NPP). Power cables supply electricity to motors, transformers, heaters, and light fixtures; 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 an NPP. These electrical cables will be 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 NPP 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 emergency core cooling system equipment. The damage was extensive because of the flammability of the cables, including ease of ignition, and flame spreading.

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 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 true fire behavior, especially plastic materials. Until these small-scale test results have been more fully validated 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 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 as they are applied to NFPA 805 applications.

1.2 Standard Cable Testing Configurations

Gonzalez and Dreisbach (2007) identified roughly 40 flame propagation tests for cables from the NFPA, UL, FM, IEEE, IEC and other standards writing organizations. Appendix A of this report includes excerpts from that study. All but six of the tests reviewed address vertical configurations; and of the six, none address the single and multiple tray configurations that are typically found throughout U.S. NPPs. Within the U.S. nuclear community, a cable is classified as “qualified” if it passes the standard test, IEEE-383. The test uses a 0.3 m (1 ft) wide, 2.4 m (8 ft) high vertical rack to support the cables. The cables are positioned in the center of the rack, 15 cm (6 in) off the rack and spaced one-half a cable diameter apart. A 21 kW air-propane pre-mixed burner is used to ignite the cables with a 20 min exposure. Cables that propagate the flames above the top of the rack fail to qualify. Most of the other standard tests cited by Gonzalez and Dreisbach are similar in scope. Almost none of the tests is of any value for fire modeling because they only determine whether a particular cable passes or fails; they do not quantify in a useful way the burning behavior of the cables.

A similar survey to that of Gonzalez and Dreisbach was performed at NIST in 1991 (Babrauskas *et al.* 1991). The study noted that test standards up to that point in time focused primarily on ignitability, flame spread rate, or distance of flame propagation. The concept of heat release rate (HRR) as a determiner of fire hazard was a relatively new idea at that time, as were devices like the Cone Calorimeter (ASTM E 1354) and measurement techniques like oxygen consumption calorimetry. The authors concluded that most of the standard test methods and cable fire experiments performed up to the point in time were not useful sources of input data for fire models. In 1991, two-zone fire models were fairly common, and these models required a fire’s HRR as input. Even the recently developed bench-scale apparatus for measuring HRR were not particularly useful without a robust methodology for extrapolating the results to full-scale.

1.3 Past Cable Fire Experiments

This section presents a time-line of past cable fire experiments performed in the U.S. and abroad. The focus is on experimental studies of *cable fires*, not electrical failure due to fires. There has been a considerable amount of work performed at various testing laboratories on thermally induced electrical failure, most recently the US NRC-sponsored CAROLFIRE program (Nowlen *et al.* 2008). However, the focus of this report is on cable fires.

- 1976-1981, Sandia National Laboratories, Cable Tray Fire Testing: A useful survey of fire experiments involving electrical cables is entitled, “A Summary of Nuclear Power Plant Safety Research at Sandia National Laboratories, 1975-1987” (Nowlen 1989). The experiments involving cables are listed as follows:

1976	Electrically Initiated Cable Fire Tests
1977	Exposure Fire Cable Fire Tests
1978	Fire Retardant Cable Coating Tests
1978	Cable Tray Fire Barrier Tests
1979	Cable Tray Fire Corner Effects Tests
1981	Burn Mode Analysis of Cable Fires

A highlight of this test program occurred in July, 1977, when a single experiment was conducted involving 14 horizontal cable trays arranged in two stacks of 7 and ignited at the base of one stack with a propane burner (Klamerus 1977). The fire propagated upwards within the stack of origin and then spread to the adjacent stack. The objective of the experiment was to determine if the fire would propagate between safety divisions mandated at the time. The cable was IEEE-383 qualified. This test followed on a series of other fire experiments involving various configurations of trays. The data collected consisted of visual observations and thermocouple (temperature) measurements to assess when the fire had reached a particular point. No large-scale calorimetry was performed either via mass loss or oxygen depletion methods; thus, no heat release rate data is available. However, an important observation was that the fire spread upwards forming a V-shaped burn pattern, the angle of which was estimated to be 35° from the vertical. This information, along with the time intervals for tray to tray spread, has been incorporated into Appendix R of the guidance document, NUREG/CR-6850.

- 1975-2000, Factory Mutual Research Corporation (FMRC): A number of bench-scale and full-scale experiments were conducted to quantify the burning behavior of electrical cables. A summary of this work is contained in Tewarson’s chapter of the SFPE Handbook, 4th Edition (2008). Highlights include the development of the Fire Propagation Apparatus (ASTM E 2058). Lee (1985), working at the National Bureau of Standards, estimated that the measured burning rates for various cables in the FMRC flammability apparatus correlated with full-scale, multiple tray cable fire experiments when a scaling factor was applied. Specifically, it was estimated by Lee that the heat release rate per unit area of cables within stacked horizontal trays was approximately 0.45 times that measured in the FMRC apparatus. This correlation is included in NUREG/CR-6850.
- 2000, Europe, FIPEC (Fire Performance of Electrical Cables) research program: A consortium of test laboratories from the UK, Italy, Sweden and Belgium conducted an extensive multi-year investigation of cable fires (Grayson *et al.* 2000). It involved both experiments and numerical modeling. The experiments were organized in the following way:

“Real-scale” experiments intended to reproduce actual cable installations
“Full-scale” standard tests in cable trays
Cone Calorimeter testing of cable segments arranged side by side in a single layer
Cone Calorimeter testing of cable materials (jackets, insulators, fillers)

The “real-scale” experiments were done either with three horizontal trays within a relatively narrow corridor or one vertical tray in a corner. The “full-scale” standard tests were conducted using a modified form of the IEC 60332-3 test standard, a vertical flame spread test similar to IEEE-383. The term “real-scale” implies that the configuration is based on actual installation practice rather than a testing standard configuration. One of the objectives of the program was to correlate the Cone Calorimeter results with both the real and full-scale results. In other words, it was shown that it is possible, to a certain extent, to predict the flammability of a particular cable type within a fully-loaded tray based on its heat and smoke production from a 10 cm by 10 cm array of cable segments subjected to a constant external heat flux.

- 1996, SP, Sweden: Bench-scale measurements of cables were performed at SP in Sweden, in addition to numerical modeling of flame spread (Van Hees and Thureson 1996).
- 1997, VTT, Finland: There has also been some experimental work on cable fires conducted at VTT Technical Research Centre of Finland (Mangs and Keski-Rahkonen 1997). Most of the experiments, however, involved very specific configurations that make it difficult to utilize the test results for other configurations or modeling.

1.4 Past Cable Fire Modeling Efforts

There have been a number of attempts to model cable fires over the past 30 years. Some of the early models were similar in concept to heat transfer models designed to study arrays of cylindrical pipes or heating elements (Hunter 1979). Models developed in the 1980s and 1990s made use of empirical correlations and concepts that were developed specifically for fire applications, like flame heights and ignition times (Van Hees and Thureson 1996; Grayson *et al.* 2000). These models also began to make use of bench-scale data from newly invented devices like the Cone Calorimeter (ASTM E 1354). In the late 1990s and continuing to the present, CFD (computational fluid dynamics) models have been modified to account for burning cables (Grayson *et al.* 2000; Hietaniemi *et al.* 2004)

In the U.S., simple calculation methods for cable fires evolved from the experimental work done at Sandia National Laboratories, Factory Mutual, and various other testing labs. NUREG/CR-6850 (2004) and NUREG-1805 (Iqbal and Salley 2004) contain surveys of experimental results that are pertinent to modeling. The information is derived from bench-scale and full-scale cable fire experiments conducted between approximately 1975 and 2000. Based on these experiments, both documents recommend a set of relatively simple calculation methods to assess various phenomena related to cable fires. For example, the recommended method of estimating the heat

release rate of a specified area of a burning cable tray is to assume that it is a fraction (0.45) of the heat release rate per unit area of a small sample of cable in a particular flammability apparatus under a constant external heat flux (60 kW/m²). The correlation was proposed by B.T. Lee (1985) of the National Bureau of Standards (now NIST) using experimental measurements made by Tewarson *et al.* (1979) and Sumitra (1982) at Factory Mutual Research Corporation. The estimate of the rate of flame spread within a single tray is not based on any experiments involving cable, but rather is a general purpose formula involving parameters such as the incident heat flux, thermal inertia of the cables, ignition temperature, and so forth. A model of upward fire spread through a stack of horizontal cable trays is based on a single experiment conducted at Sandia National Laboratories (Nowlen, 1989).

1.5 Current Research Needs

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 heat release rate of a stack of cable trays. Guidance documents, like the SFPE Handbook (2008), NUREG-1805, *Fire Dynamics Tools* (Iqbal and Salley 2004), and NUREG/CR-6850, 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 predict the heat release rate of a stack of cable trays using a simple or a detailed fire model. The main reasons for the current state of affairs are:

- While there are numerous standard tests used to “qualify” cables, most tests address vertical configurations of very specific cable arrangements, and almost all produce nothing more than a “Pass” or “Fail” rating. This information is very important for selecting appropriate types of cable, but it is not useful for modeling purposes.
- Past cable fire experiments, for the most part, have been conducted to assess very specific scenarios and configurations. It is difficult to extract from such experiments information, like burning rates, that can be applied to a wider variety of scenarios. Few of the experiments were designed to provide input data for current generation fire models. Indeed, during the 1970s and 1980s, fire models were little more than empirical correlations, and there was no need at the time for detailed material properties, like kinetic constants.
- Efforts by Tewarson (SFPE 2008) and others to compile a database of cable material properties has yielded lengthy lists of properties for different cable materials, but these data are difficult to apply in modeling because the properties are dependent on the configuration of the measurement apparatus. Also, cables are made up of multiple materials, including a substantial amount of copper, and thermo-physical properties of the individual materials cannot be easily combined into “effective” properties for the entire cable.
- Past modeling efforts have produced a number of useful concepts for both simplified and detailed models, but these models often rely on empirical data that is tied to a particular configuration (vertical or horizontal, for example), or data that is difficult to obtain (like

spreading rates), or data that varies from test apparatus to test apparatus (heat of combustion, for example).

- Those models that have been developed for cable fires require experimental data for validation: Many of the large-scale experiments performed over the past 40 years have been used to develop empirical models of cable fire growth and spread. As such, these experiments cannot be used to *validate* fire models because they have already been used to *calibrate* the models. For example, much of the guidance in NUREG/CR-6850 for calculating the heat release and spread rates of cables fires is derived directly from the experiments performed by Sandia National Laboratories and Factory Mutual Research Corporation.
- Past experiments that could potentially be used for model validation often have little information about the properties of the cables. In such cases, only the simplest of fire models that do not require detailed property information can make use of these experiments.
- Experiments performed prior to the 1980s often do not include a heat release rate measurement based on oxygen-consumption calorimetry or mass loss. In such cases, there is very little information that can be used to validate a fire model because the primary quantity that the typical model needs to predict the effects of a fire is its heat release rate.

The CHRISTIFIRE program seeks to fill some of the gaps that currently exist for modeling cable fires. The most important aspect of the program is the conduct of realistic, full-scale fires of typical cable installations, along with the necessary information about the cables to perform simple and detailed model calculations. The degree to which the various models can or cannot predict the heat release rate of these fires will indicate the usefulness of certain kinds of data or certain numerical techniques.

2 TECHNICAL APPROACH

2.1 Objective of CHRISTIFIRE

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 and energy 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.

The related project CAROLFIRE (Cable Response to Live Fire, NUREG/CR-6931) has provided much needed 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 heat release and spread rates of burning cables. CAROLFIRE demonstrated that ignition and electrical failure often occur within seconds of each other, but measurements were not made to quantify the burning behavior beyond the point of electrical failure.

CHRISTIFIRE addresses the burning behavior of a cable 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 both vertically and laterally within stacks of cable trays. Phase 1 of CHRISTIFIRE focuses on stacks of horizontal trays.

The CHRISTIFIRE Phase 1 experimental program has two main thrusts – bench-scale measurements of the effluent from small samples of burning cables and full-scale measurements of the heat release and fire spread rate of cables burning within typical ladder-type trays. Both sets of measurements are designed to provide the necessary input data for numerical fire models that are typically used to assess the consequences of accidental fires within various compartments in an NPP. 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 Phase 1 involves only horizontal trays because these are found in virtually every compartment of a plant.

2.2 Overview of CHRISTIFIRE Phase 1 Experiments

The CHRISTIFIRE test program shares a number of aspects with those described in the previous chapter. Given that there are innumerable permutations of cable types, trays, barriers, orientations and so forth, it is impractical to develop a comprehensive testing program to evaluate all possible arrangements. However, if it can be shown that relatively inexpensive bench-scale experiments can be used to predict the outcome of large-scale experiments, and if the same bench-scale data can be used as input for fire models, the need for expensive large-

scale testing decreases significantly. The simplest example of such an approach is the current estimation technique for heat release rate recommended in NUREG/CR-6850 (2004) and NUREG-1805 (Iqbal and Salley, 2004), in which bench-scale heat release rate measurements using a device similar in design to the Cone Calorimeter are used for large-scale calculations. The existing approach, however, is based on only a handful of experiments performed under a single set of conditions. One objective of the current program is to make measurements of heat release rates under a variety of conditions and at a number of different scales.

The CHRISTIFIRE research program consists of experiments performed on a variety of length scales, from micro-scale chemical analyses to full-scale, realistic cable tray configurations. Table 2-A summarizes the experiments. The experiments can be roughly divided into two types: (1) measurements of heat release and spread rates, and (2) measurements of the composition of the cable materials and combustion products. From the perspective of fire modeling, these experiments quantify the production rates of mass and energy from a tray of burning cables.

Table 2-A. Outline of CHRISTIFIRE Experimental Program

Scale	Description	Number of Tests	Related Standard
Small	Tube Furnace	9 cables	ISO/TS 19700
Micro	Micro-Combustion Calorimeter	12 insulators; 12 jackets	ASTM D 7309
Small	Cone Calorimeter	12 cables at 3 heat fluxes	ASTM D 6113
Intermediate	Radiant Panel Apparatus	33	None
Full	Stacked Horizontal Trays	26	None

2.3 Chemical Composition of Cables and Combustion Products

The Tube Furnace (ISO/TS 19700) is a bench-scale device specifically designed to measure the composition of the effluent of a burning item. The objective of these measurements is to quantify the *yields* of the major combustion products from burning cables. This information is needed in fire modeling to quantify the production rates of various gases.

Whereas the Tube Furnace measurements provide a detailed breakdown of the combustion products, it is not possible within the scope of the project to obtain a more detailed description of the cable materials other than the basic polymers used in the insulation and jacket. Fire models typically do not use this information. Instead, they require information about the thermal decomposition of the materials. For this reason, a device known as a Micro-Combustion Calorimeter or MCC (ASTM D 7309) was used to measure the mass loss rate of a slowly heated, small sample of material, from which various reaction parameters can be derived. There are two reasons for performing this measurement. First, it identifies the temperatures at which the main decomposition reactions occur, providing explanations for, and a ranking of, experimental results at larger scale. Second, these data can be used in the more detailed numerical models of fire as an alternative to specifying explicitly the heat release and spread rates. Such data are necessary for *predicting*, as opposed to *specifying*, the burning rate of the cables.

2.4 Heat Release and Spread Rates of Cable Fires

In CHRISTIFIRE Phase 1, cables were burned at three scales: full, intermediate, and bench-scale. The bench-scale apparatus was the Cone Calorimeter (ASTM E 1354; ASTM D 6113; ISO 5660-1), which measures the heat release rate per unit area (HRRPUA) of a 10 cm by 10 cm (4 in by 4 in) single layer of cable segments.

The intermediate-scale experiments involve a specially-designed device referred to as the Radiant Panel Apparatus. This device uses radiant panels to expose a roughly 1 m (3 ft) long section of cable within a 0.45 m (18 in) wide tray to a constant heat flux. Much like the Cone Calorimeter in design, the Radiant Panel Apparatus provides a heat release rate per unit area of a more realistic arrangement of cables within a commonly used ladder-back tray. One of the objectives of the radiant panel experiments is to compare the measured HRRPUA with that of the Cone Calorimeter. The Radiant Panel Apparatus is not a standard device, nor is it intended to be. It is expensive and requires a considerable amount of electrical power. It is not practical to burn samples of every cable type used in nuclear plants throughout the United States, past, present and future, in such a device. If it can be shown that the burning rate measured in the Cone Calorimeter, set to a particular exposing heat flux, is similar to the Radiant Panel Apparatus, then the Cone Calorimeter measurement can be used for fire model analysis. Past experimental programs to assess cable burning behavior have almost all used more or less this same strategy.

The full-scale experiments consist of vertical stacks of horizontal trays that are up to 3.6 m (12 ft) in length. Unlike the Cone Calorimeter and Radiant Panel Apparatus, the full-scale experiments involve no external radiant heat source. Instead, a 40 kW natural gas burner is used to ignite the cables within the lowest tray, and the fire spreads upwards. The heat feedback within the stack of trays is provided naturally by the burning cables above and below. These tests are to be used to validate the models that make use of the micro, bench and intermediate-scale measurements.

3 CABLE PROPERTIES

In the summer of 2006, two shipping containers filled with new, used, and aged electrical cables were shipped from Brookhaven National Laboratories to the Large Fire Laboratory at 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. The cables that were studied in the CHRISTIFIRE project were selected from this collection, plus a few newer samples were surplus from circuit testing at Sandia National Laboratories in Albuquerque, New Mexico. Twelve different cables were selected for testing at all scales, plus about 20 other cable types were chosen for the second multiple tray test series. The basis of selection was mainly variety and quantity. For many of the cable samples, there was not sufficient quantity to test at all scales. These cables were mixed together with others in a specified ratio and used in the full-scale experiments.

3.1 Properties of Cables Used in CHRISTIFIRE

The tables on the following pages contain a general description of the cables used in Phase 1 of the project. Note that the "Item No." or "Cable #" is merely an identifier and has no relevance beyond this project. Note also that the cables shown in the photograph (Figure 3-1) are those for which tests at all scales were conducted. The property data was obtained by dissecting 20 cm (8 in) segments into their constituent parts – jacket, filler, insulators, conductors.

Table 3-A. Cables used in CHRISTIFIRE

Item No.	Source	Date	Cable Markings
2	Rockbestos		No Markings
3	Rockbestos		ROCKBESTOS® 600V FIREWALL® III XHHW NEC TYPE TC (UL)
7	Rockbestos		ROCKBESTOS® 600V FIREWALL® III XHHW NEC TYPE TC (UL)
11	Rockbestos	1980	ROCKBESTOS® 600V FIREWALL® III XHHW NEC TYPE TC (UL)
13	Rockbestos		ROCKBESTOS® 600V FIREWALL® III XHHW NEC TYPE TC (UL)
15	Rockbestos		ROCKBESTOS® FIREWALL® III XHHW NEC TYPE TC (UL)
16	Rockbestos	1981	ROCKBESTOS® 600V FIREWALL® III XHHW NEC TYPE TC (UL)
17	Rockbestos		ROCKBESTOS® 600V FIREWALL® III XHHW NEC TYPE TC (UL)
20	Rockbestos		ROCKBESTOS® FIREWALL® III 1978-8A469
21	Rockbestos		ROCKBESTOS® FIREWALL® III XHHW NEC TYPE TC (UL)
22	Rockbestos		ROCKBESTOS® 600V FIREWALL® III XHHW NEC TYPE TC (UL)
23	Rockbestos	1981	ROCKBESTOS® FIREWALL® III 600V 6/C 16 AWG
25	Rockbestos		ROCKBESTOS® 90 °C DRY 75 °C WET Firewall III NEC Type TC
34	Rockbestos		ROCKBESTOS® 600V FIREWALL® III 12/C 16 AWG
43	Rockbestos	1975	ROCKBESTOS® FIREWALL® III 600V 12/C 16 AWG
45	Rockbestos		ROCKBESTOS® FIREWALL® III XHHW NEC TYPE TC (UL)
46	Rockbestos	1981	ROCKBESTOS® 600V FIREWALL® III XHHW NEC TYPE TC (UL)
47	Rockbestos		ROCKBESTOS® FIREWALL® III Thermocouple extension cable ASA/ISA Type KX
212	Anaconda		ANACONDA FLAME-GUARD
219	Anaconda		ANACONDA FLAME-GUARD 1KV
220	Anaconda		ANACONDA FLAME-GUARD 1KV
261	Suprenant		ITT SUPRENANT Div. L/U 9941 COMPOSITE CABLE
269	Brand-Rex		BRAND-REX TS75285 TRIAX RG-11A/U TYPE
270	Brand-Rex		BRAND-REX TRIAXIAL CABLE RG11 A/U TYPE
271	Brand-Rex		BRAND-REX XLP/CU POWER & CONTROL CABLE 2/C #14 600V SUN RES XHHW TYPE TC (UL)
272	Brand-Rex		BRAND-REX SHIELDED COMPOSITE CABLE RG 62B/U+1/C 20KV +6/C 300V

Item No.	Source	Date	Cable Markings
273	Brand-Rex		BRAND-REX INSTRUMENT CABLE 90C MJ6T
312	Okonite		OKONITE CO. PLT#7 Cu Class 1E 1C12
327	General Cable		GENERAL CABLE XLP
337			No Markings
367	Kerite	1989	KERITE 1989 #6 AWG CU 5KV HTK NON SHIELDED CABLE TEST # M0325
503	Rockbestos		ROCKBESTOS® FIREWALL® III XHHW NEC TYPE TC (UL)
505	Rockbestos		ROCKBESTOS® FIREWALL® III XHHW NEC TYPE TC (UL)
612	Rockbestos		ROCKBESTOS® FIREWALL® III XHHW NEC TYPE TC (UL)
700	Rockbestos-Surprenant	2005	7/C 12 AWG 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
701	General Cable BICC	2006	GENERAL CABLE® BICC® BRAND SUBSTATION CONTROL CABLE 7/C #12AWG 600V 30 MAY 2006



11 13 15 16 20 21 23 43 46 219 220 269 270 271 367 700 701

Figure 3-1. Photograph of some of the cables used in CHRISTIFIRE.

Table 3-B. Properties of the cables used in CHRISTIFIRE

Cable No.	Insulation Material	Jacket Material	Classification	Conductors	Diameter (mm)	Jacket Thickness (mm)	Insulator Thickness (mm)	Mass per unit Length (kg/m)	Copper Mass Fraction	Jacket Mass Fraction	Insulation Mass Fraction	Filler Material Mass Fraction
2	XLPE	Neoprene	TS	4	19	2	1.5	0.568	0.46	0.33	0.17	0.04
3	XLPE	Neoprene	TS	19	24	2.5	1	1.104	0.53	0.26	0.21	0.00
7	XLPE	Neoprene	TS	12	21	2.5	1	0.752	0.48	0.32	0.19	0.00
11	XLPE	CSPE	TS	37	32	3.1	1.1	1.985	0.55	0.23	0.22	0.00
16	XLPE	Neoprene	TS	4	19	2.2	1.8	0.671	0.52	0.27	0.18	0.03
17			TS	5	14	1.8	1	0.345	0.44	0.35	0.18	0.03
22			TS	9	18.5	2.1	1	0.606	0.45	0.34	0.19	0.02
23	XLPE	CSPE	TS	6	14	2.7	0.9	0.253	0.31	0.48	0.16	0.05
25	XLPE	Neoprene	TS	3	10	1.6	1	0.146	0.32	0.47	0.19	0.02
34			TS	12	19	2.2	0.7	0.499	0.38	0.40	0.17	0.05
43	XLPE	Neoprene	TS	12	15	2.3	0.8	0.357	0.38	0.38	0.21	0.03
45			TS	7	17	2	0.9	0.456	0.47	0.36	0.15	0.01
46	XLPE	Neoprene	TS	7	15	1.9	1.2	0.437	0.48	0.32	0.20	0.00
47			TS	2	9	1.6	0.9	0.114	0.30	0.54	0.12	0.03
212	EPR	CSPE	TS	3	13	2	1.5	0.247	0.23	0.45	0.22	0.10
219	EPR	CSPE	TS	3	14	2.4	1.5	0.296	0.39	0.39	0.22	0.00
220	EPR	CSPE	TS	7	18	2.6	1.2	0.560	0.38	0.32	0.30	0.00
261	XLPE	XLPE	TS	10	18	2.5	0.9	0.397	0.27	0.42	0.29	0.02
269	XLPE	CSPE	TS	1	12	1.0	0.6/3.6	0.240	0.47	0.30	0.23	0.00
270	XLPE	CSPE	TS	1	12	0.6	0.8/3.5	0.235	0.49	0.27	0.24	0.00
271	XLPE	XLPE	TS	2	10	1.6	0.9	0.123	0.30	0.48	0.15	0.07
272			TS	8	14	1.5	0.7	0.252	0.40	0.31	0.26	0.04
273	XLPE	XLPE	TS	18	20	1.9	0.7	0.532	0.57	0.29	0.12	0.02
312	EPR	Neoprene	TS	3	12	1.6	1	0.239	0.38	0.45	0.16	0.00
327			TS	5	17.5	2.5	1.5	0.454	0.33	0.46	0.19	0.02
337			TS	1	24	6	N/A	1.381	0.72	0.28	0.00	0.00
367	EPR		TS	1	16	2.3	3.5	0.441	0.27	0.45	0.28	0.00

Cable No.	Insulation Material	Jacket Material	Classification	Conductors	Diameter (mm)	Jacket Thickness (mm)	Insulator Thickness (mm)	Mass per unit Length (kg/m)	Copper Mass Fraction	Jacket Mass Fraction	Insulation Mass Fraction	Filler Material Mass Fraction
503			TS	7	15.5	2.2	1	0.457	0.48	0.33	0.19	0.00
505			TS	2	10	1.2	1	0.120	0.31	0.44	0.14	0.11
612			TS	3	12	1.7	1	0.237	0.39	0.41	0.16	0.04
700	XLPE		TS	7	12	1.0	0.7	0.322	0.67	0.17	0.16	0.00
701	PE	PVC	TP	7	14	1.5	0.8	0.366	0.58	0.24	0.18	0.00

Notes:

1. The accuracy of each table entry is implied by the number of significant digits.
2. The Classification of thermoset (TS) or thermoplastic (TP) is applied to the entire cable based on the composition of its materials and its electrical performance at high temperature.
3. Filler Material is considered to be anything that is non-metallic and does not serve as an outer jacket or insulator.
4. The Jacket and Insulation Thicknesses were measured with calipers accurate to a hundredth of a mm but rounded to the nearest tenth because of local variations in material thickness.
5. Cable #269 and #270 are triaxial cables with an outer jacket, two layers of metal shielding, and an inner and outer insulation material. The thicker of the two insulation layers surrounds the single conductor.
6. The size of the conductors, as indicated by the AWG (American Wire Gauge) value, is not a useful parameter for this project. Of more value is the Copper Mass Fraction, which indicates the overall mass of copper in the cable.
7. The Insulation Material and Jacket Material are based on the cable inventory list provided by Brookhaven National Laboratory.

3.2 Classification of Plastic Materials

The information in this section has been taken from Appendix F of NUREG/CR-6931, Volume 1 (Nowlen and Wyant 2007). It is important because throughout this report, cables are referred to as either thermoset or thermoplastic. The distinction is of importance when developing simplified models of burning behavior. Thermoplastics can be heated, melted, and then cooled to solid form. Thermosets, if heated, will reach their decomposition temperature before their melting temperature, and will degrade irreversibly if exposed to sufficiently high temperatures. Of relevance to fire performance is the fact that thermoset cables tend to withstand higher temperatures and burn at lower rates than thermoplastics.

3.2.1 Thermoplastics

Thermoplastics can be deformed and/or liquefied by heat addition and can be cooled to solid form. At the molecular level, the long polymer molecules attract each other by Van der Waals forces, dipole-dipole interactions, and hydrogen bonding and/or aromatic ring stacking, but there is no direct bonding or linking between molecular chains. These forces and interactions are inversely proportional to the temperature and the distance between the molecules. In the solid form the long polymer molecules are close together and the force between them keeps the material solid. If the thermal energy of the molecules is increased the molecules will separate and expand. If the heat addition is continued, the plastic will become more malleable but will not flow until it reaches its melting point. Once melted, the plastic will flow as a viscous fluid depending on the polymer characteristics and degree of polymerization. If heat continues to be added, the plastic will reach its degradation temperature. Once the degradation temperature is reached, the energy added to the molecules is large enough to break the covalent bonds of the molecules causing irreversible change in the properties of the plastic.

3.2.2 Thermosets

Unlike thermoplastics, thermoset molecules, once cured, are covalently bonded to each other. They cannot be liquefied by heat addition and cooled to solid form. If heat is added, the kinetic energy of the molecules will increase and the molecules will increase their vibration, but they will not be able to separate excessively. When temperature increases, the plastic might get softer but the degradation temperature will be reached before its glass transition temperature. Once the degradation temperature is reached, the plastic molecules will begin to lose molecular integrity and the covalent bonds will start to break. Once this happens, the process is irreversible and the polymer will have lost its original chemical and physical properties. In general, thermoset polymers have better mechanical properties, are stiffer, and can withstand higher temperatures during longer periods of time than thermoplastic polymers.

4 MICRO-CALORIMETRY MEASUREMENTS

4.1 Description

Micro-combustion calorimetric (MCC) measurements were made using the pyrolysis combustion flow calorimeter (PCFC) developed by Lyon and co-workers at the U.S. Federal Aviation Administration (FAA) William J. Hughes Technical Center (Lyon *et al.* 2004). This device, shown in Figure 4-1, is used to measure the heat generated from the combustion of small (4 mg to 6 mg) material samples by oxygen depletion calorimetry. Samples are pyrolyzed at a specified heating rate in an anaerobic atmosphere (typically N₂) and the resulting gases are mixed with excess oxygen and combusted in a separate chamber. The heat release rate (HRR) from the specimen is obtained from measurements of the concentration of oxygen in the effluent exiting the combustor as a function of time. The methodology is the basis for the standard test ASTM D 7309.

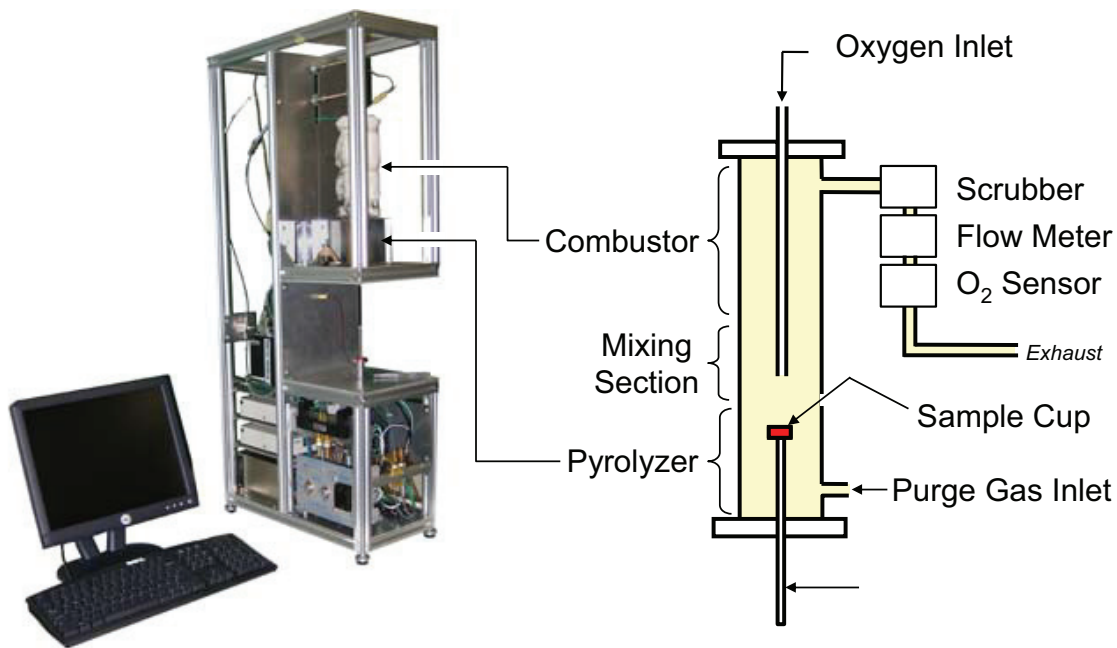


Figure 4-1. Pyrolysis Combustion Flow Calorimeter (PCFC).

4.2 Results

The results of the PCFC measurements for 12 cables are shown in Figure 4-2 through Figure 4-5. For each cable, the insulation and jacket material were tested separately, and at least three replicates were performed for each (only one replicate is shown for each sample). The samples, weighing between 4 mg and 6 mg, were cut from the cable jackets and conductor insulation

material of each of the 12 cables. These samples were pyrolyzed in the PCFC at a rate of 1.0 °C/s from 100 °C to 600 °C in a nitrogen atmosphere and the effluent combusted at 900 °C in a mixture consisting of 20 % O₂ and 80 % N₂.

The resulting curve shows the heat release rate of the sample as it was heated, normalized by the mass of the original sample. There are usually one, two or three noticeable peaks in the curve, corresponding to temperatures where an important decomposition is occurring. Each peak can be characterized by the maximum value of the heat release rate (q_p), the temperature (T_p), and the fraction of the original sample mass that is pyrolyzed in the reaction (Y_0). This last value is estimated from the relative area underneath that particular peak. The heat of combustion (ΔH) is the area under the entire curve divided by the factor, $(1 - v_r)$, where v_r is the fraction of the original mass that remains as residue. Sometimes this is referred to as the “char yield.”

The temperatures and heat release rates corresponding to the peaks in the curve are important in that they convey when, and at what rate, these various materials burn. A further benefit of these results is that it is possible to derive the kinetic parameters, A_i and E_i , that define the decomposition reactions:

$$\frac{dY_i}{dt} = -A_i Y_i e^{-E_i/RT} \quad ; \quad Y_i(0) = Y_{i,0} \quad (4.1)$$

Here, Y_i is the mass fraction of the i -th component of the solid. Whenever there is a peak in the heat release rate curve, the second derivative of Y_i is zero, and it is possible to obtain values of the kinetic parameters simply by estimating values of q_p , T_p , and Y_0 from the plots. In fact, each plot on the following pages shows a dashed line and a solid line. The dashed line is the original measurement, and the solid line is the solution of the decomposition equation above using kinetic parameters obtained from the values of q_p , T_p , and Y_0 .

Although the value of the maximum HRR is sensitive to heating rate, this dependency can be effectively removed by dividing it by the heating rate. The resulting quantity, which has the same units as heat capacity, is called heat release capacity. According to Lyon (2004), these variables (T_p , THR, HRC) along with char yield (ratio of the mass of the residual char to the original mass of the sample), are reliable indicators of materials flammability. Their physical significance is as follows. The char yield is the fraction of material that does not volatilize under the prescribed conditions and is clearly related to the total heat release, which is the effective fuel load per gram of material. The pyrolysis temperature, T_p , is comparable to the ignition temperature of the material, and the heat release capacity represents the maximum amount of heat a gram of sample can release (per unit temperature increase) in a fire.

The test specification (ASTM D 7309-07) states that the estimated standard relative uncertainty based on the reproducibility of the heat release rate measurement is $\pm 6\%$, with the majority of the error arising from the uncertainty in the assumed heat released by complete combustion per unit mass of oxygen consumed (13.1 MJ/kg).

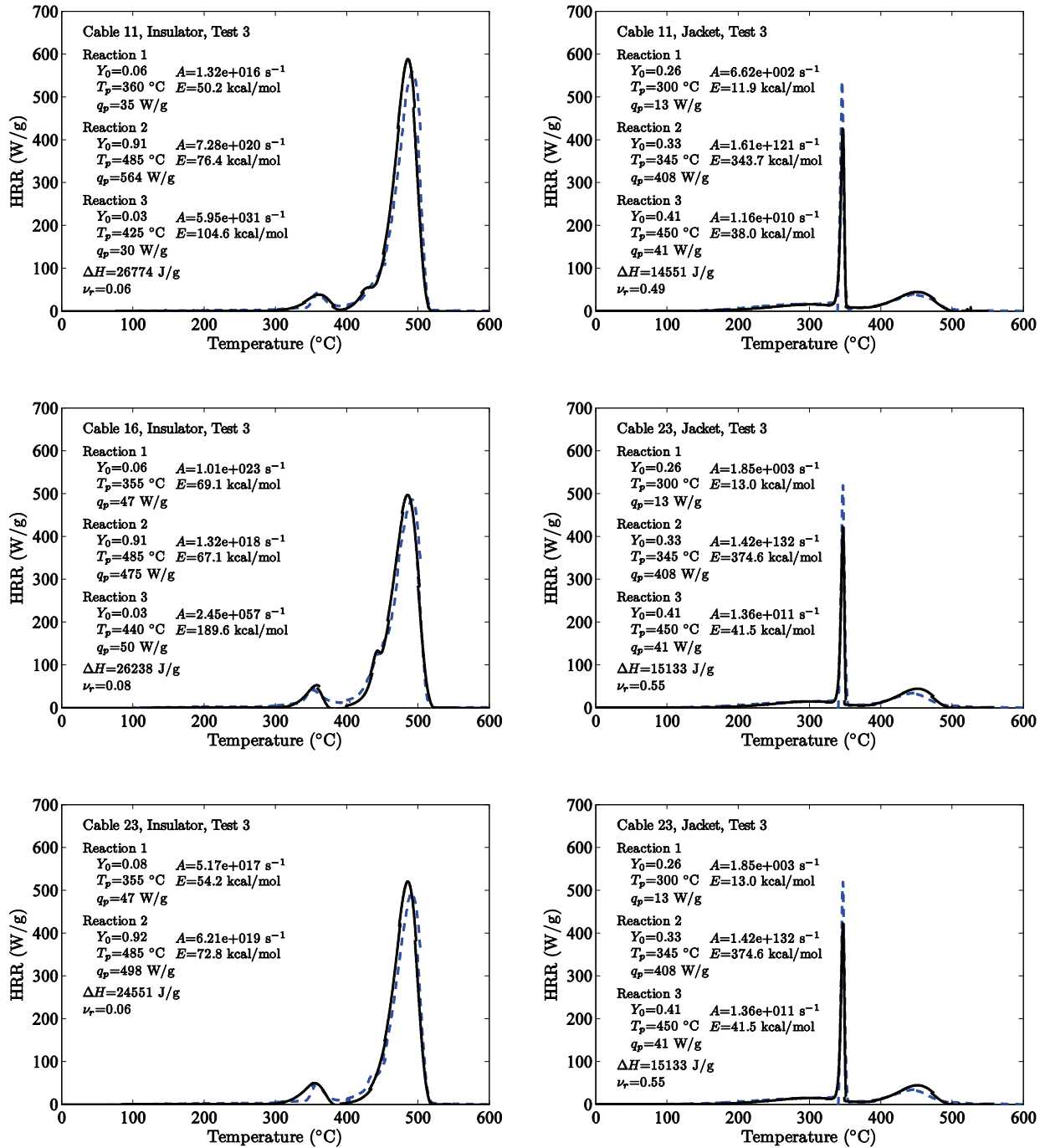


Figure 4-2. Micro-Calorimetry results for Cables 11, 16 and 23.

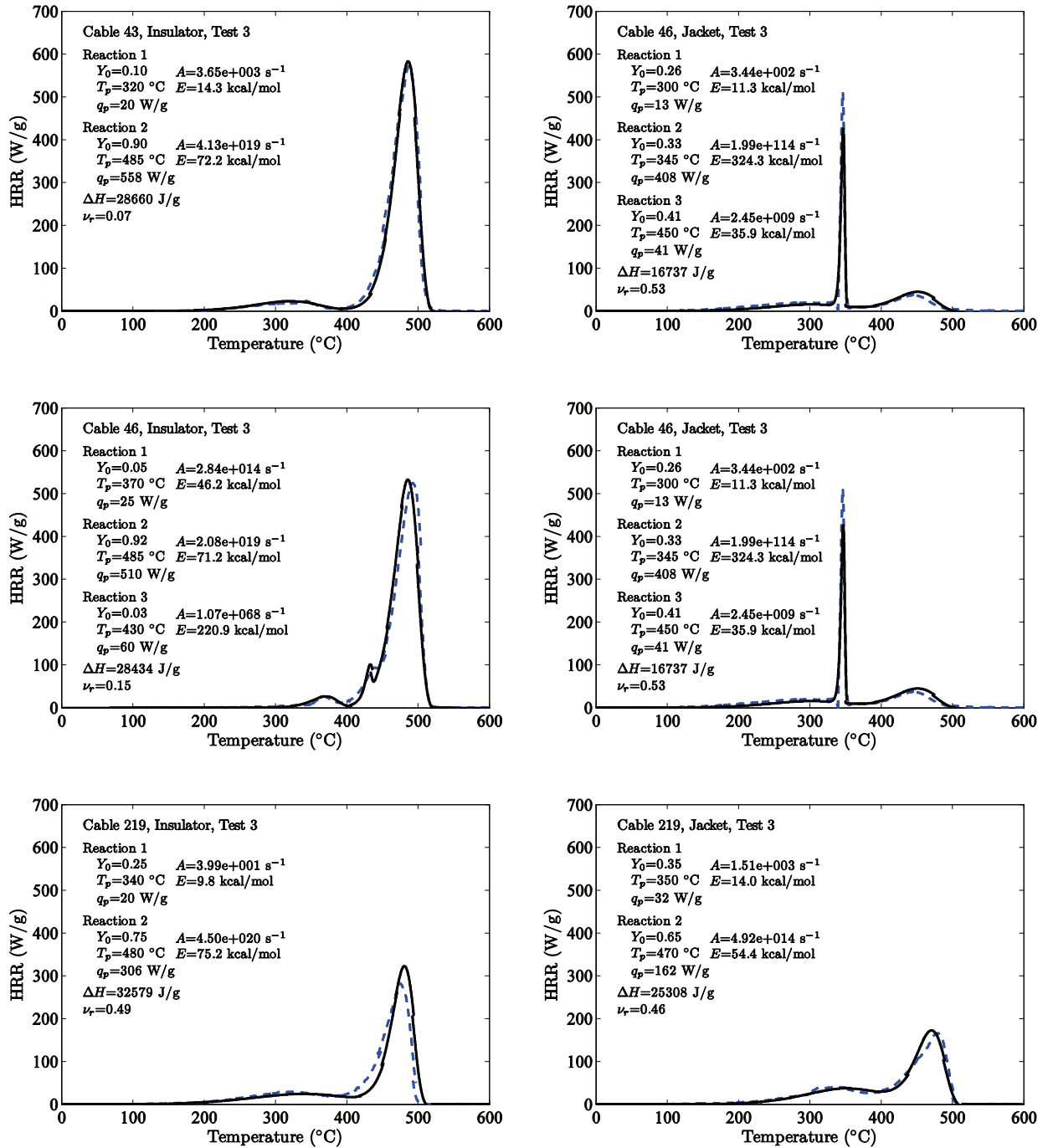


Figure 4-3. Micro-Calorimetry results for Cables 43, 46 and 219.

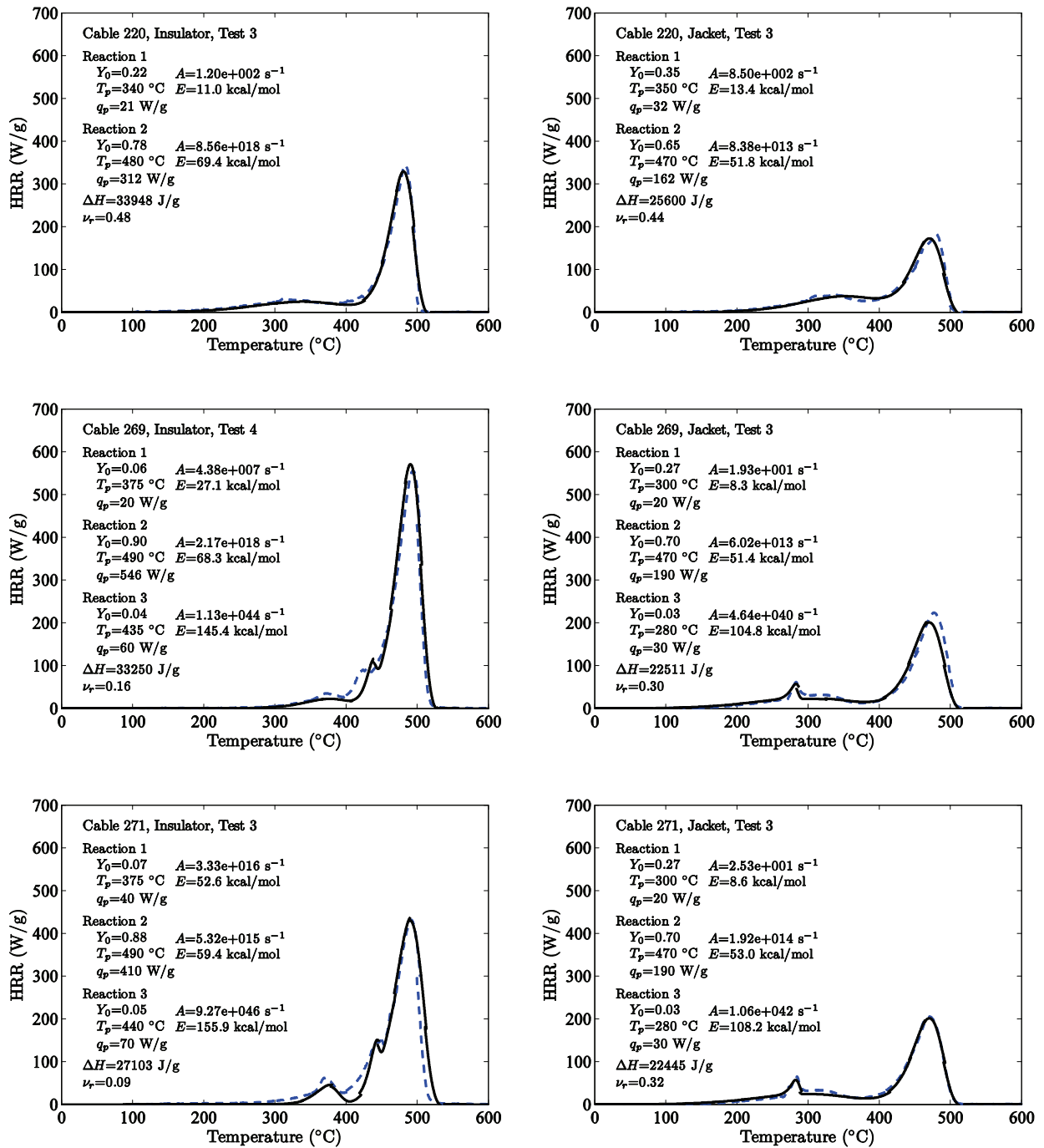


Figure 4-4. Micro-Calorimetry results for Cables 220, 269 and 271.

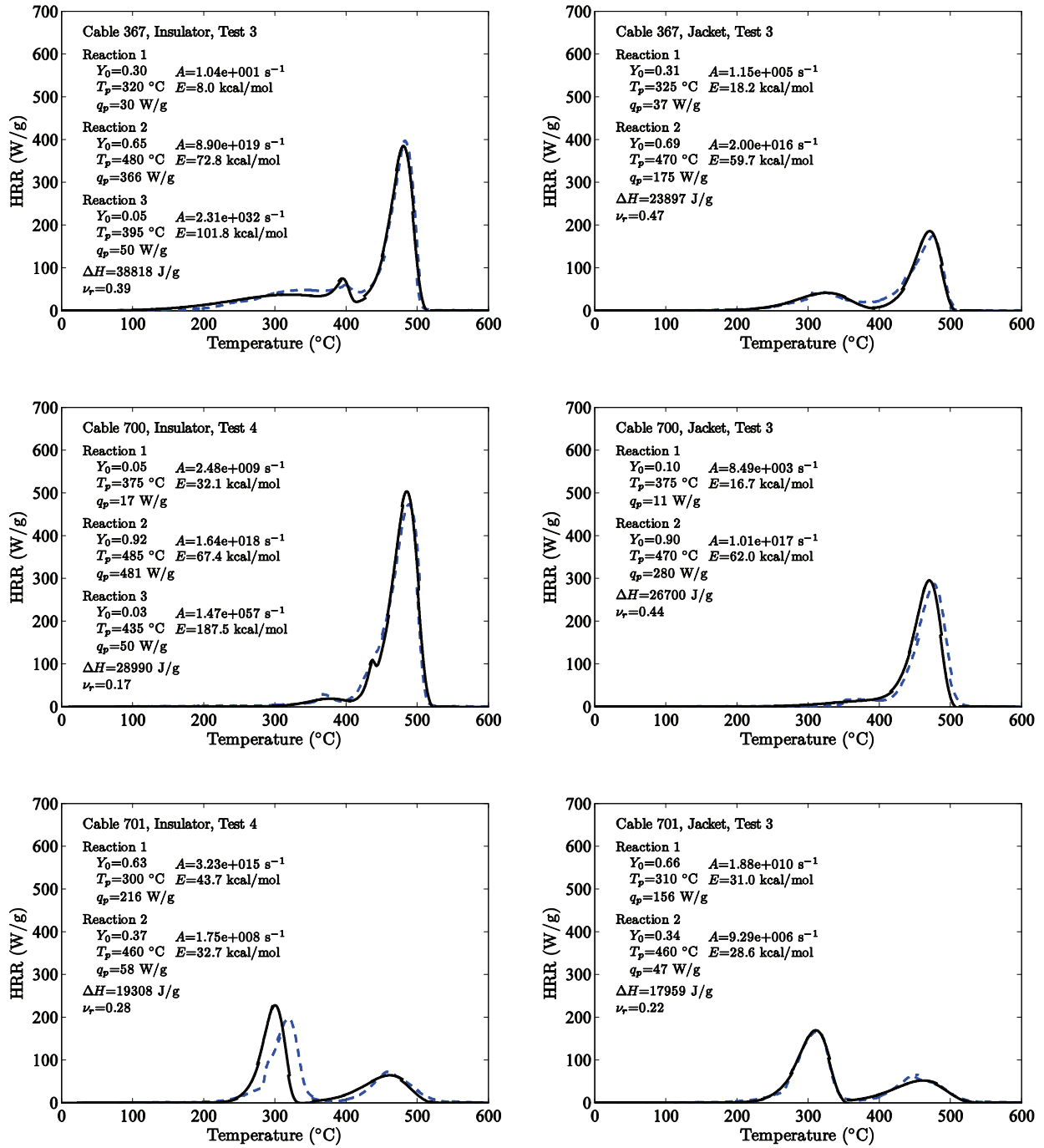


Figure 4-5. Micro-Calorimetry results for Cables 367, 700 and 701.

Table 4-A. Summary of the Micro-Calorimetry Experiments

No.	Cable Comp.	$Y_{0,1}$	$Y_{0,2}$	$Y_{0,3}$	T_1 (°C)	T_2 (°C)	T_3 (°C)	$q_{p,1}$ (W/g)	$q_{p,2}$ (W/g)	$q_{p,3}$ (W/g)	v_r	ΔH (kJ/g)
11	Insulator	0.06	0.91	0.03	360	485	425	35	564	30	0.06	26.7
16	Insulator	0.06	0.91	0.03	355	485	440	47	475	50	0.08	26.1
23	Insulator	0.08	0.92	---	355	485	---	47	498	---	0.06	25.0
43	Insulator	0.10	0.90	---	320	485	---	20	558	---	0.07	30.8
46	Insulator	0.05	0.92	0.03	370	485	430	25	510	60	0.15	29.7
219	Insulator	0.25	0.75	---	340	480	---	20	306	---	0.49	32.6
220	Insulator	0.22	0.78	---	340	480	---	21	312	---	0.48	33.7
269	Insulator	0.06	0.90	0.04	375	490	435	20	546	60	0.16	33.8
271	Insulator	0.07	0.88	0.05	375	490	440	40	410	70	0.09	26.6
367	Insulator	0.30	0.65	0.05	320	480	395	30	366	50	0.39	38.4
700	Insulator	0.05	0.92	0.03	375	485	435	17	481	50	0.17	28.7
701	Insulator	0.63	0.37	---	300	460	---	216	58	---	0.28	17.5
11	Jacket	0.26	0.33	0.41	300	345	450	13	408	41	0.49	15.5
16	Jacket	0.26	0.33	0.41	300	345	450	13	408	41	0.48	16.4
23	Jacket	0.26	0.33	0.41	300	345	450	13	408	41	0.55	14.0
43	Jacket	0.26	0.33	0.41	300	345	450	13	408	41	0.51	17.2
46	Jacket	0.26	0.33	0.41	300	345	450	13	408	41	0.53	14.8
219	Jacket	0.35	0.65	---	350	470	---	32	162	---	0.46	25.0
220	Jacket	0.35	0.65	---	350	470	---	32	162	---	0.44	24.6
269	Jacket	0.27	0.70	0.03	300	470	280	20	190	30	0.30	22.6
271	Jacket	0.27	0.70	0.03	300	470	280	20	190	30	0.32	22.1
367	Jacket	0.31	0.69	---	325	470	---	37	175	---	0.47	25.0
700	Jacket	0.10	0.90	---	375	470	---	11	280	---	0.44	27.6
701	Jacket	0.66	0.34	---	310	460	---	156	47	---	0.22	18.0

5 TUBE FURNACE MEASUREMENTS

5.1 Description

Bench-scale experiments to determine cable fire effluent composition were conducted in a Tube Furnace as specified by ISO/TS 19700, “Controlled equivalence ratio method for the determination of hazardous components of fire effluents,” depicted in Figure 5-1. It consists of three main parts: (1) a quartz tube running through an electrically heated furnace; (2) a 30 L dilution and sampling chamber; and (3) a specimen boat and drive mechanism, which can advance the specimen into the furnace at a controlled rate. Air is supplied at both the upstream end of the quartz tube and in the dilution and sampling chamber. By controlling the upstream air flow rate and the specimen feed rate, the equivalence ratio in the Tube Furnace can be adjusted to model several fire stages. All experiments were conducted under well-ventilated conditions, with the temperature and equivalence ratio (normalized fuel to air ratio) set as specified in ISO 19706 (650 °C and 0.5, respectively). However, in some cases, to promote flaming combustion of the cables it was necessary to increase the temperature to as high as 825 °C, and even then, not all cables would sustain continuous flaming combustion.

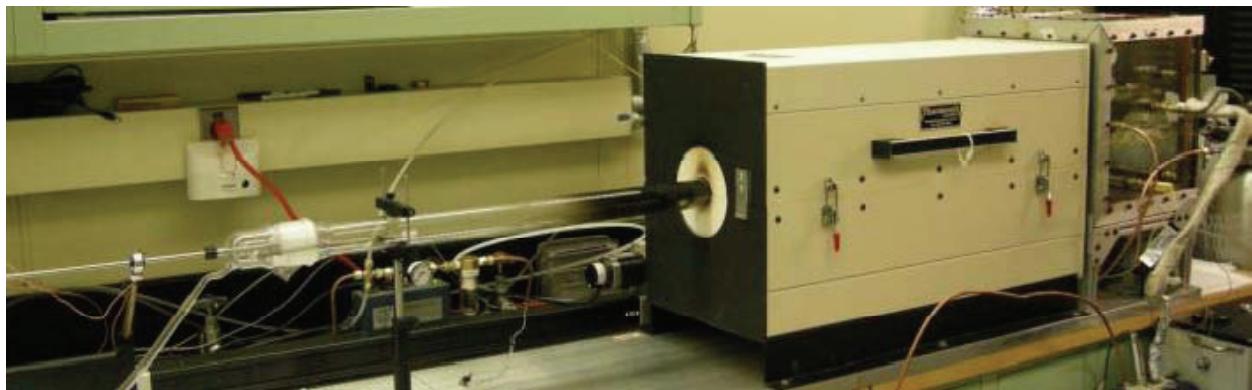


Figure 5-1. ISO/TS 19700 Tube Furnace.

5.1.1 Test Procedure

Test specimens were placed in the sample boat, which was then placed in the (cool) upstream end of the quartz tube. Once the appropriate temperature and air flow rates were established, the drive mechanism was activated to advance the specimen into the furnace. At the same time, a

portion of the exhaust from the dilution chamber was diverted to gas analysis instruments. Ideally, the combustion of the specimen reaches a steady-state, at which point gas concentrations can be recorded and yields derived. However, complex items like multi-conductor cables burn in a less uniform manner than, for example, common plastics. However, it is still possible to identify ignition and extinction events, and to determine average yields from the period in between.

In many cases, the cables were too large to be fed through the furnace intact. In these cases, the cables were disassembled into the component insulated conductor, filler, and jacket material and the same relative fraction of each was used. For example, one out of four insulated conductors, a fourth of the filler, and a fourth of the jacket, sliced longitudinally. It has been found by way of simple experiments that it makes essentially no difference whether a specimen is intact. However, it is important that the linear density of each component remain constant along the boat.

For each cable and set of conditions, three separate experiments were conducted; for each experiment the yield of each gas and soot was measured. The average of the three yields is reported, and the uncertainty is their standard deviation, representing the run-to-run variation of the measurement.

5.1.2 Quantification of CO and CO₂

CO and CO₂ were quantified using a non-dispersive infrared (NDIR) gas analyzer; oxygen was quantified by a paramagnetic analyzer in the same instrument. Gas was continuously drawn from the exposure chamber by a small pump and passed through a series of traps and filters, first a coiled tube immersed in a water ice bath, then an impinger bottle immersed in dry ice, with its upper half filled with glass wool, and finally a glass fiber disk filter. The intent was to remove particulates and condensable species, including water, that would otherwise interfere with and possibly harm the analyzer. While sampling, the flow was maintained at 1 L/min for the CO and CO₂ detectors and 0.2 L/min for the O₂ detector. The analyzer itself was calibrated daily with zero and span gases (a mixture of 5000 µL/L CO and 0.08 L/L of CO₂ in nitrogen, and ambient air 0.207 L/L oxygen).

5.1.3 Quantification of HCN, HCl and HBr

HCN, HCl, and HBr were quantified using a Fourier Transform Infrared (FTIR) Spectrometer, equipped with a stainless steel flow cell with 2 mm KBr windows and a 0.1 m path length, maintained at 170 °C. Gas samples were drawn through a heated 0.635 cm (0.25 in) stainless steel tube from the sampling and dilution chamber, at approximately the same location as the sampling line for the NDIR. The sample was pulled through the sampling line and flow cell by a small pump located downstream from the flow cell, and then exhausted into the lab exhaust duct. The pump flow was measured at 10 L/min maximum, but was at times lower due to fouling of the sampling lines with smoke deposits. The signal to noise ratio was also improved by averaging up to several hundred spectra prior to quantification. An example of a spectrum

resulting from this procedure is shown in Figure 5-2. Using these spectra, HCN, HCl, and HBr were quantified using the Autoquant, a software package for performing real time and off-line quantitative analyses of target compound based on the Classical Least Squares (CLS) algorithm as described by Haaland *et. al* (1985). In this method, the measured spectra are fit to linear combinations of reference spectra corresponding to the target compounds.

Calibration spectra were obtained from a quantitative spectral library assembled by the Midac Corporation (1999) and from a collection of spectra provided by the Federal Aviation Administration who performed bench-scale fire tests on similar materials (Speitel 2001). In this analysis, the least squares fits were restricted to characteristic frequency regions or windows for each compound that were selected in such a way as to maximize the discrimination of the compounds of interest from other components present in fire gases. Table 5-A lists the species included in this analysis and the frequency windows used for their quantification. Other species including acetylene and acrolein were initially included in the analysis, but after a careful examination of the spectra recorded in the experiments, it was determined that they are not present in measurable quantities. Although CO and CO₂ are not quantified by this method, they are included in the analysis so that their presence does not produce “false positives” in other species that absorb in the same frequency regions. All reference spectra were recorded at 170 °C and ambient pressure.

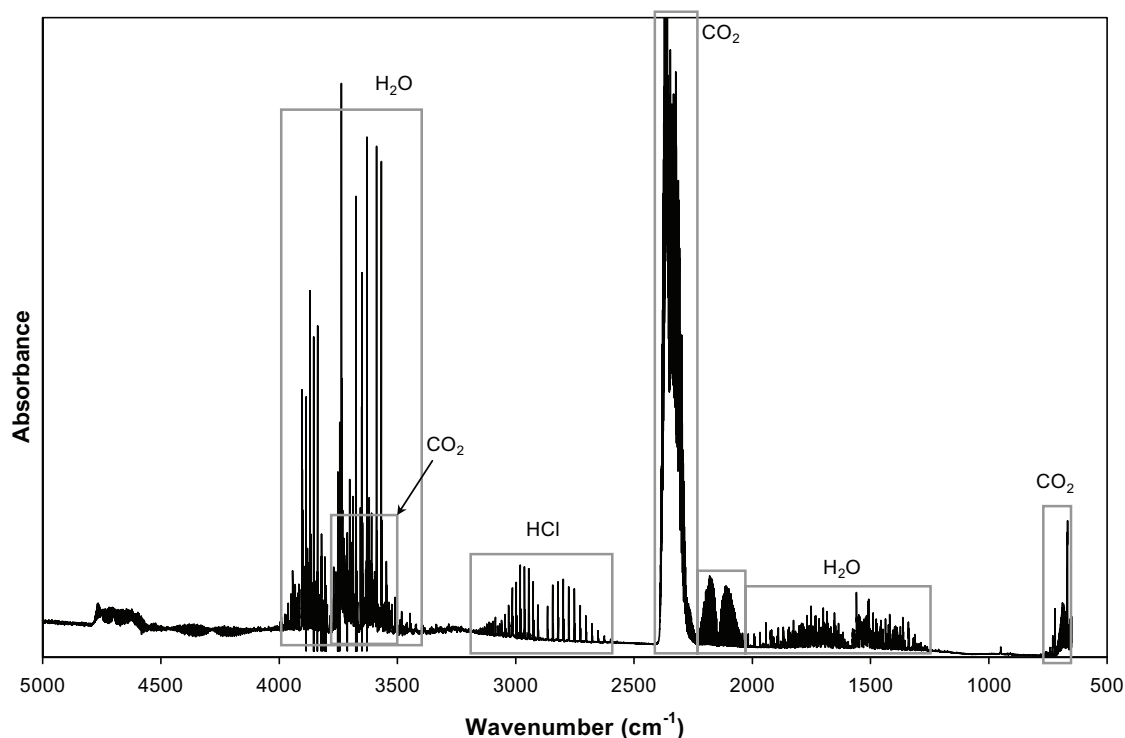


Figure 5-2. FTIR spectrum of the products of burning electrical cable.

Table 5-A. Species and Frequency Windows for FTIR Analysis.

Compound	Reference Volume Fraction (μL/L)	Frequency Window (cm ⁻¹)	Minimum Detection Limit (μL/L)
C ₃ H ₄ O	2250	850 to 1200, 2600 to 2900	20
C ₂ H ₂	387	3190 to 3420	NA ^a
CH ₄	483	2800 to 3215	NA ^a
CO	2410	2050 to 2225	20
H ₂ O	100 000	1225 to 2150, 3400 to 4000	NA ^a
HBr	2260	2400 to 2800	20
HCl	9870	2600 to 3100	20
HCN	507	710 to 722, 3200 to 3310	30
CO ₂	47 850	2230 to 2300	50

^aBecause these compounds do not contribute to toxicity, their minimum detection limits were not quantified.

5.1.4 Quantification of soot

Soot was quantified gravimetrically by drawing gas from the sampling and dilution chamber at a fixed rate of 1 L/min through a 47 mm diameter Teflon membrane filter. The filter was weighed before and after sampling, resulting in an average soot yield for the entire experiment.

5.2 Results

Nine of the cables tested at other scales were selected for testing in the Tube Furnace. An additional six cables that appeared visually different from these were also tested, but did not yield appreciably different results. In general, there are no clear trends linking cable appearance, burning behavior, and yields of gases of interest. Nor are there any correlations between measured product gases.

Cables were burned in over-ventilated conditions with an average equivalence ratio of 0.53 with a run-to-run variation of ±0.18.

Figure 5-3 shows the yields of gases produced from burning cables. Yields, in units of g/g, range as follows: 0.59 to 1.72 for CO₂; 0.19 to 0.50 (although one of the other cables had a CO yield of essentially zero); 0.01 to 0.28 for HCl¹; and 0.008 to 0.064 for soot. HCN was not detected in any experiment. Error bars depicted in the plot are the standard deviations of that specific gas yield across three separate experiments. For cables 23 and 271, an instrumentation failure

¹ Note that during the first series of full-scale, Multiple Tray Experiments in May, 2009, a considerable amount of acidic liquid accumulated in the ducts that carried the exhaust gases from the fire. It is believed that the high levels of HCl in the smoke reacted with the galvanized portion of the duct work to form the corrosive liquid. A professional cleaning crew was hired to clean the ducts.

prevented the measurement of HCL, and the uncertainties for those two cables are the maximum yield measured from any other cable.

Figure 5-4 shows the cross-correlations of yields of pairs of measured gases as well as soot. Each point represents a specific number cable. Based on the extremely low R^2 values and the scatter about the least-squares fit, there appears to be no mathematical correlation between the yields of any of these gases or the soot. This is unfortunate in that it will not be possible to extrapolate the yield of any one gas from any other, and emphasizes that in equipment testing, all must be measured independently.

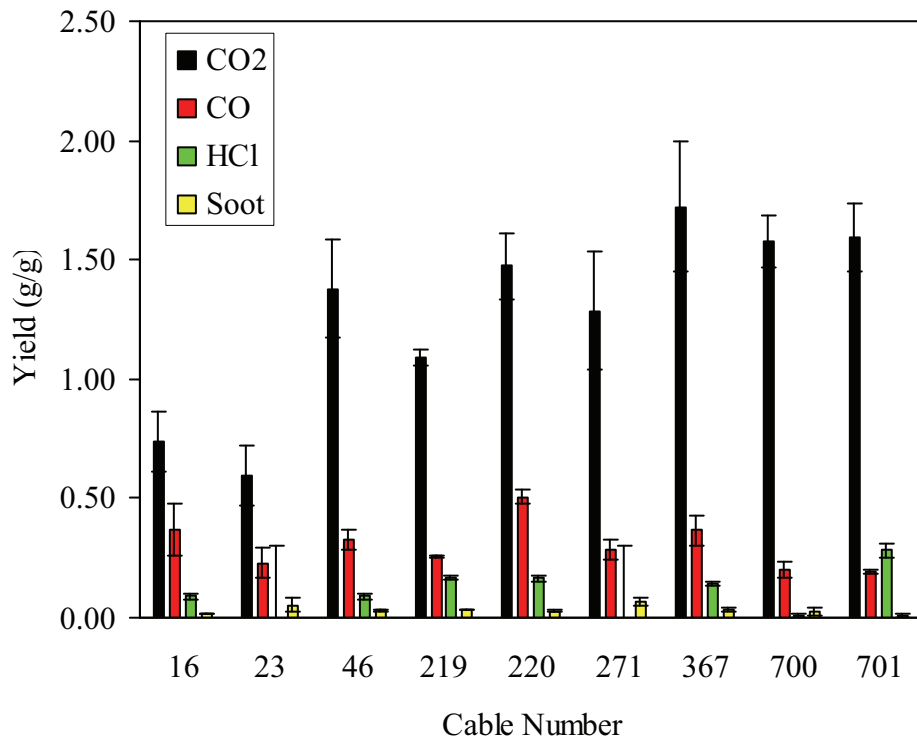


Figure 5-3. Yields of various product gases.

Finally, the mass of residue as a function of the initial presumed combustible mass was measured. In other words, this is the final mass remaining in the sample boat after an experiment, less the mass of the metal conductors, divided by the initial mass of the cable specimen, less the mass of the metal conductors. These ranged from 0.04 to 0.29, and did not have any noticeable correlation with the gas or soot yields. These numbers are substantially lower than those measured in the micro-calorimeter, a difference attributable to the fact that in the micro-calorimeter, the specimens are exposed to an oxygen-free environment, while in the well-ventilated Tube Furnace they are exposed to fresh air, even when flaming has subsided.

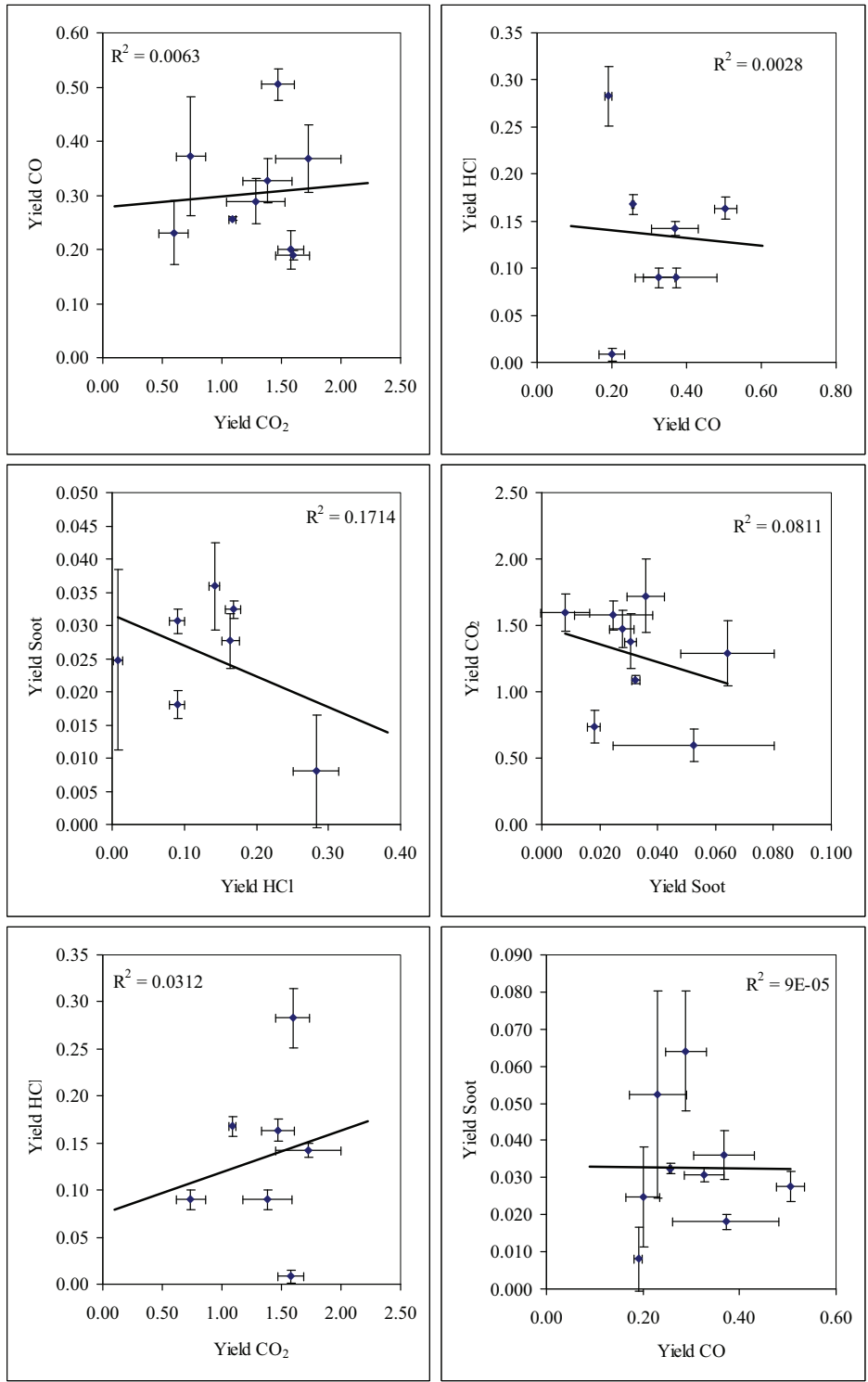


Figure 5-4. Cross-correlations of gas pairs

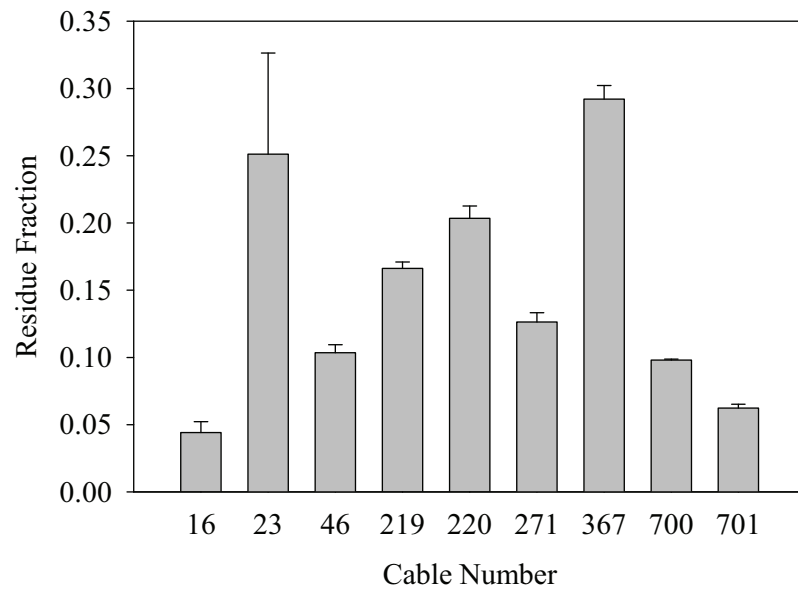


Figure 5-5. Residue/char yield of various cables

6 CONE CALORIMETER MEASUREMENTS

6.1 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 the CHRISTIFIRE program, 12 cable samples were tested at 3 different heat fluxes (25 kW/m², 50 kW/m², and 75 kW/m²) to determine at which flux the burning rate of cables best matched that measured in the Radiant Panel Apparatus and in the Multiple Tray Experiments.

The Cone Calorimeter measurements were performed at the University of Dayton Research Institute in October, 2009. The experiments were conducted on a FTT Dual Cone Calorimeter at three imposed heat fluxes (25, 50, and 75 kW/m²) with an exhaust flow of 24 L/s using the standardized Cone Calorimeter procedure for cable burns, 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.” Sample preparation for all cable samples used the procedure outlined in Sections 8.1.2 and 8.1.4 of the standard, with some modifications as described in the procedure below. The heat release rate measurements have a standard relative uncertainty of ±10 %, based on an assumed specimen surface area of 88.4 cm² (13.7 in²). All samples were tested in triplicate at each heat flux, except for the cases at 75 kW/m².

6.1.1 Procedure for preparing cable samples for Cone Calorimeter testing

Step 1. Cable samples were cut into 10 cm (4 in) segments and wrapped in aluminum foil with shiny side up (Figure 6-1).

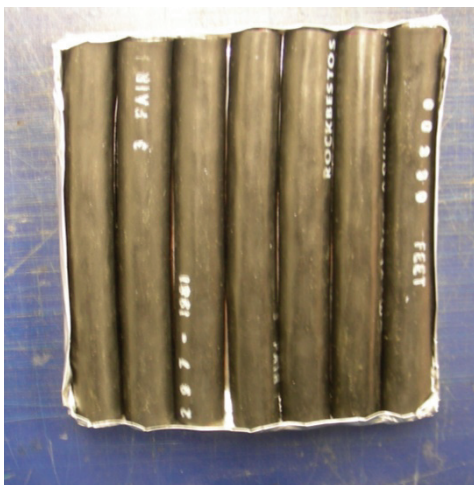


Figure 6-1. Typical cable sample for Cone Calorimeter.

Step 2. Supplies included the frame bottom, tray, ceramic insert, mineral wool, sample, grid, and frame top (Figure 6-2).

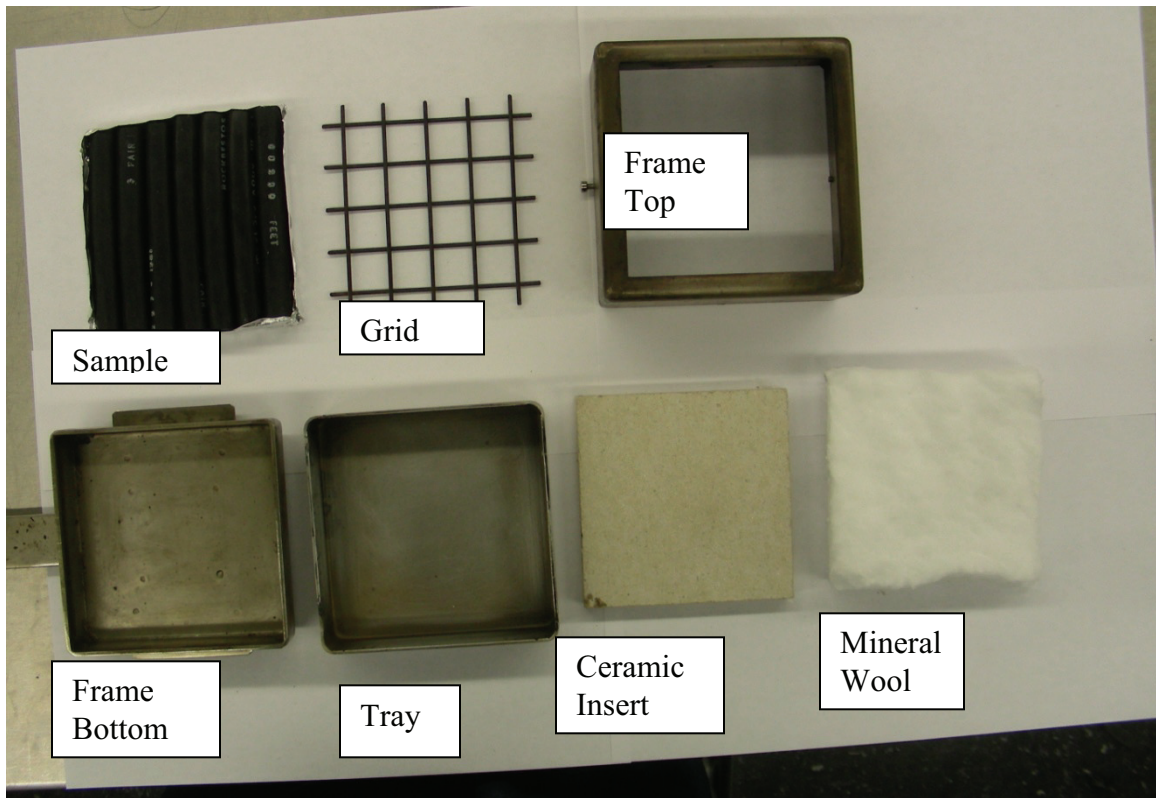


Figure 6-2. Sample holder for Cone Calorimeter.

Step 3. Depending on the make-up of the cables, specimens were sometimes prepared using trays. The tray was placed on top of the frame base, and the ceramic insert and mineral wool were placed into the tray (Figure 6-3).

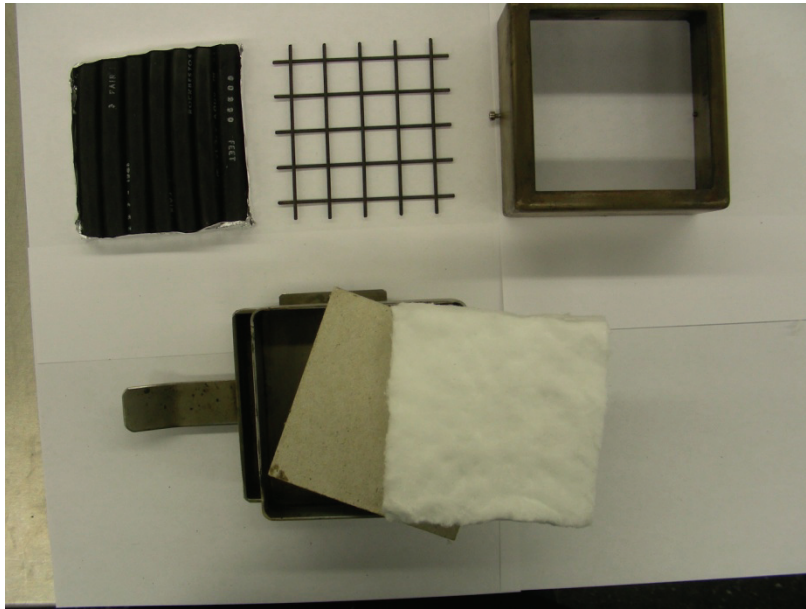


Figure 6-3. Tray for holding cables in Cone Calorimeter.

Step 4. The sample and grid were then placed on top of the mineral wool (Figure 6-4).

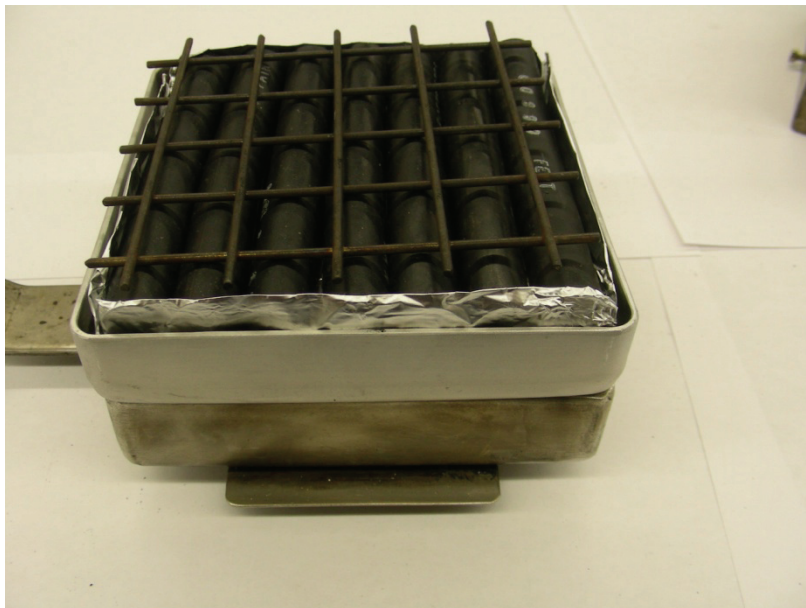


Figure 6-4. Sample holder assembly for Cone Calorimeter.

Step 5. Finally, the entire specimen and tray assembly were covered with the top of the frame (Figure 6-5).



Figure 6-5. The completed holder assembly for the Cone Calorimeter.

Note 1. If no tray was necessary, Steps 1 through 5 were followed but the ceramic insert, mineral wool, sample and grid were placed directly into the frame base (Figure 6-6).

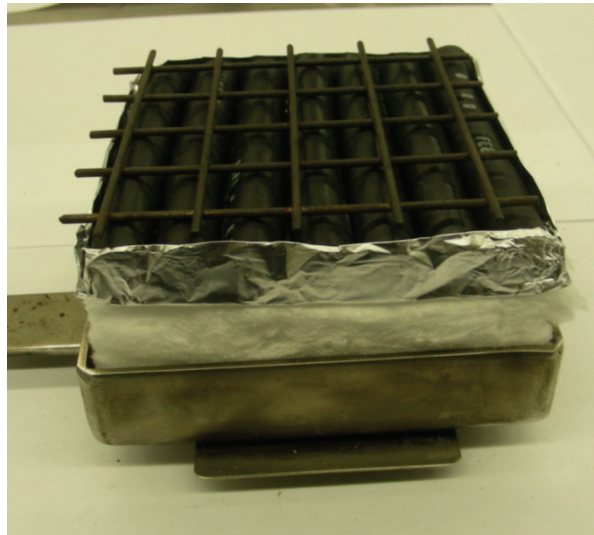


Figure 6-6. Modified sample holder for Cone Calorimeter.

Note 2. In order to make certain that the entire sample assembly fit into the sample frame, several combinations of ceramic tile and thicknesses of mineral wool were used.

6.2 Results for Individual Cable Types

The following pages contain a brief description² of the Cone Calorimeter measurements, along with the measured heat release rates for the cable samples at the different heat flux exposures. As part of the analysis, an effective heat release rate per unit area (HRRPUA) is calculated. Figure 6-7 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:

$$Q'' = \int_0^{\infty} \dot{q}''(t) dt \quad (6.1)$$

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:

$$0.1 Q'' = \int_0^{t_1} \dot{q}''(t) dt \quad ; \quad 0.9 Q'' = \int_{t_2}^{\infty} \dot{q}''(t) dt \quad (6.2)$$

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

$$\overline{\dot{q}''} = \frac{\int_{t_1}^{t_2} \dot{q}'' dt}{t_2 - t_1} \quad (6.3)$$

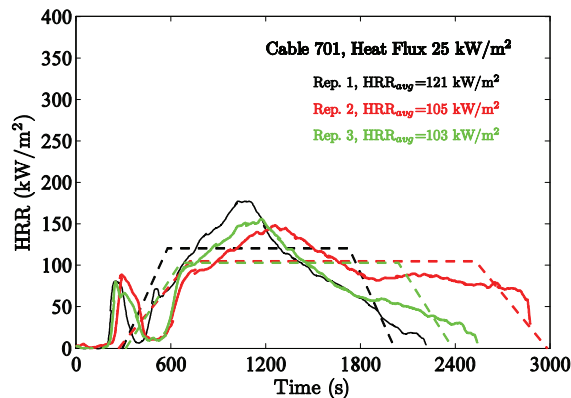


Figure 6-7. Sample output from Cone Calorimeter.

² Note that there is no narrative for the measurements performed with an imposed heat flux of 75 kW/m².

6.2.1 Cable #11

Imposed Heat Flux: 25 kW/m²

At the beginning of the test, occasional loud pops and crackling were heard, followed by a prolonged period of flashing, and then the flames went out. The spark igniter was left in for another 300 s, but the smoke production eventually stopped, the mass loss decreased to zero, and the sample did not reignite. The samples appeared to be mostly intact at the end of the test with only some surface damage. The underlying jacket and internal insulation appeared to be completely undamaged. No aluminum trays were used with these samples.



Figure 6-8. Photograph of Cable #11 after Cone Calorimeter test at 25 kW/m².

Imposed Heat Flux: 50 kW/m²

Sample #1 in this set smoked, then loud popping was heard after exposure to the heater. This was followed by flashing and then unsteady ignition and then the flame went out. The spark was re-inserted and sporadic flashing continued, but eventually this stopped as well. The spark was left in for 400 s with no re-ignition and mass loss decreased significantly. The sample after this test showed mostly surface damage and some discoloration of the insulation material. Sample #2 showed the same behavior as Sample #1, but the spark was left in for 600 s after the first flameout. The sample did not ignite after 600 s, but more smoke was noted even though the mass loss rate was fairly low. More discoloration of the insulation was noted in the sample after the test. Sample #3 showed the same behavior as the first two samples, but the spark was left in for 900 s. The sample exhibited sporadic flashing. The spark was left in for another 300 s and finally the sample reignited, but the flames were still unsteady. Some dripping was noted out the bottom of the holder which eventually became a steady stream of molten/decomposing polymer and insulation that leaked out the bottom of the holder. The final sample residue was greatly damaged and most of the interior insulation had been burned away leaving just metal wires that had collapsed down and some soot/char residues. No aluminum trays were used with this sample.



Figure 6-9. Photograph of Cable #11 after Cone Calorimeter test at 50 kW/m².

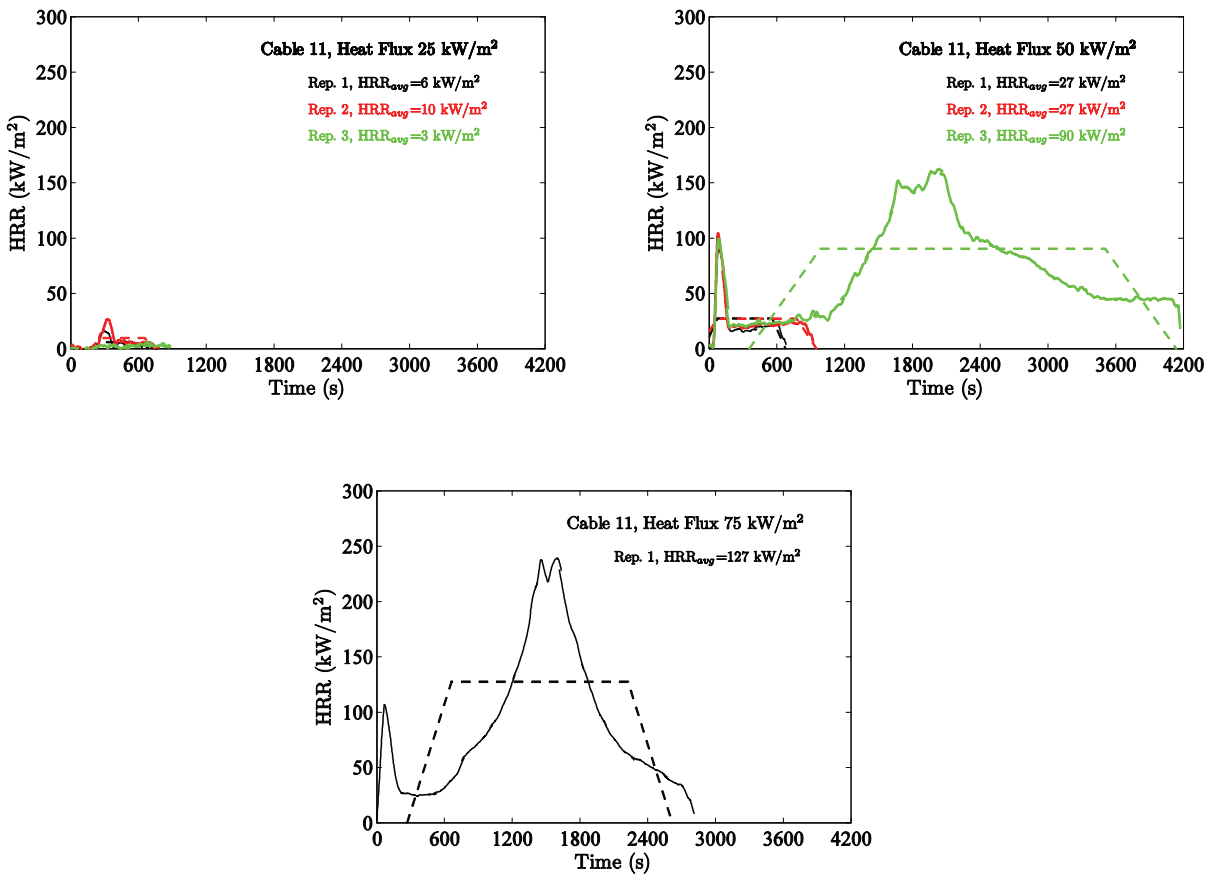


Figure 6-10. Heat Release Rates for Cable #11 in the Cone Calorimeter.

6.2.2 Cable #16

Imposed Heat Flux: 25 kW/m²

The cables smoked for a long time under this heat flux before igniting, with some flashing (unsteady ignition) noted directly under the spark igniter noted. Later, the sample generated popping noises along with a prolonged flashing period before the sample finally ignited. The sample then burned for a short time. The spark was reinserted with more flashing noted, but eventually this stopped and the sample would not re-ignite – even smoking of the sample slowed down and the mass loss rate greatly decreased. During this flashing period there was substantial soot buildup on the spark igniter, making it difficult to keep the sample ignited. Sample 3 in this set was tested without a metal tray since dripping from the insulation appeared to be minimal. While the sample took even longer to ignite without the tray, the fire behavior was the same. From the sample pictures below, it appears that the outer jacket chars and protects the underlying insulation from further thermal damage other than some dripping/flowing of the insulation out the ends of the cable.



Figure 6-11. Photograph of Cable #16 after Cone Calorimeter test at 25 kW/m².

Imposed Heat Flux: 50 kW/m²

Samples 1 and 3 ignited quickly and burned for a few minutes, then extinguished. Sample 2, however, burned much longer to leave a white ash all over the sample surface. The underlying insulation was melted for Samples 1 and 3, but it did not ignite. No aluminum trays were used.



Figure 6-12. Photograph of Cable #16 after Cone Calorimeter test at 50 kW/m².

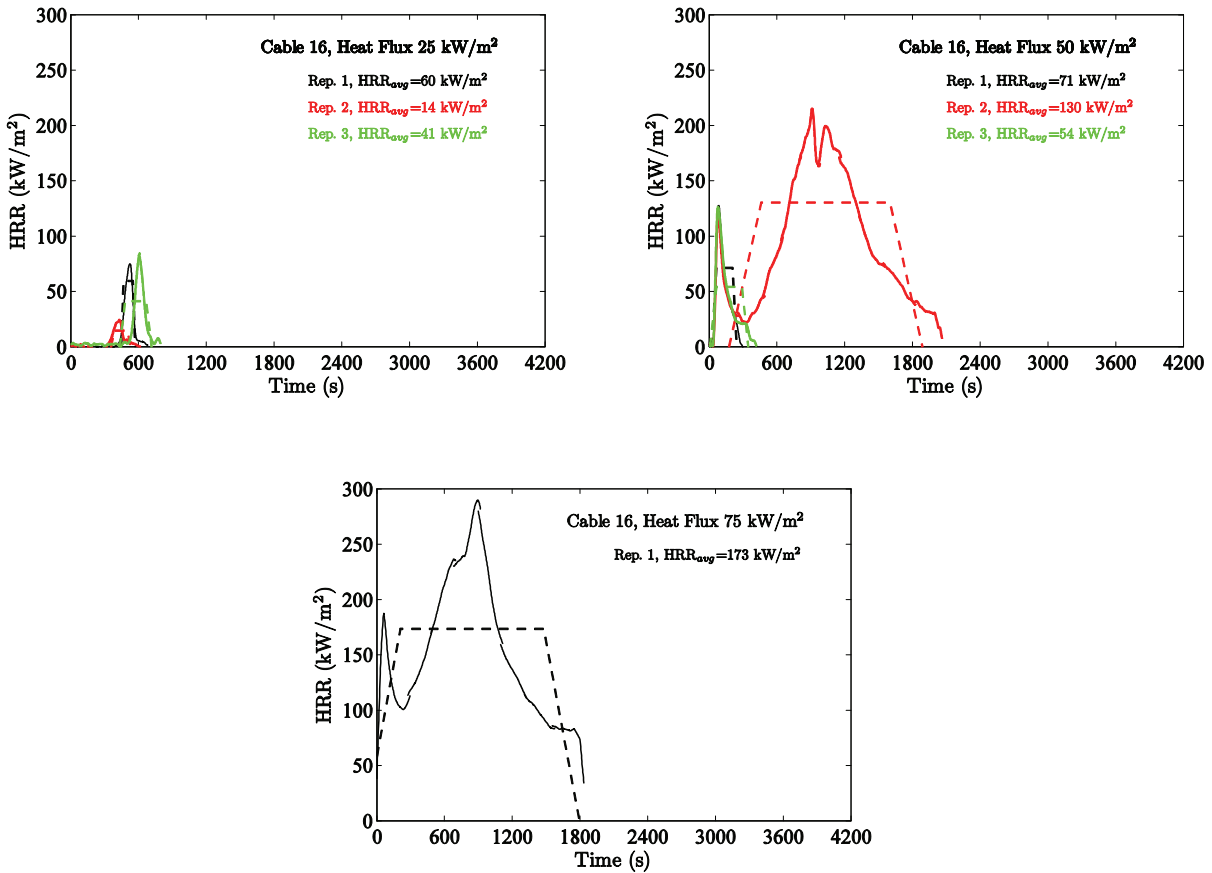


Figure 6-13. Heat Release Rates for Cable #16 in the Cone Calorimeter.

6.2.3 Cable #23

Imposed Heat Flux: 25 kW/m²

Sample 1 smoked, flashed, and then ignited with a crackling noise heard during burning. The sample went out and the spark was reinserted but the sample would only flash and not re-ignite. The spark was left in for 600 s with flashing only occurring at the spark and not at the sample surface. At 800 s the sample finally reignited, but only at the edges of the sample holder. Some dripping was noted out the bottom of the sample holder at the end of the test – no aluminum tray was used for the first sample. For the second and third samples, the aluminum tray was used and dripping no longer occurred and fire behavior was otherwise the same. However, Sample 2 and 3 were even harder to keep lit with the reinserted spark and Sample 3 would not re-ignite at all, even after 800 s of additional exposure. Sample 3 does not exhibit burning damage except for the melting of the blue filler material that leaked out at the ends. The other samples show significant damage to the cable surface and the underlying insulation.

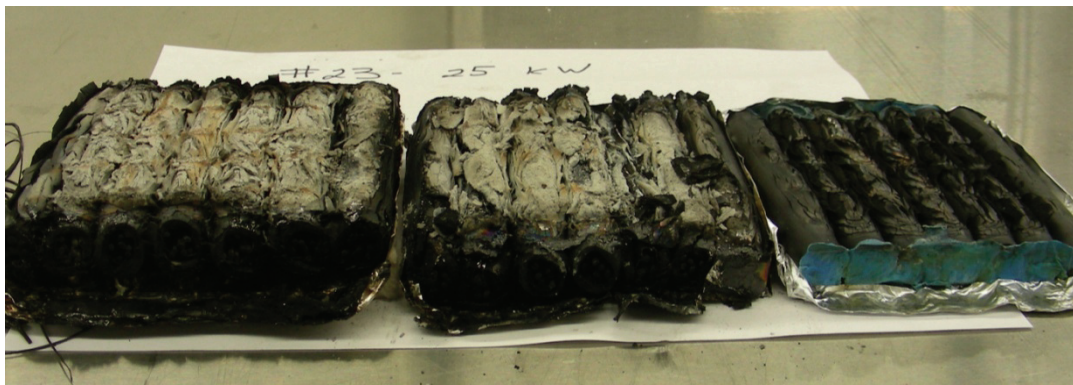


Figure 6-14. Photograph of Cable #23 after Cone Calorimeter test at 25 kW/m².

Imposed Heat Flux: 50 kW/m²

Upon exposure to the cone heater, Sample 1 smoked, flashed quickly, and then ignited. However, the flames quickly went out and the spark was reinserted. The sample did nothing at first and then began to flash again, eventually reigniting but the flames always appeared unsteady through the entire test. Smoke was observed followed by lots of non-flaming drips out the bottom of the sample holder. This sample used no aluminum tray. Aluminum trays were used for Samples 2 and 3, which did not change fire behavior any and only partially mitigated the dripping behavior.

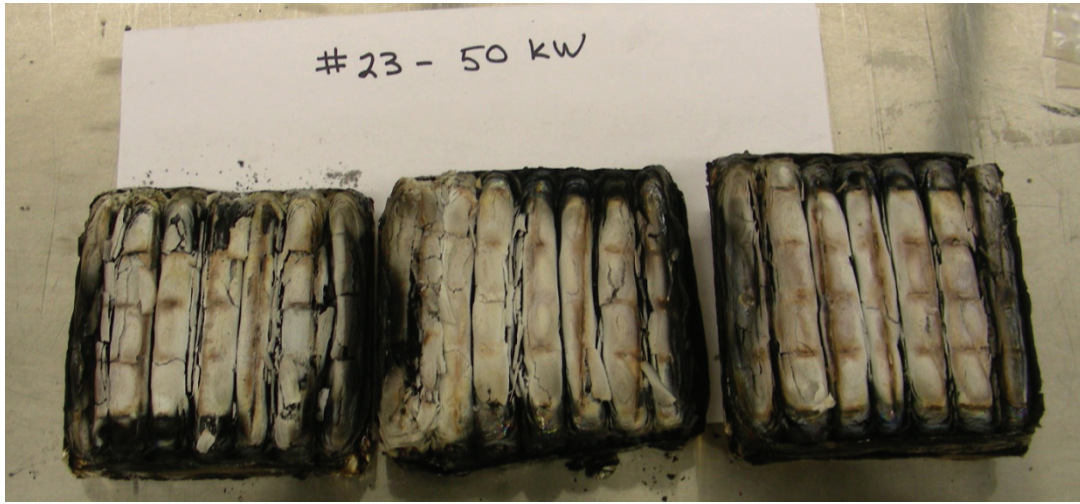


Figure 6-15. Photograph of Cable #23 after Cone Calorimeter test at 50 kW/m².

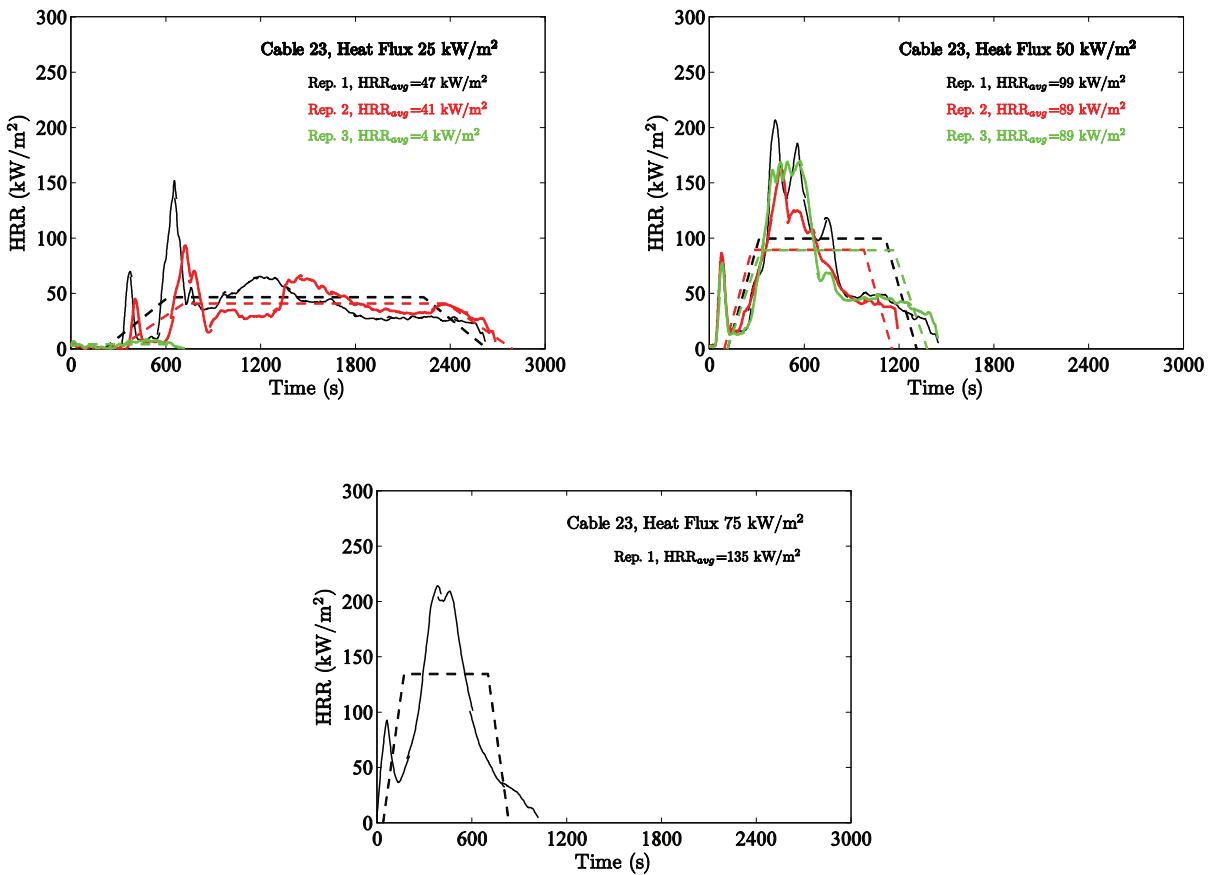


Figure 6-16. Heat Release Rates for Cable #23 in the Cone Calorimeter.

6.2.4 Cable #43

Imposed Heat Flux: 25 kW/m²

The samples smoked, popped a bit (some blistering was noted) with some flashing, but there was no sustained ignition. The test was stopped at 500 s due to no significant mass loss and decrease in smoke release. The inner insulation for this sample set appears to be mostly undamaged after the test. No aluminum trays were used with this sample set.



Figure 6-17. Photograph of Cable #43 after Cone Calorimeter test at 25 kW/m².

Imposed Heat Flux: 50 kW/m²

The samples smoked, followed by some crackling, some flashing, and then the sample ignited. They burned for a while and then went out and could not be reignited with the spark. The samples appear to be mostly undamaged, much like the 25 kW/m² sample data. No aluminum trays were used with this sample set.



Figure 6-18. Photograph of Cable #43 after Cone Calorimeter test at 50 kW/m².

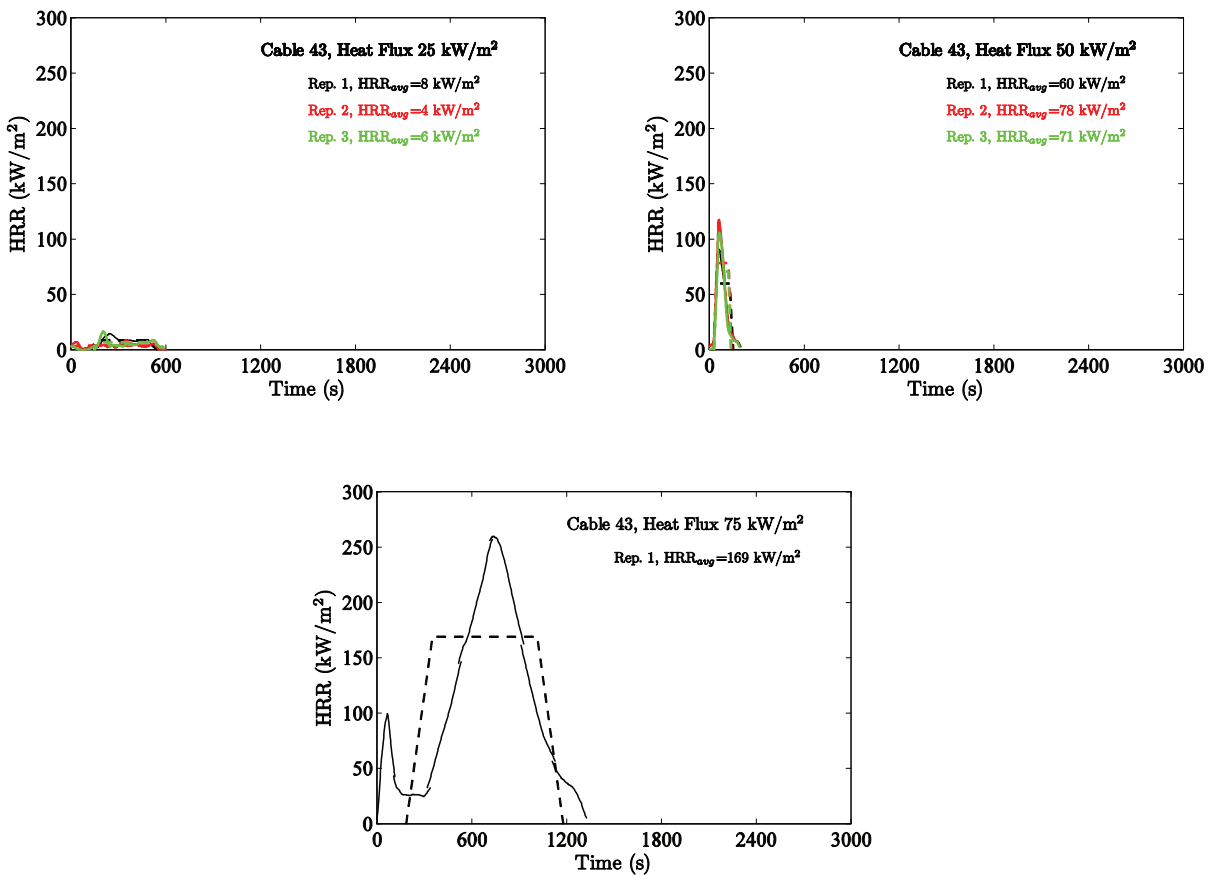


Figure 6-19. Heat Release Rates for Cable #43 in the Cone Calorimeter.

6.2.5 Cable #46

Imposed Heat Flux: 25 kW/m²

Fire behavior was the same as that noted for Cable #43, but no crackling or popping noises were heard and the surface of the samples did not blister. Some damage to the inner insulation was noted. No aluminum trays were used with this sample set.



Figure 6-20. Photograph of Cable #46 after Cone Calorimeter test at 25 kW/m².

Imposed Heat Flux: 50 kW/m²

Fire behavior for this sample set was the same as that noted for Cable #43, but no crackling or popping heard. No damage to underlying insulation was noted. No aluminum trays were used with this sample set.



Figure 6-21. Photograph of Cable #46 after Cone Calorimeter test at 50 kW/m².

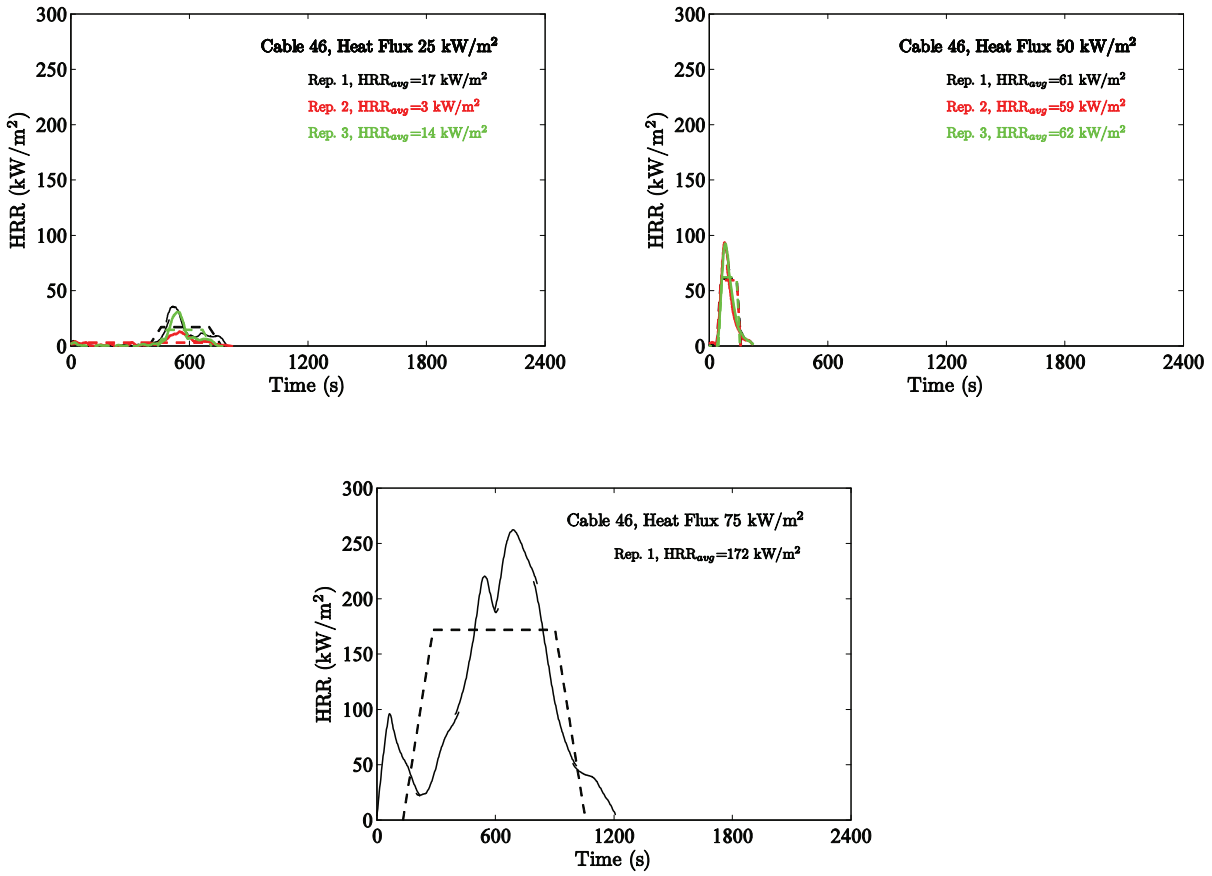


Figure 6-22. Heat Release Rates for Cable #46 in the Cone Calorimeter.

6.2.6 Cable #219

Imposed Heat Flux: 25 kW/m²

When the cables ignited, the flame spread all over the sample surface with a steady flame. Some blue colored flames were noted near the bottom edges of the sample during burning. No aluminum trays were used with this sample set. The samples by the end of the burn were completely consumed with only a fragile white ash on the surface.



Figure 6-23. Photograph of Cable #219 after Cone Calorimeter test at 25 kW/m².

Imposed Heat Flux: 50 kW/m²

The samples ignited quickly with lots of popping heard followed by pieces of the sample surface flying out of the top of the sample holder. This behavior died down as the flames died down in intensity. No aluminum trays were used with this sample set.

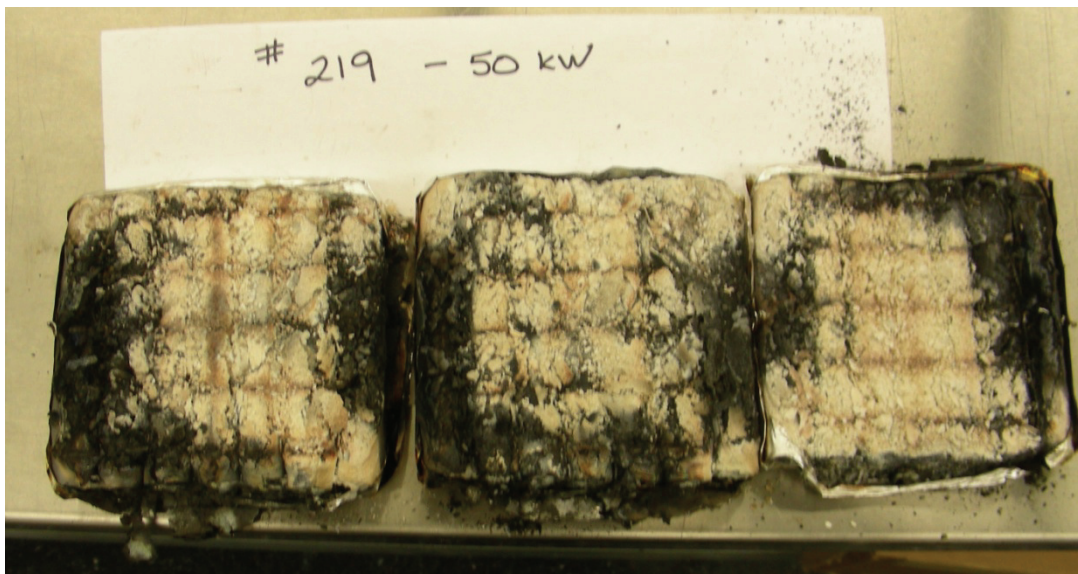


Figure 6-24. Photograph of Cable #219 after Cone Calorimeter test at 50 kW/m².

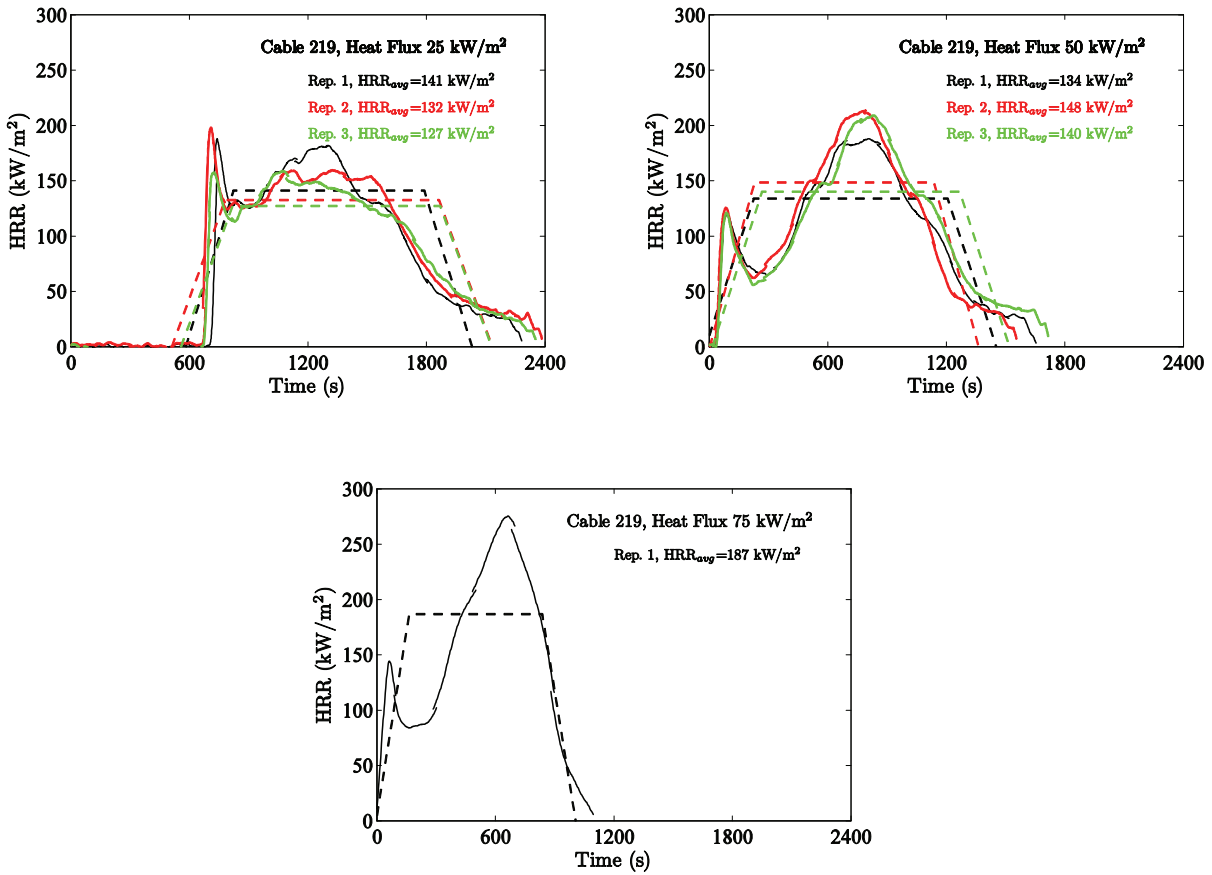


Figure 6-25. Heat Release Rates for Cable #219 in the Cone Calorimeter.

6.2.7 Cable #220

Imposed Heat Flux: 25 kW/m²

The first sample took a very long time to ignite with fire behavior similar to that of Cable #219. Later in the test, there were flaming drips out the bottom of the holder noted, and an aluminum tray was used for Sample 2. This sample however did not ignite even by 1000 s (see charred cable in the middle of the photograph below). So for Sample 3 the aluminum tray was removed and the sample ignited at 980 s with flaming drips noted again out the bottom of the sample holder later in the test.



Figure 6-26. Photograph of Cable #220 after Cone Calorimeter test at 25 kW/m².

Imposed Heat Flux: 50 kW/m²

Upon exposure to the heater, the samples smoked, with some flashing and popping heard before ignition occurred. Some pieces popped and flew out of sample holder, but not as extensive as that noted with Cable 219. Sample 2 extinguished after burning for a little bit but reignited after 60 s of spark re-exposure. No aluminum trays were used with these samples.

Note that no test was done at 75 kW/m².



Figure 6-27. Photograph of Cable #220 after Cone Calorimeter test at 50 kW/m².

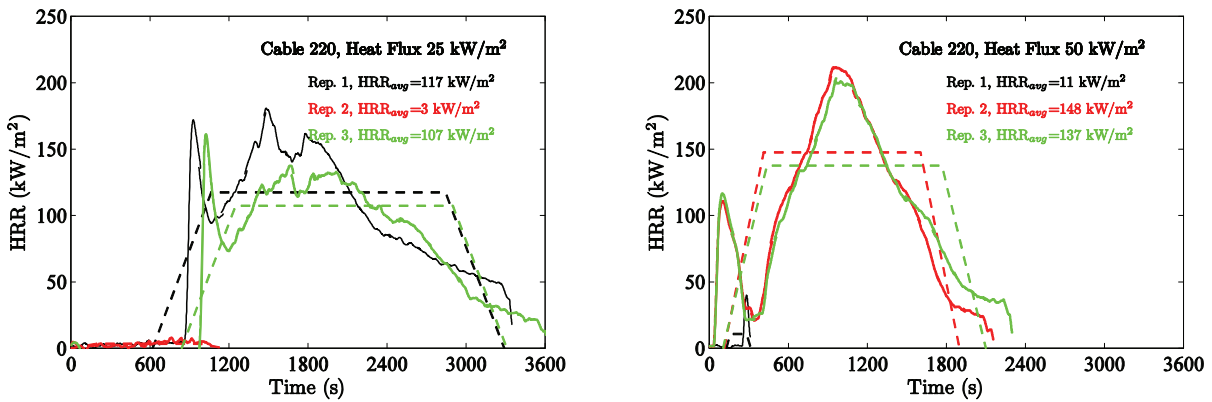


Figure 6-28. Heat Release Rates for Cable #220 in the Cone Calorimeter.

6.2.8 Cable #270

Imposed Heat Flux: 25 kW/m²

Following ignition, some bubbling was noted beneath the surface of the jacket material. Eventually the bubbling subsided as the flame grew bigger. Some smoke was observed coming out the bottom of the sample holder later in the test. By the end of the test the sample surface was badly damaged and the sample frame and grid showed significant corrosion/discoloration from the samples combustion gases. Prying apart the frame and grid at the end of the experiment showed that some dripping had occurred so an aluminum tray was used for the second sample. Fire behavior for the second sample was the same as the first, but the ignition was delayed a bit. Smoke was still observed to come out the bottom of the sample holder though, and so for the third sample, the aluminum tray was not used. Fire behavior of the third sample was identical to that of the first.



Figure 6-29. Photograph of Cable #270 after Cone Calorimeter test at 25 kW/m².

Imposed Heat Flux: 50 kW/m²

Following ignition, the sample suddenly extinguished. Upon reinserting the spark, the sample quickly reignited and began to burn vigorously. Some pieces of char would deform and flow over the top edge of the holder with flaming drips noted. During the growth of the peak flame height, a high pitched whining sound could be heard. Occasional smoke and drips out the bottom of the holder were noted. The final sample residues were notable in that the copper braid was intact and quite rigid, forming hollow tubes where the center copper wire had fallen to the bottom of the tube. No insulation or jacket material beyond char was left behind for these badly damaged samples. No aluminum trays were used with this sample set.

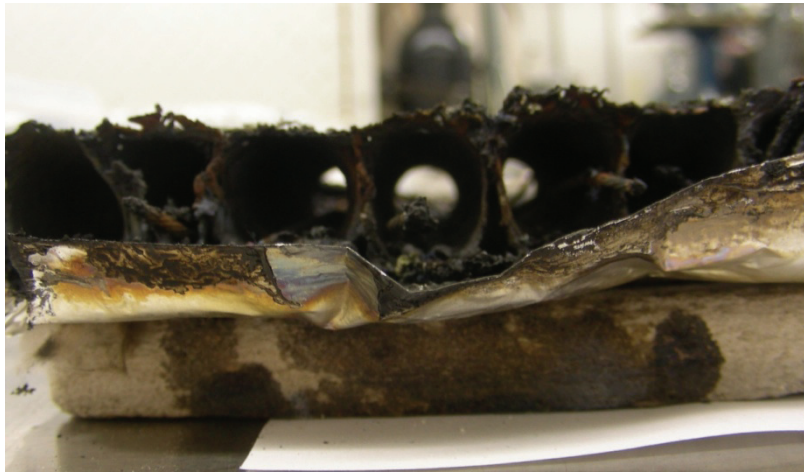


Figure 6-30. Photograph of Cable #270 after Cone Calorimeter test at 50 kW/m².

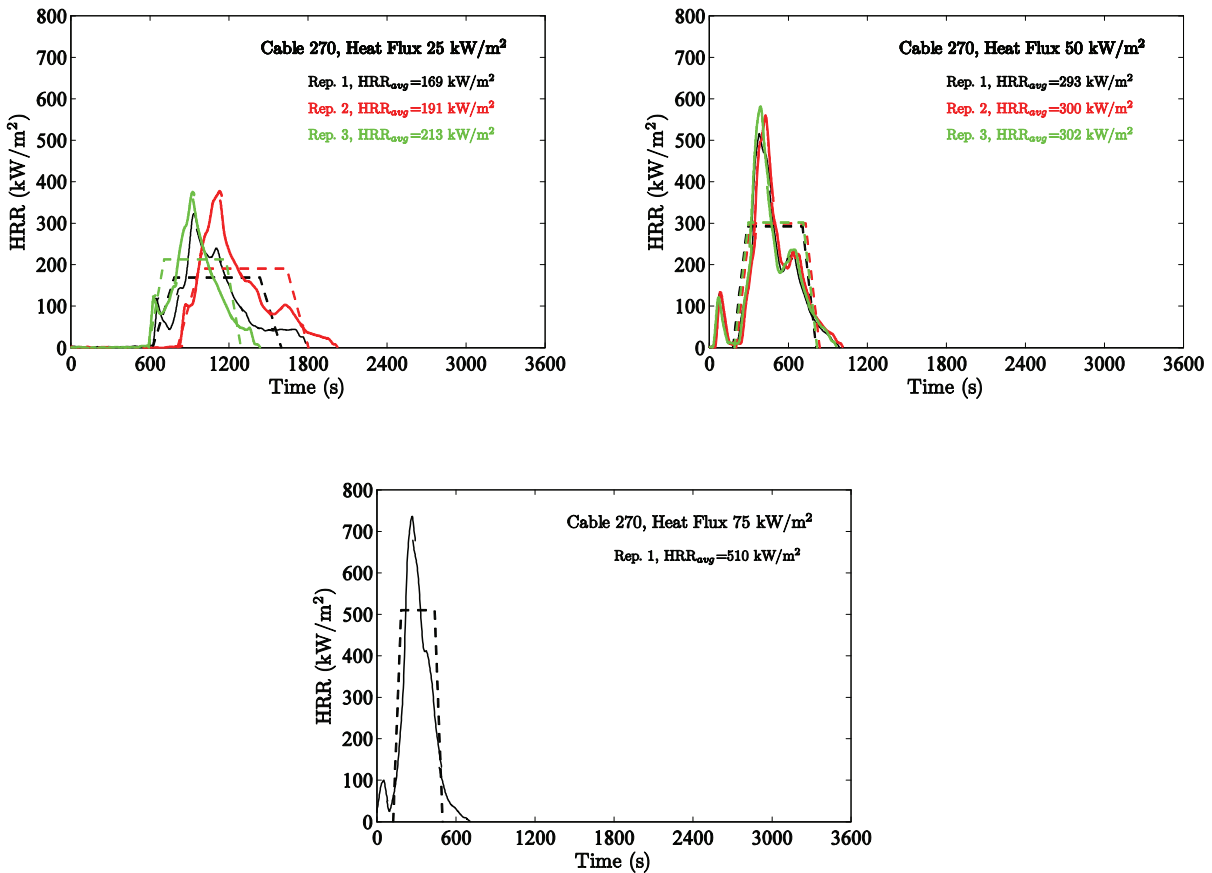


Figure 6-31. Heat Release Rates for Cable #270 in the Cone Calorimeter.

6.2.9 Cable #271

Imposed Heat Flux: 25 kW/m²

During the early stages of burning, some popping of pieces off the sample surface occurred, but the sample did not burn long. The spark igniter was reinserted with some minor flashing observed but no sustained ignition was observed. Interior insulation appears to be mostly undamaged, again indicating that the jacket was providing significant thermal protection for the underlying material. No aluminum trays were used with this sample set.

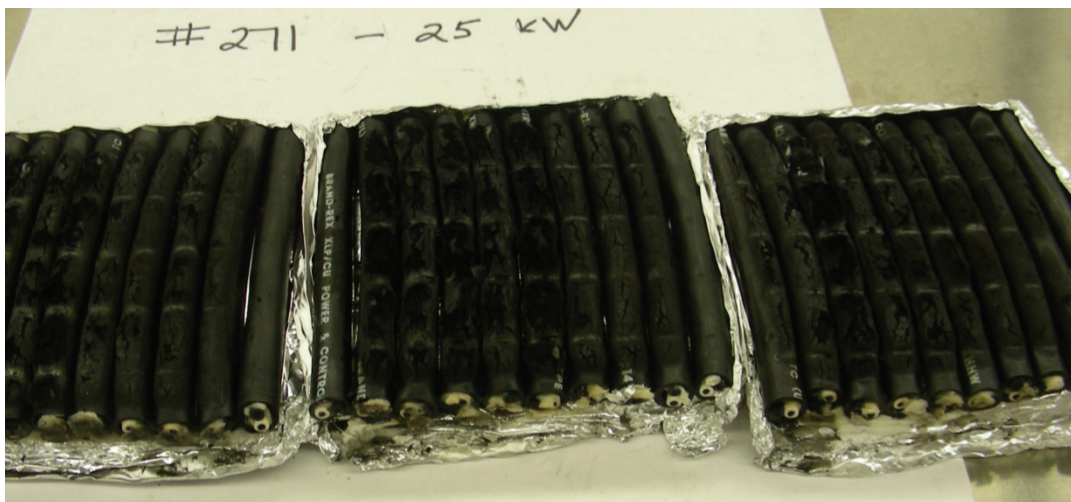


Figure 6-32. Photograph of Cable #271 after Cone Calorimeter test at 25 kW/m².

Imposed Heat Flux: 50 kW/m²

Then the sample smoked and ignited with more little glowing sparks/coals coming off the sample surface during testing. Eventually this stopped and the sample continued burning for awhile and then extinguished. While the surface of the sample was badly damaged, the underlying material was still mostly untouched. No aluminum trays were used with this sample set.

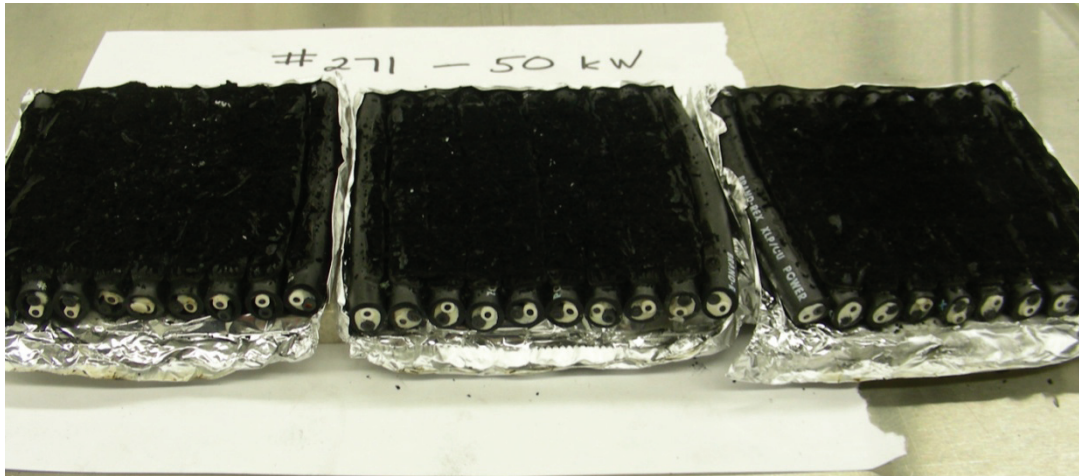


Figure 6-33. Photograph of Cable #271 after Cone Calorimeter test at 50 kW/m².

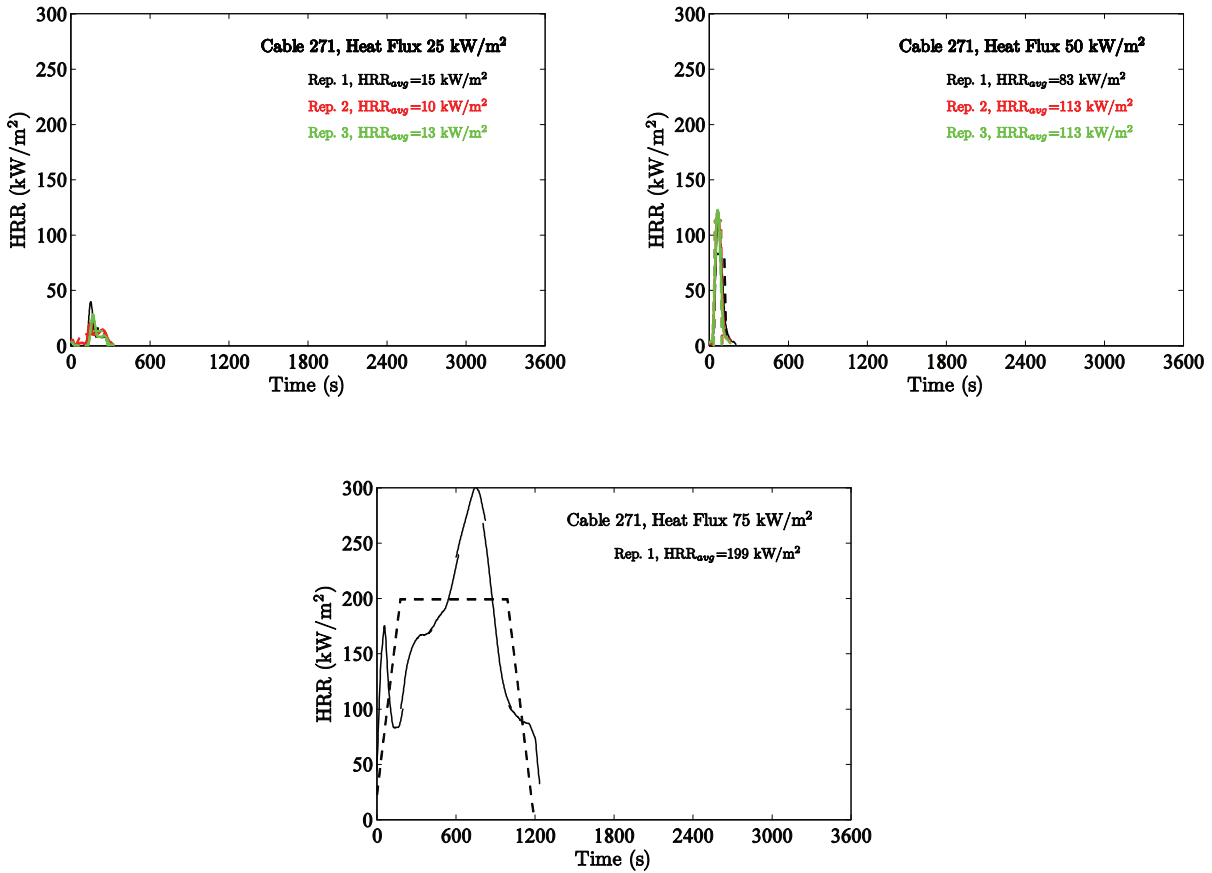


Figure 6-34. Heat Release Rates for Cable #271 in the Cone Calorimeter.

6.2.10 Cable #367

Imposed Heat Flux: 25 kW/m²

The samples ignited with some spitting of surface pieces out of the sample holder and crackling sounds were noted. The pieces that landed outside the holder left white marks on the metal and corroded parts of the aluminum foil used to protect the load cell under the sample. The sample only burned for a little while and then would not reignite. The underlying insulation appeared undamaged although the surface of the sample appeared heavily damaged from the short 130 s to 140 s burn time. No aluminum trays were used.



Figure 6-35. Photograph of Cable #367 after Cone Calorimeter test at 25 kW/m².

Imposed Heat Flux: 50 kW/m²

Numerous flaming particles were observed “spitting” out of the sample surface initially in the fire. The fire growth then began to die down and eventually picked back up, growing steadily and then burning for a very long time (50 min). Some dripping out of the sample holder was noted. The final samples were badly damaged, composed of fragile white ash on the surface and partially collapsed char tubes and damaged copper wire deeper into the sample. No aluminum trays were used.



Figure 6-36. Photograph of Cable #367 after Cone Calorimeter test at 50 kW/m².

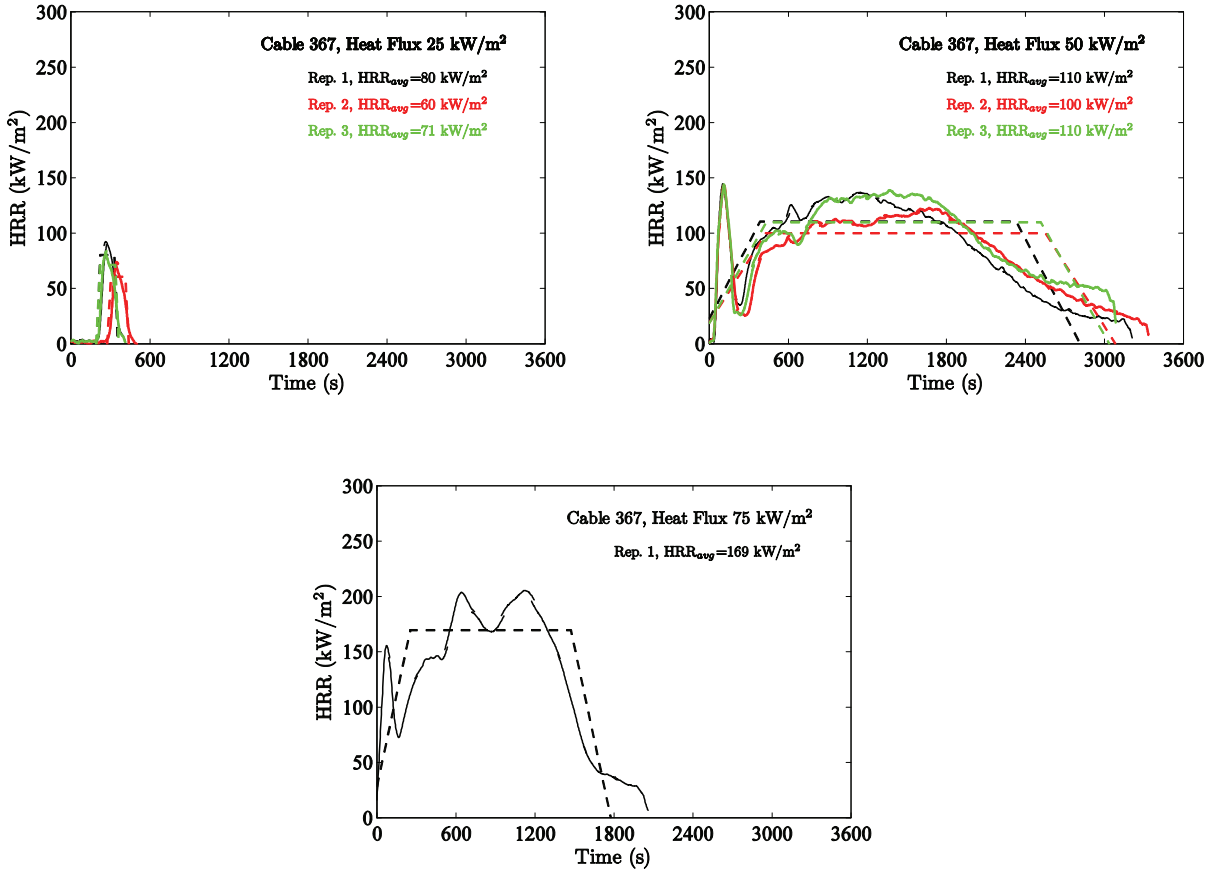


Figure 6-37. Heat Release Rates for Cable #367 in the Cone Calorimeter.

6.2.11 Cable #700

Imposed Heat Flux: 25 kW/m²

There was very little smoke or mass loss even up to 600 s and no ignition noted. The third sample was exposed for 800 s, after which it finally ignited but then extinguished again after a short burning period. The spark igniter was reinserted for another 200 s with prolonged flashing noted, but the sample would not stay lit. Excessive soot buildup on the spark igniter caused the spark to go out more than once and resulted in stopping the test for Sample 3. Due to its prolonged heat exposure, Sample 3 exhibited more thermal damage to the surface and insulation than the other two samples (sample at far right in pictures below). No aluminum trays were used.



Figure 6-38. Photograph of Cable #700 after Cone Calorimeter test at 25 kW/m².

Imposed Heat Flux: 50 kW/m²

The samples smoked and then ignited with no flashing noted. As the flame intensity grew, the flame turned green in color, followed by a blue color and then eventually turned yellow with some dark blue noted at the edges of the sample holder. Later in the burn smoke was observed to come out of the sample followed by occasional flames. Sample 1 used no aluminum tray, but Samples 2 and 3 did. However, there was no significant difference in the fire behavior. The final sample residues were badly damaged with bare copper wires noted sticking out the ends of the samples.

Note that no sample was tested at 75 kW/m².



Figure 6-39. Photograph of Cable #700 after Cone Calorimeter test at 50 kW/m².

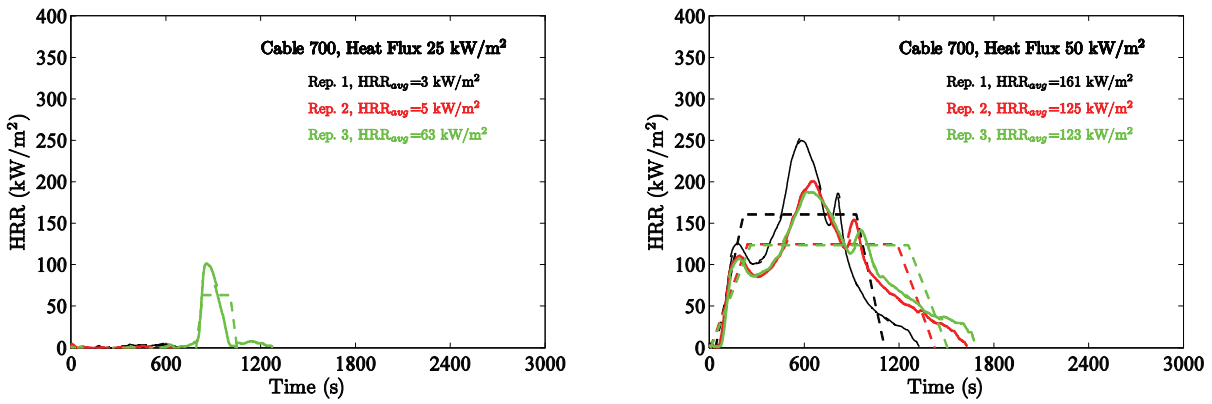


Figure 6-40. Heat Release Rates for Cable #700 in the Cone Calorimeter.

6.2.12 Cable #701

Imposed Heat Flux: 25 kW/m²

The samples smoked, flashed several times, ignited briefly, and extinguished. The spark was reinserted. Eventually the samples began to flash again and then finally re-ignited with a much larger peak of heat release noted. Much later into the test a dark blue flame could be seen at the edges of the sample holder and some occasional drips out the bottom of the sample holder noted shortly before the sample extinguished. Blue-green flames were noted at the ends of the cables deep in the char right before the sample extinguished. No aluminum trays were used. Significant damage to the sample surface was noted as can be seen in the pictures below, including exposure of the bare copper wire.



Figure 6-41. Photograph of Cable #701 after Cone Calorimeter test at 25 kW/m².

Imposed Heat Flux: 50 kW/m²

The samples smoked, flashed, and ignited fairly quickly. The samples deformed greatly while burning, with the char surface forming blisters that would crack open and eventually burn back. Blue colors noted later into the burning of the sample with some blue and green colors noted right before extinguishment. No aluminum trays were used.

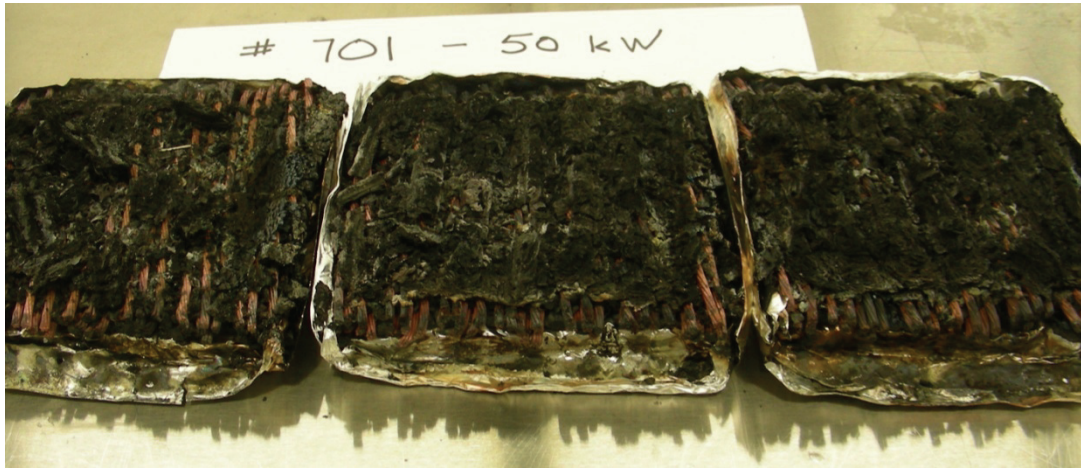


Figure 6-42. Photograph of Cable #701 after Cone Calorimeter test at 50 kW/m².

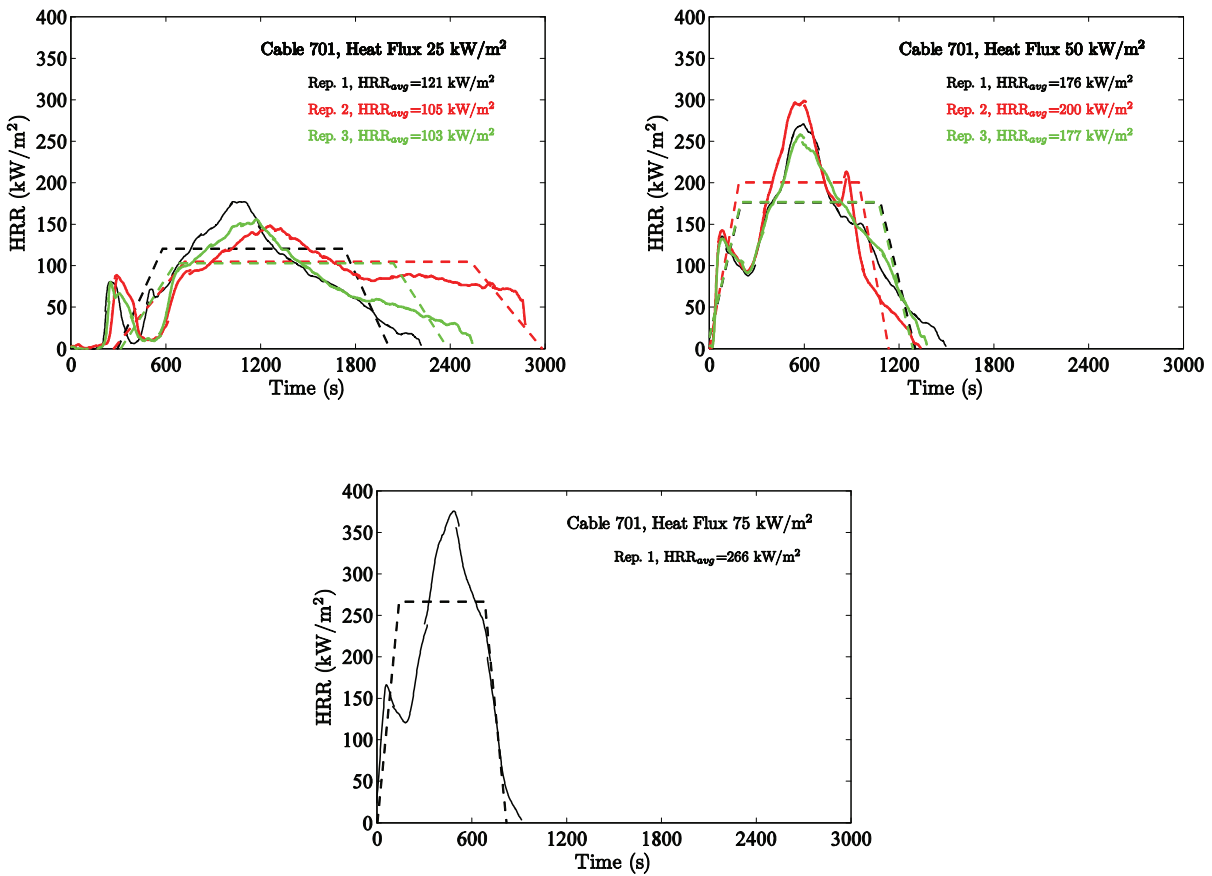


Figure 6-43. Heat Release Rates for Cable #701 in the Cone Calorimeter.

6.3 Summary of Results

The results of the Cone Calorimeter measurements are summarized in Table 6-A. For each cable and each imposed heat flux level, the average heat release rate per unit area is listed. In some cases, the average value was calculated after rejecting one or two of the replicate trials where the cable did not ignite or burn sufficiently long to derive appropriate values.

Table 6-A. Measured heat release rates from Cone Calorimeter experiments

Cable Number	HRRPUA (kW/m ²)		
	Imposed Heat Flux (kW/m ²)		
	25	50	75
11	6	90	127
16	50	130	173
23	44	92	135
43	6	70	169
46	15	61	172
219	133	140	187
220	112	143	No Test
270	191	298	510
271	13	113	199
367	70	107	169
700	63	136	No Test
701	110	184	266

7 RADIANT PANEL EXPERIMENTS

7.1 Overview

The Radiant Panel (RP) Apparatus consists of a single horizontal ladder-back cable tray containing varying numbers of cables that are exposed to an array of radiant panels that are positioned overhead. The tray is 1.2 m (4 ft) long and 0.45 m (18 in) wide. There are six radiant panels³ positioned in two symmetric banks. See Figure 7-1 and Figure 7-2 for photographs of the apparatus. Measurements with a heat flux gauge demonstrated that this configuration could produce a heat flux of approximately 30 kW/m² over a length of 0.6 m (2 ft) of the cable tray. The heat flux varied from the end of the tray to the middle by approximately 10 %.

The objective of these experiments was to compile a table of heat release rates per unit area (HRRPUA) for a variety of heat flux levels and tray fill levels. The cables were arranged in a way that is typical of “random fill” installations, although each experiment made use of only one type of cable. The number of cables was varied between approximately 25 % and 75 % of the amount allowed by the National Electric Code (NEC), 2008 Edition (NFPA 70). The NEC limits the total cross-sectional area of the cables within a 0.45 m (18 in) tray to 135 cm² (21 in²).

It should be noted that the Radiant Panel Apparatus was designed and built specifically for the CHRISTIFIRE project, and it is not intended to be used as a standard testing apparatus. Its purpose is to determine if the HRRPUA measured in the Cone Calorimeter (a standard apparatus) is consistent with the burning rate at a larger scale.

³ The radiant panels are manufactured by Chromalox, model CPHI-1224T quartz faced panels. They are 25 cm by 30 cm (10 in by 12 in), run on 480 V AC, and produce a maximum radiant output of 4.8 kW each, or a maximum heat flux of 62 kW/m². The uncertainty of the radiative output was not determined for an individual panel. The heat flux from the group of six was determined by a radiometer positioned approximately at the center of the tray prior to the experiment.

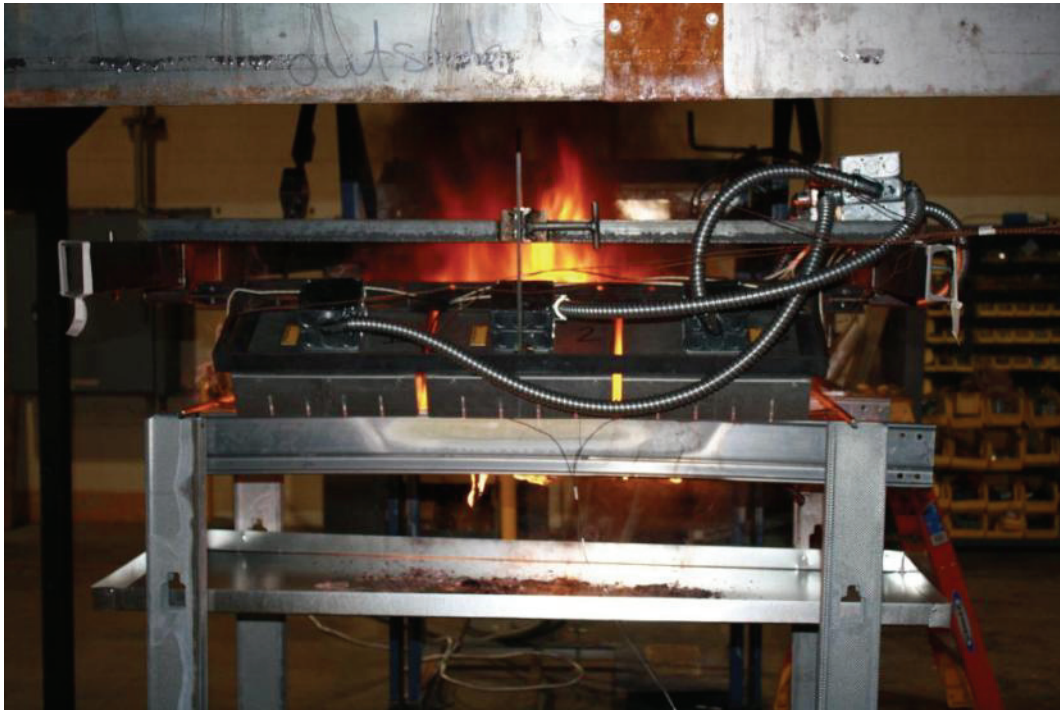


Figure 7-1. Side view of Radiant Panel Apparatus

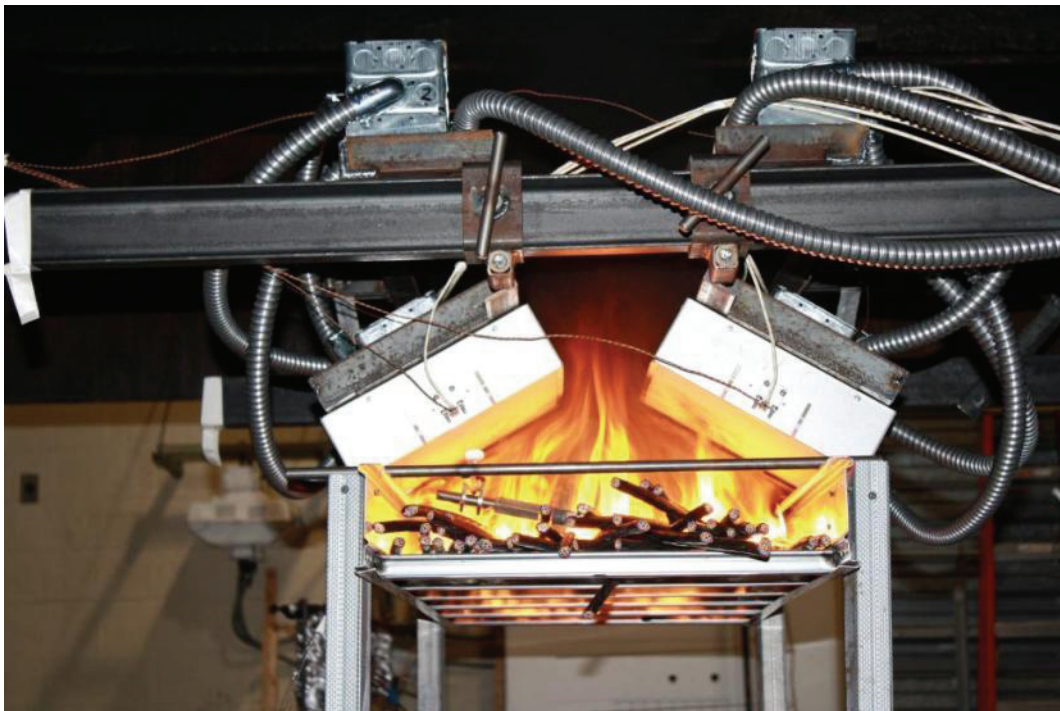


Figure 7-2. End view of Radiant Panel Apparatus.

7.2 Experimental Measurements

The measurements in the Radiant Panel Apparatus consisted of the following:

- Heat Release Rate: The Radiant Panel Apparatus was positioned beneath the 1 MW hood in the NIST Large Fire Laboratory. Using the measured HRR⁴, the heat release rate per unit area (HRRPUA) was calculated by assuming that the area of burning cables was the product of the width of the tray (0.45 m or 18 in) and the length of cables exposed to the radiant panels (approximately 1 m or 3 ft).
- Mass Loss Rate: The cable tray and its supporting rig was placed on a single scale⁵. By calculating the first derivative of its output, a mass loss rate could be calculated. The effective heat of combustion was calculated by determining (via linear regression) the ratio of the HRR determined from oxygen consumption calorimetry and the mass loss rate.
- Combustible Mass: Not all of the combustible (non-metallic) mass was consumed by the fire. For many of the cables, char and ash remained in the tray after the experiment. For each test, the fraction of the combustible mass that was actually consumed by the fire was calculated based on the mass loss rate of the entire apparatus.
- Adiabatic Surface Temperature: Three plate thermometers (EN 1363-1 2000) were positioned approximately 30 cm (1 ft) apart along the centerline of the tray. They were used to monitor the “exposing” temperature of the radiant panels.

7.3 Results

Twelve different cables were tested in the Radiant Panel series. Altogether there were 33 tests conducted (numbered 0 through 32), usually with each cable tested at two different exposing heat fluxes. For some cables, there were other parameter variations, like the amount of cables in the tray. Table 7-A summarizes the results of the Radiant Panel Series. Note that an important parameter in the experiments was the extent to which the cables were packed densely or loosely in the tray. Most of the experiments involved a single row of cables. “Dense” packing implies that the cables were packed tightly in a single row with gaps between cables of approximately 1 mm, while “Loose” implies that no particular effort was made to pack the cables tightly.

⁴ The procedure and accuracy of the oxygen consumption calorimetry used in the NIST Large Fire Laboratory is documented by Bryant (2004). In brief, the expanded uncertainty (95 % confidence interval) is 9 % of the measured value of the HRR for fires under the 1 MW hood. A significant portion of the uncertainty is due to the fact that the chemical composition of the fuel is not completely known.

⁵ The scale used in the experiment was manufactured by Mettler Toledo, under the model name Jaguar KC300. For an applied load of 50 kg (110 lb), the manufacturer reports the accuracy (95 % confidence interval) to be 0.02 %. This means that the reported mass is accurate to within approximately ± 10 g (0.4 oz).

7.3.1 Cable #11

Test No.	Nominal Heat Flux (kW/m ²)	No. of Cables	Packing	Max HRR (kW)
RP-21	32	14	Dense	135
RP-22	32	7	Loose	140



Cable #11 was notably larger than all of the other cables used in the program. Its size was a consideration when testing it in the Radiant Panel Apparatus. In Test 21, 14 cables were laid tightly in a single row with little gaps in between, whereas in Test 22, only 7 cables were laid in a row, with roughly one cable diameter spacing. Both tests showed peak HRRPUA values of about 300 kW/m², although not surprisingly the loosely packed configuration allowed the fire to grow faster.

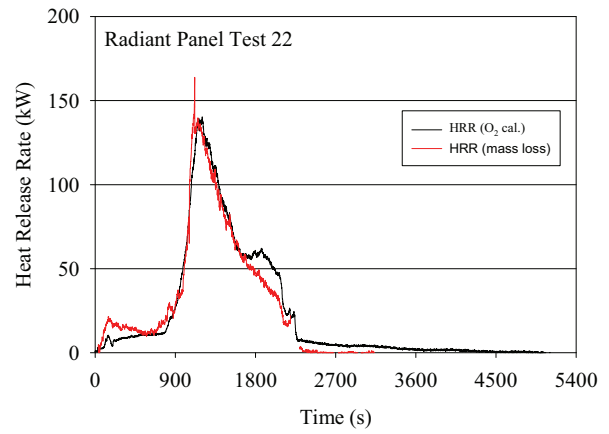
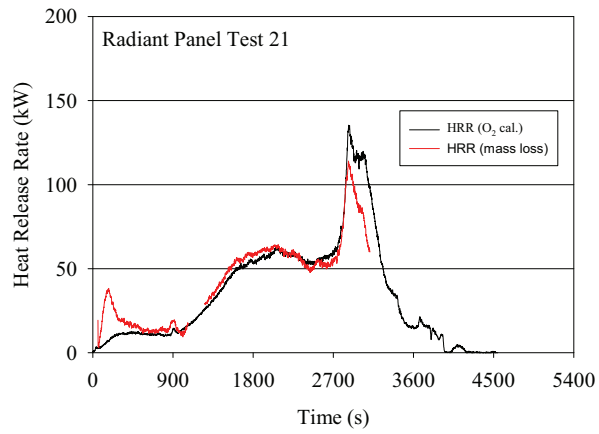
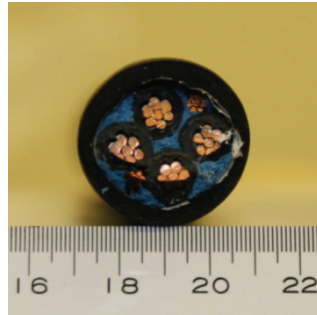


Figure 7-3. Photographs and HRR of RP Tests 21 and 22, Cable #11.

7.3.2 Cable #16

Test No.	Nominal Heat Flux (kW/m ²)	No. of Cables	Packing	Max HRR (kW)
RP-6	32	24	Loose	55
RP-7	16	24	Loose	55
RP-8	5	24	Loose	45
RP-9	22	24	Loose	51
RP-10	32	24	Loose	76



Cable #16 was used to assess the effect of the radiant panel heat flux on the burning rate. Tests 6 and 7 demonstrate that a lower heat flux delays ignition, but does not significantly change the peak HRR. With a very low heat flux, as in Test 8, it is difficult to maintain steady burning over the full extent of the exposed tray. Test 9 was similar to Tests 6 and 7, with a heat flux falling between the two. Test 10 was meant to replicate Test 6, and it demonstrates that slight differences in the way the cables are laid into the tray can lead to noticeable changes in the HRR.

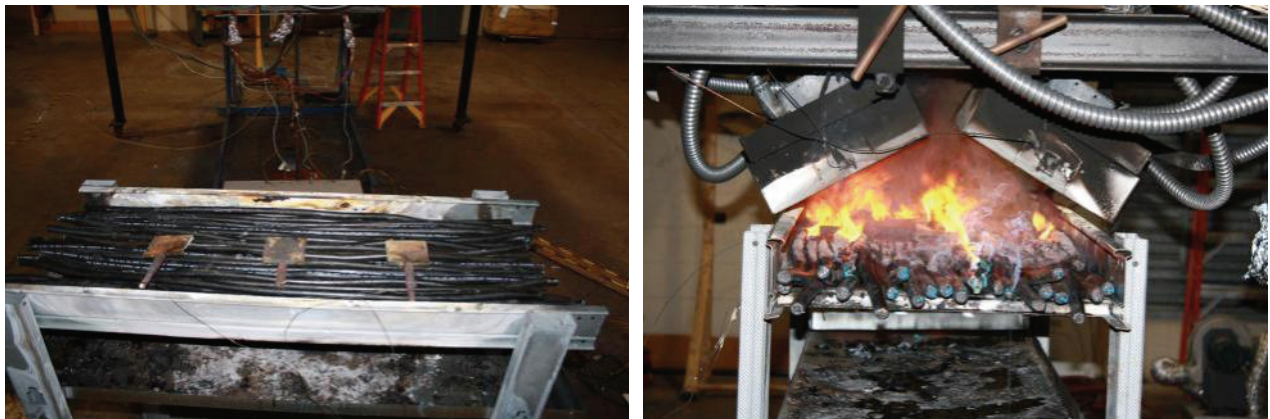


Figure 7-4. Photographs of RP Test 6.

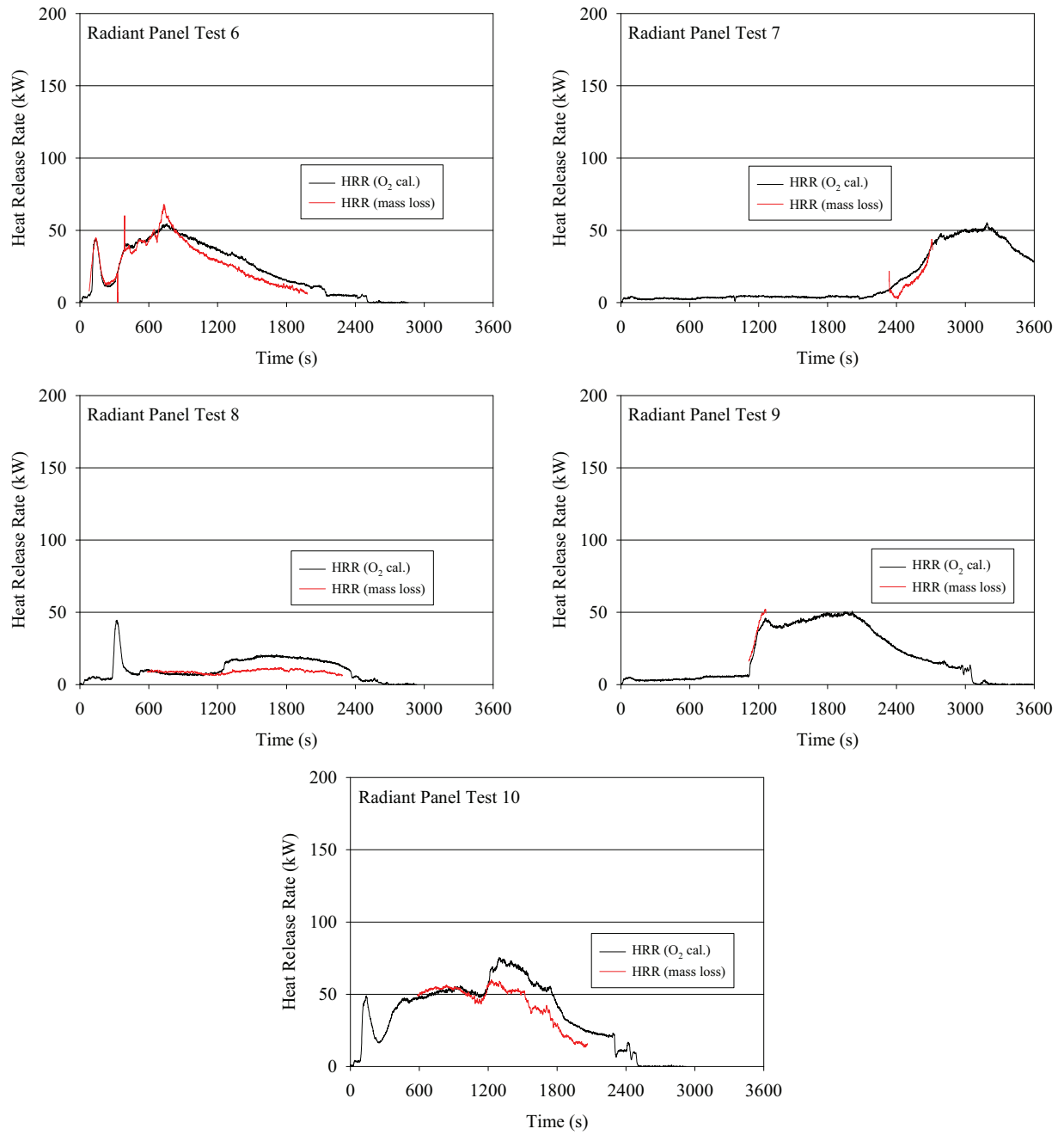


Figure 7-5. HRR of RP Tests 6-10, Cable #16.

7.3.3 Cable #23

Test No.	Nominal Heat Flux (kW/m ²)	No. of Cables	Packing	Max HRR (kW)
RP-27	28	34	Dense	78
RP-28	14	34	Dense	95
RP-29	15	66	Dense	111



This series of experiments demonstrates that doubling the number of cables in a tray does not significantly increase the HRR, but it does increase the duration of the fire. Figure 7-6 shows a single and double layer of cables in the tray.



Figure 7-6. Photographs of RP Test 28 (left) and 29 (right).

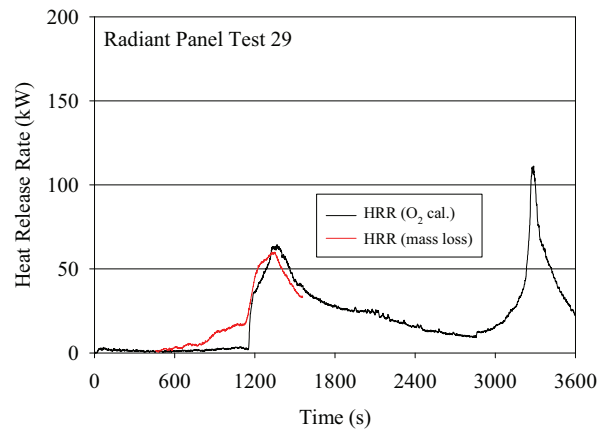
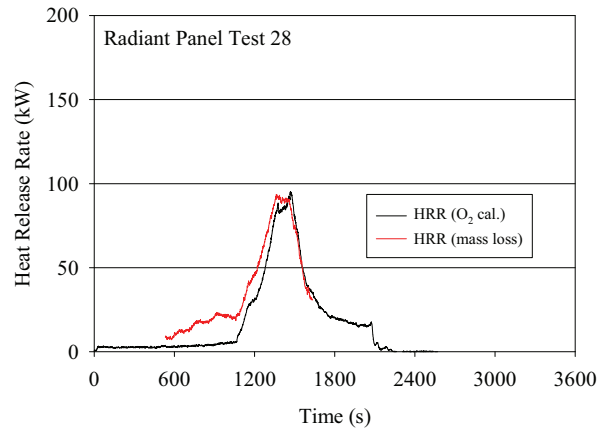
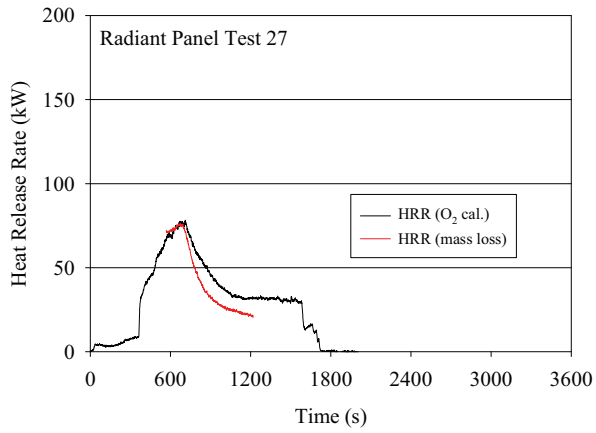
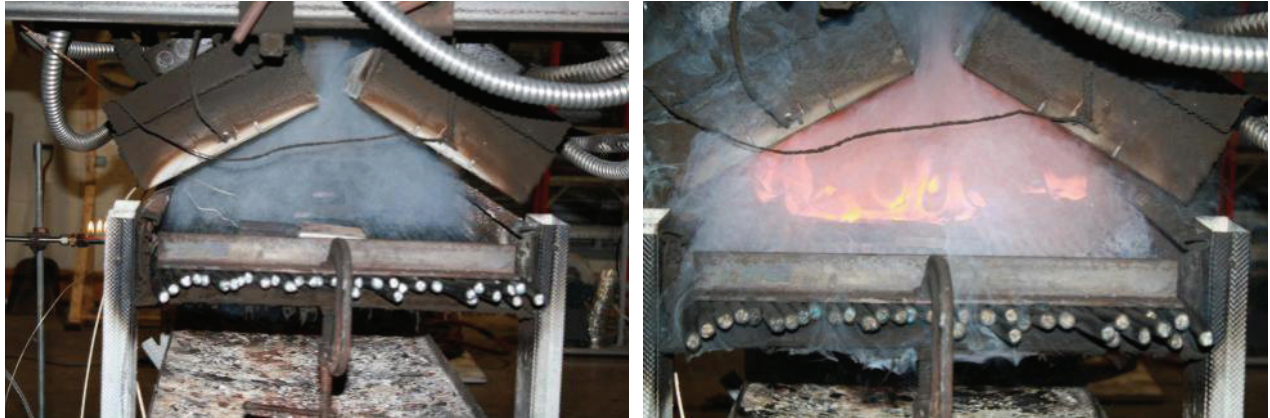
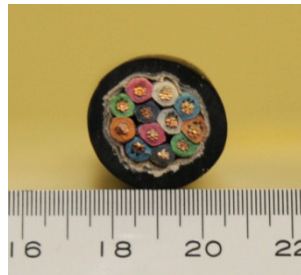


Figure 7-7. Photographs of RP Test 28 and HRR of Tests 27-29, Cable #23.

7.3.4 Cable #43

Test No.	Nominal Heat Flux (kW/m ²)	No. of Cables	Packing	Max HRR (kW)
RP-14	32	30	Dense	93
RP-15	17	30	Dense	63



These two radiant panel tests show that a higher exposing heat flux (typically) brings on ignition more quickly and a higher peak heat release rate. Note that the mass loss data for these experiments could not be used for a second estimate of the HRR because the tray made contact with the radiant panels several times during the tests.

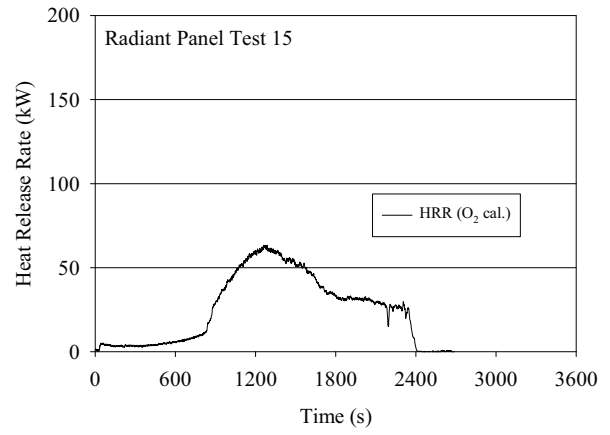
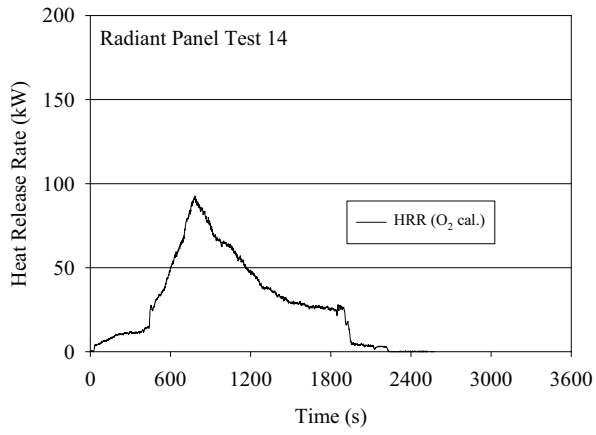
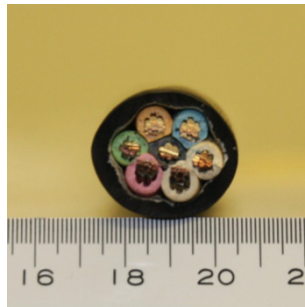


Figure 7-8. Photographs of RP Test 14 and HRR of Tests 14 and 15, Cable #43.

7.3.5 Cable #46

Test No.	Nominal Heat Flux (kW/m ²)	No. of Cables	Packing	Max HRR (kW)
RP-16	26	28	Dense	55
RP-17	15	28	Dense	47



The results of these two tests were as expected in that the higher exposing heat flux ignited the cables more quickly, but the peak heat release rate was not significantly higher.

There was no spread of the fire beyond the end of the radiant panels.

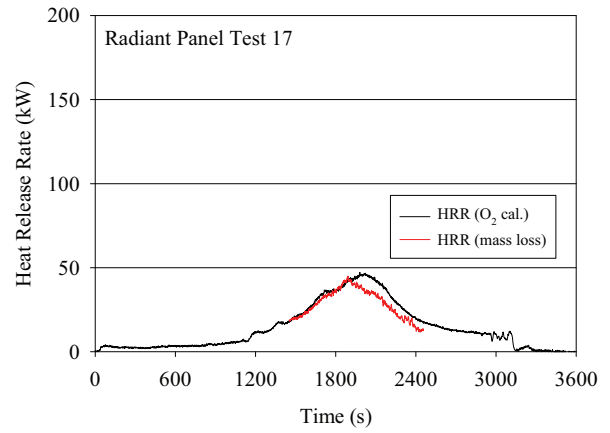
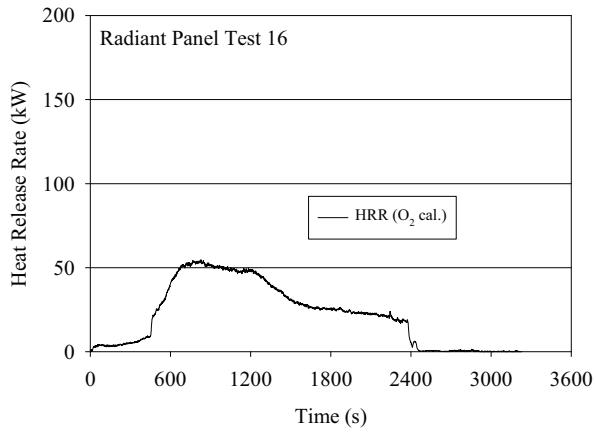
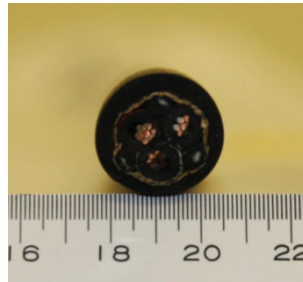


Figure 7-9. Photographs of RP Test 16 and HRR of Tests 16 and 17, Cable #46.

7.3.6 Cable #219

Test No.	Nominal Heat Flux (kW/m ²)	No. of Cables	Packing	Max HRR (kW)
RP-23	32	32	Dense	118
RP-24	13	32	Dense	192



The results of these two tests are not typical because the one with the lower exposing heat flux had the higher peak heat release rate.



Figure 7-10. Photograph of the remains of the cables in RP-24.

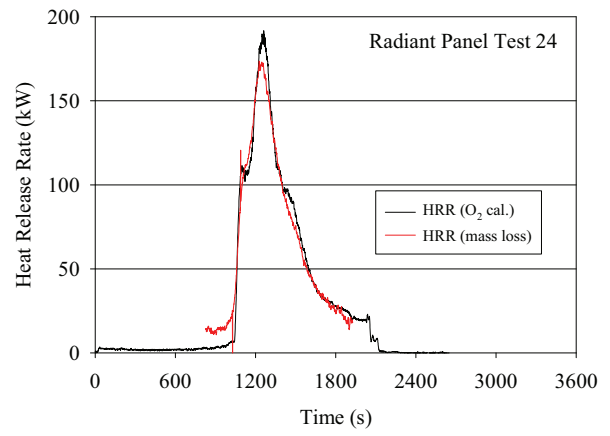
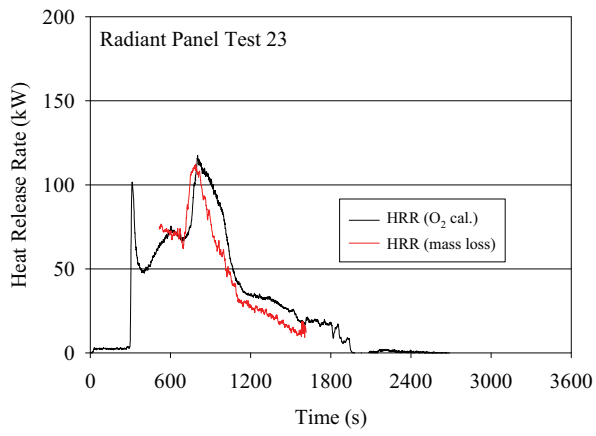
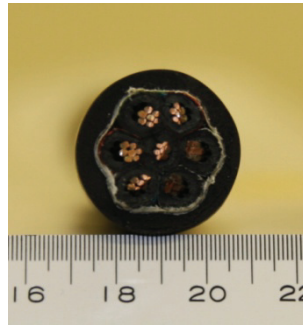


Figure 7-11. Photographs of RP Test 23 and HRR of Tests 23 and 24, Cable #219.

7.3.7 Cable #220

Test No.	Nominal Heat Flux (kW/m ²)	No. of Cables	Packing	Max HRR (kW)
RP-25	27	24	Dense	221
RP-26	17	24	Dense	213



This cable is similar in construction and materials to #219, but the results of these two tests do not show the anomalous behavior that was seen in Figure 7-11. Note in Figure 7-12 that there was a considerable amount of dripping material burning in the catch pan during the test.



Figure 7-12. Fairly vigorous burning in RP-25.

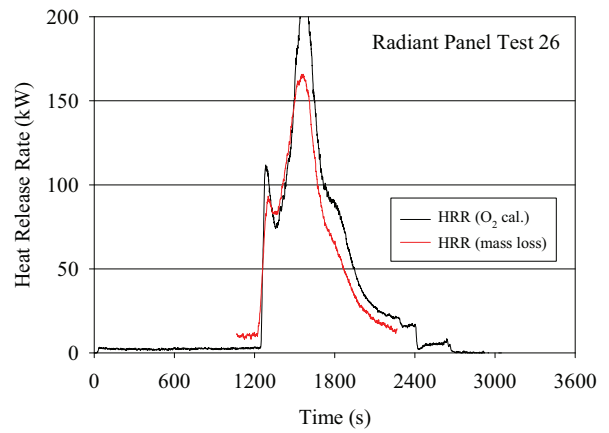
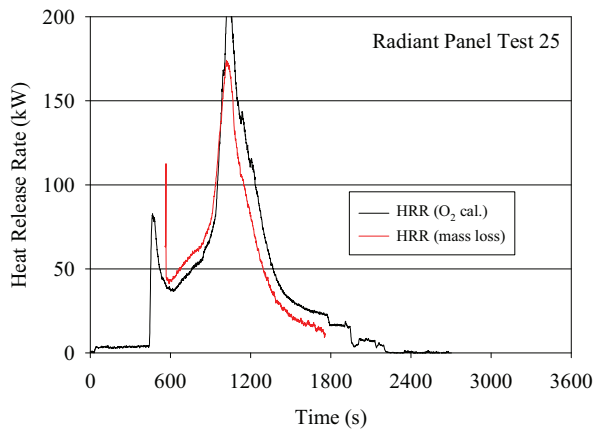
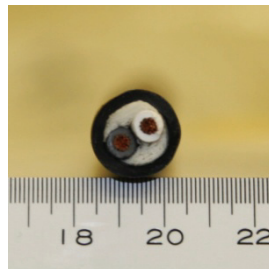


Figure 7-13. Photographs of RP Test 25 and HRR of Tests 25 and 26, Cable #220.

7.3.8 Cable #271

Test No.	Nominal Heat Flux (kW/m ²)	No. of Cables	Packing	Max HRR (kW)
RP-18	26	44	Dense	224
RP-19	13	44	Dense	149
RP-20	14	44	Dense	143



This was a relatively small cable, but it burned fairly vigorously with a fair amount of dripping/burning in the catch pan.

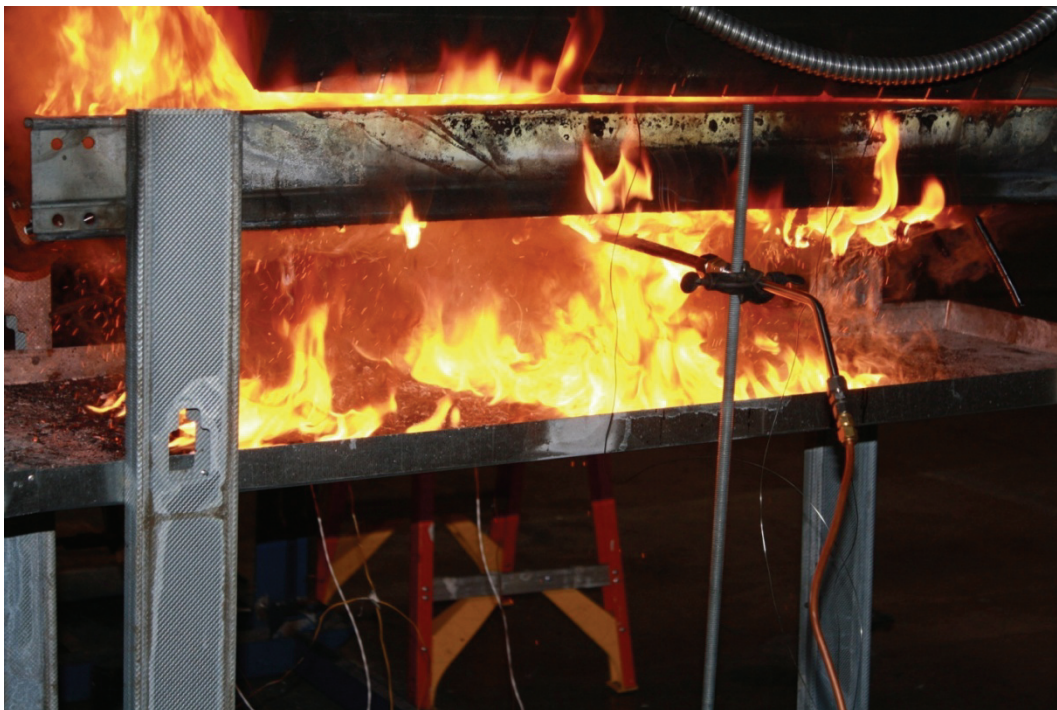


Figure 7-14. Photograph of RP Test 18 showing dripping and burning in the catch pan.

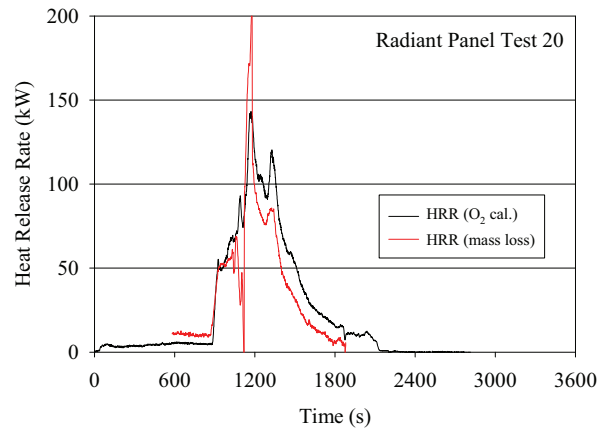
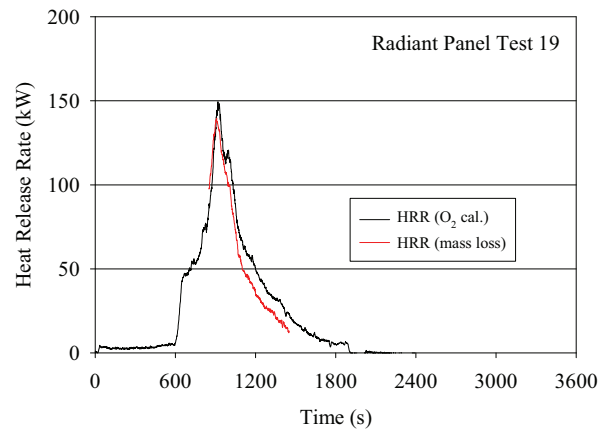
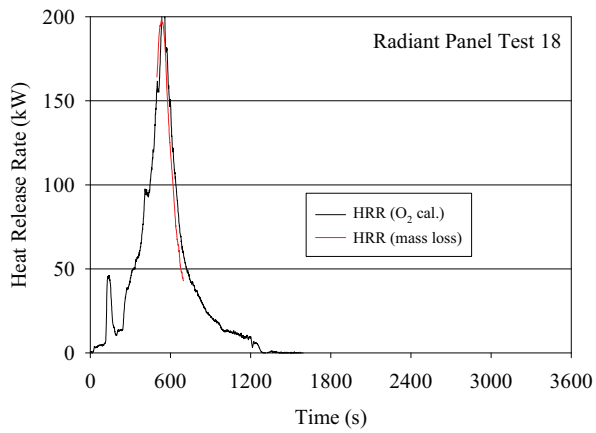
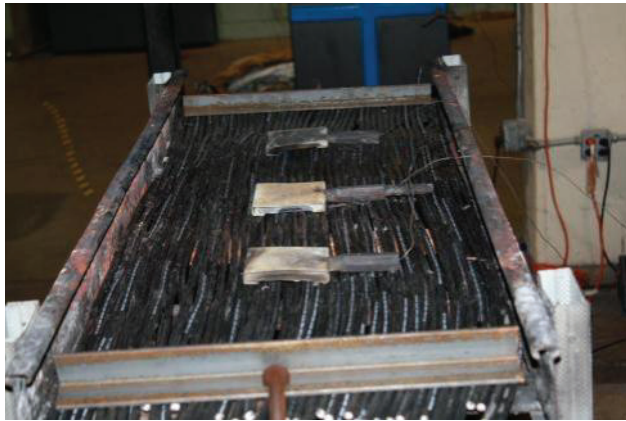
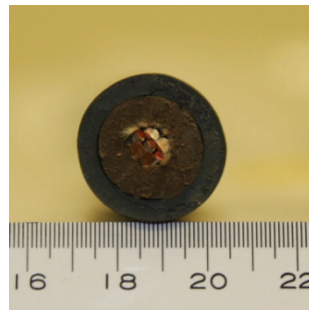


Figure 7-15. Photographs of RP Test 18 and HRR of Tests 18-20, Cable #271.

7.3.9 Cable #367

Test No.	Nominal Heat Flux (kW/m ²)	No. of Cables	Packing	Max HRR (kW)
RP-11	32	25	Dense	181
RP-12	17	25	Dense	124
RP-13	15	25	Dense	143



This cable burned fairly vigorously and the measured heat release rates followed typical trends based on the exposing heat flux. Note that the fire spread to the very end of the tray, as shown in Figure 7-16.



Figure 7-16. Photograph of RP Test 11 showing burning to the end of the tray.

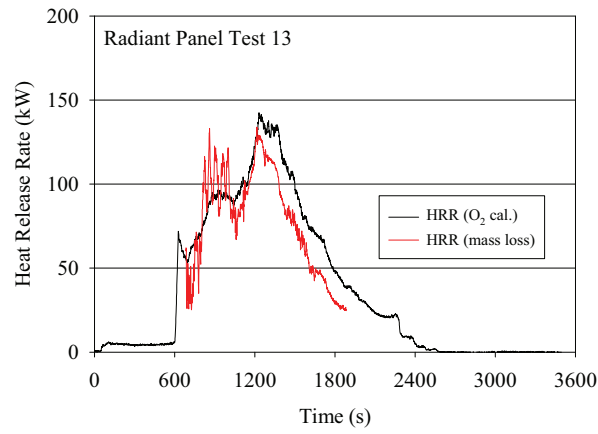
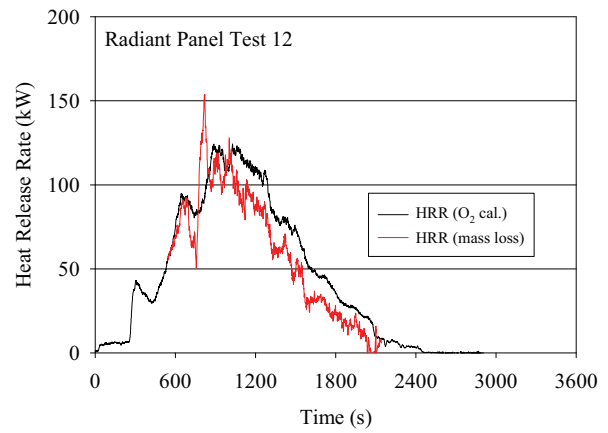
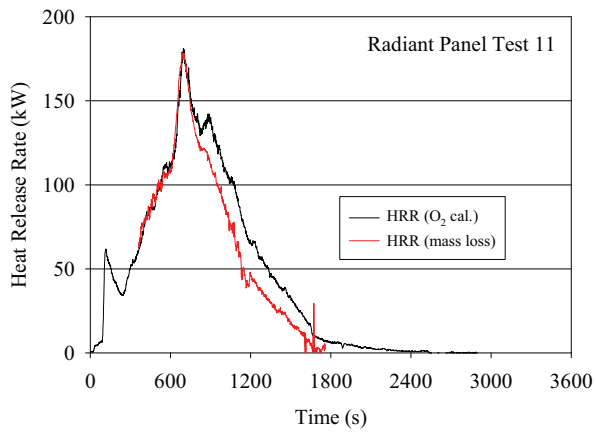
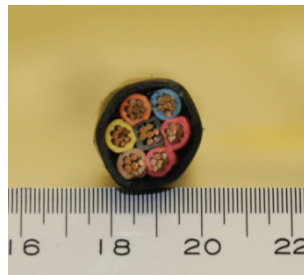


Figure 7-17. Photographs of RP Test 11 and HRR of Tests 11-13, Cable #367.

7.3.10 Cable #700

Test No.	Nominal Heat Flux (kW/m ²)	No. of Cables	Packing	Max HRR (kW)
RP-0	27	40	Loose	79
RP-1	24	80	Loose	60
RP-2	32	40	Loose	104



These three tests demonstrate how doubling the load of cable does not necessarily yield a larger fire, but rather a longer one. Notice from the HRR plot for RP-1 that each row of cables appears to burn independently.



Figure 7-18. Photograph of RP Test 1, showing a relatively heavy load of cable.

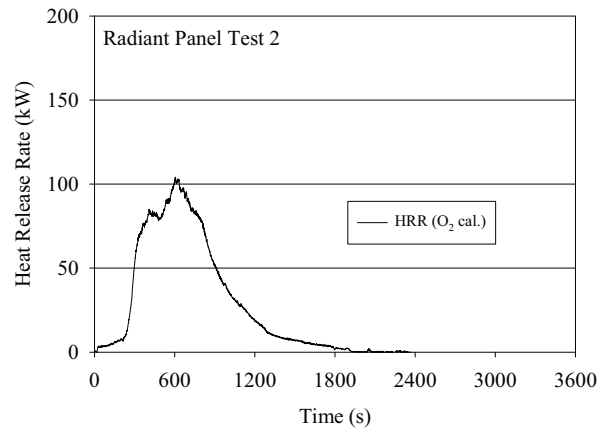
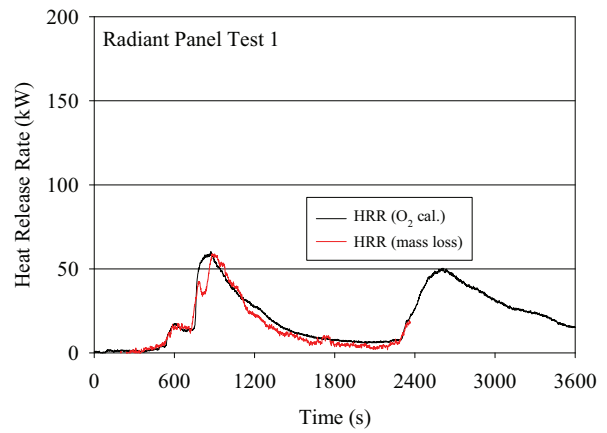
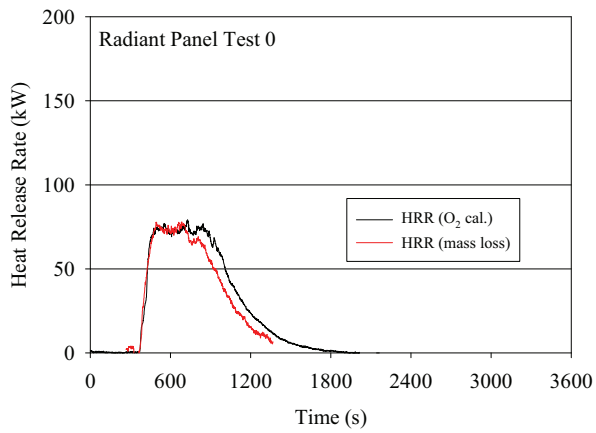
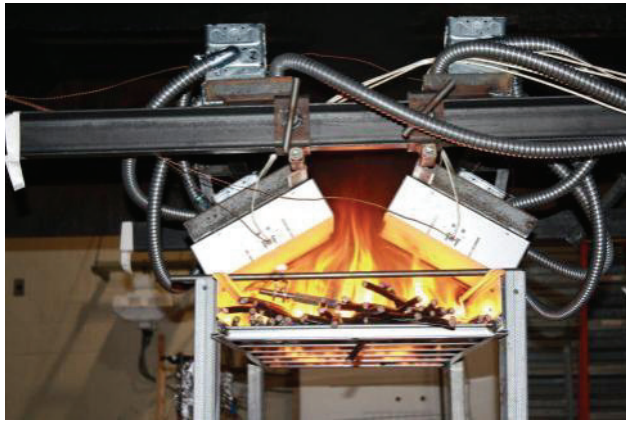
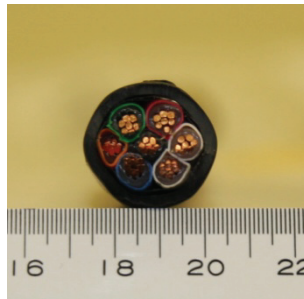


Figure 7-19. Photographs of RP Test 0 and HRR of Tests 0, 1 and 2, Cable #700.

7.3.11 Cable #701

Test No.	Nominal Heat Flux (kW/m ²)	No. of Cables	Packing	Max HRR (kW)
RP-3	32	44	Loose	163
RP-4	16	22	Loose	172
RP-5	17	22	Loose	160
RP-30	14	44	Dense	244
RP-31	28	44	Dense	258



This cable demonstrates burning behavior of a typical thermoplastic cable. It melts and drips, and it burns almost all of the plastic cable content away. In other words, there is very little residue left after the burn.



Figure 7-20. Photographs of RP Test 3.

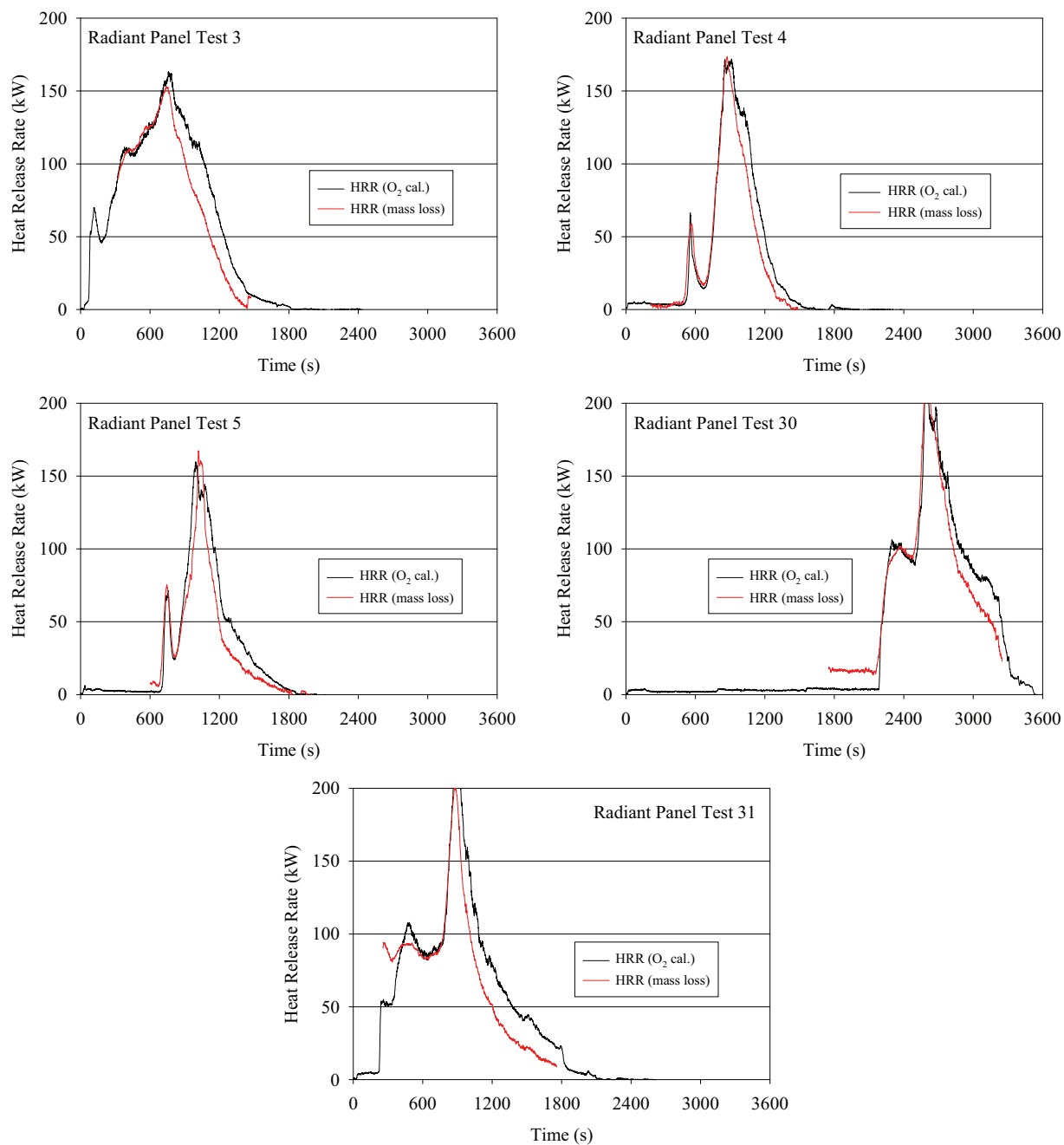


Figure 7-21. HRR of RP Tests 3-5 and 30-31, Cable #701.

Table 7-A. Summary of the Radiant Panel Experiments

Test No.	Cable No.	Nominal Heat Flux (kW/m ²)	No. of Cables	Percent of NEC Fill Limit	Packing	Max HRR (kW)	Avg HRRPUA (kW/m ²)	Heat of Comb. (MJ/kg)	Mass Consumed (kg)	Residue (% of total plastic)
RP-0	700	27	40	33	Loose	79	138	19.4	2.4	44
RP-1	700	24	80	67	Loose	60	55	18.9	4.5	48
RP-2	700	32	40	33	Loose	104	153	--	4.0	5
RP-3	701	32	44	50	Loose	163	264	16.1	8.1	0
RP-4	701	16	22	25	Loose	172	252	16.6	4.5	0
RP-5	701	17	22	25	Loose	160	184	15.6	3.3	18
RP-6	16	32	24	50	Loose	55	82	14.4	3.9	49
RP-7	16	16	24	50	Loose	55	64	19.8	4.2	46
RP-8	16	5	24	50	Loose	45	30	9.4	2.2	72
RP-9	16	22	24	50	Loose	51	88	15.6	4.3	44
RP-10	16	32	24	50	Loose	76	119	14.8	5.8	25
RP-11	367	32	25	37	Dense	181	234	18.1	6.9	15
RP-12	367	17	25	37	Dense	124	199	17.6	6.2	23
RP-13	367	15	25	37	Dense	143	205	17.6	6.1	25
RP-14	43	32	30	39	Dense	93	116	--	4.3	35
RP-15	43	17	30	39	Dense	63	100	--	4.7	30
RP-16	46	26	28	37	Dense	55	85	--	4.2	34
RP-17	46	15	28	37	Dense	47	60	15.9	2.9	54
RP-18	271	26	44	26	Dense	224	210	16.5	3.5	8
RP-19	271	13	44	26	Dense	149	160	16.1	3.5	7
RP-20	271	14	44	26	Dense	143	167	14.6	3.7	2
RP-21	11	32	14	84	Dense	135	142	16.3	9.0	28
RP-22	11	32	7	42	Loose	140	184	17.1	5.9	6
RP-23	219	32	32	36	Dense	118	135	15.7	4.6	20
RP-24	219	13	32	36	Dense	192	214	19.3	4.1	30
RP-25	220	27	24	45	Dense	221	180	17.1	5.0	40
RP-26	220	17	24	45	Dense	213	236	17.6	4.6	45
RP-27	23	28	34	39	Dense	78	104	12.3	3.9	35
RP-28	23	14	34	39	Dense	95	107	16.0	3.3	45
RP-29	23	15	66	75	Dense	111	66	12.2	10.6	8

Test No.	Cable No.	Nominal Heat Flux (kW/m ²)	No. of Cables	Percent of NEC Fill Limit	Packing	Max HRR (kW)	Avg HRRPUA (kW/m ²)	Heat of Comb. (MJ/kg)	Mass Consumed (kg)	Residue (% of total plastic)
RP-30	701	14	44	50	Dense	244	266	18.3	7.1	12
RP-31	701	28	44	50	Dense	258	231	15.2	7.4	9
RP-32	270	24	80	67	Loose	167	270	13.9	11.4	1

7.4 Discussion

The purpose of the Radiant Panel Apparatus is to measure the heat release rate per unit area (HRRPUA) of a tray filled with cable at a larger scale than the Cone Calorimeter. The area in this case refers to the tray, not the cable itself. In other words, it is the heat release rate divided by the length times the width of the tray over which the fire is burning. The HRRPUA takes on a range of values depending on the test configuration, exposing heat flux, and overall scale. For example, the HRRPUA determined in the Cone Calorimeter is expected to differ from the Radiant Panel Apparatus because of the difference in the size of the fire and the corresponding difference in the heat fed back to the cable surface. Figure 7-22 displays the range of values for the CHRISTIFIRE cables that were tested in the Radiant Panel Apparatus. Note that in most cases, the measured HRRPUA increases with increasing exposing heat flux. For cases like Cables #219 that show the opposite trend, the cables heated up at the lower heat flux but did not ignite for a considerable amount of time. When the cables did ignite, they burned with a relatively high HRRPUA because they had already reached high enough internal temperature to support the higher pyrolysis rate.

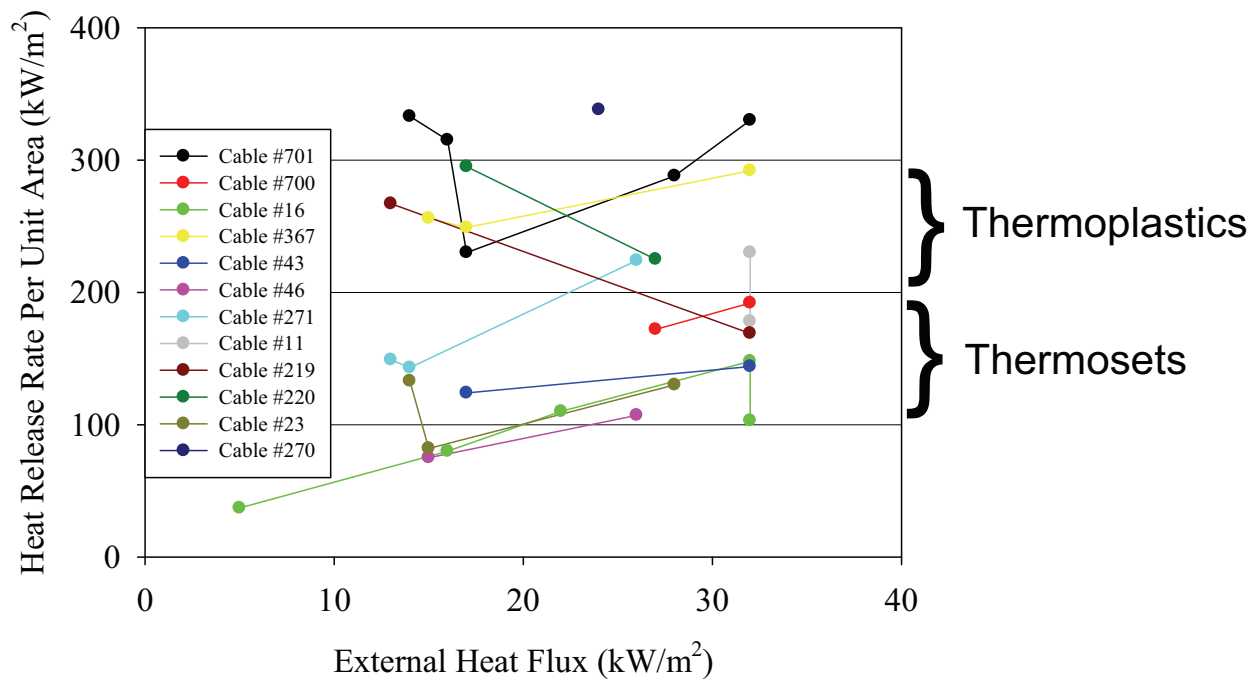


Figure 7-22. Summary of the radiant panel heat release rates.

Typical thermoset cables burn at a rate of approximately 150 kW/m^2 and typical thermoplastics burn at a rate of approximately 250 kW/m^2 . These values are similar to those put forth in NUREG/CR-6850, Appendix R, which are based on measurements by Tewarson that are reported in the SFPE Handbook.

8 MULTIPLE TRAY EXPERIMENTS

8.1 General Description

The multiple tray (MT) experiments were composed of vertical stacks of three to seven cable trays (one test involved only one tray). There were 26 experiments conducted in total, labeled MT-1 through MT-26. These 26 experiments were divided into two series. Series 1 consists of Tests MT-1 through MT-16, conducted in May, 2009. Series 2 consists of Tests MT-17 through MT-26, conducted in January and February, 2010.

Series 1 addresses a fairly common tray configuration where 0.45 m (18 in) horizontal, ladder-backed trays are stacked over top of each other with 0.3 m (1 ft) spacing. The type and amount of cables in each tray was varied. The cables in a given tray (or often for a given experiment) were typically of a single type. The aim was to test at full-scale those cables that were tested in the Radiant Panel Apparatus and in the Cone Calorimeter. Because of the limited amount of cable of any one type, it was not possible to vary the tray width or vertical spacing in the Series 1 experiments. The purpose of Series 1 was to determine if the burning rate data collected at bench and intermediate-scales could be applied to the full-scale experiments. A summary of the test parameters for Series 1 is given in Table 8-A.

Series 2 involved mixtures of cables that were not tested under the Radiant Panel Apparatus or the Cone Calorimeter. This series was designed to assess the effect of changing the vertical tray spacing, tray width, and tray fill. As with Series 1, they also provide experimental data for model validation. A summary of the test parameters for Series 2 is given in Table 8-B.

Figure 8-1 shows a typical experiment (MT Test 1) from Series 1. A small 0.3 m by 0.3 m (1 ft by 1 ft) square, gravel-packed natural gas burner was placed approximately 20 cm (8 in) below the lowest tray. The natural gas flow rate to this burner was calibrated to provide $40 \text{ kW} \pm 5 \text{ kW}$. The support rig and cable trays were placed upon four scales⁶. The heat release rate of the fire was measured in two ways. First, the amount of oxygen consumed by the fire was measured via oxygen consumption calorimetry instrumentation in the hood⁷. Second, the measured mass loss rate was multiplied by the heat of combustion that was estimated using data from the small scale experiments.

⁶ The scales used in the experiment were manufactured by Mettler Toledo, under the model name Jaguar KC300. For an applied load of 100 kg (220 lb), the manufacturer reports the accuracy (95 % confidence interval) to be 0.01 %. This means that the mass reported by each scale is accurate within approximately $\pm 10 \text{ g}$ (0.4 oz).

⁷ The procedure and accuracy of the oxygen consumption calorimetry is documented by Bryant (2004). In brief, the expanded relative uncertainty (95 % confidence interval) is 11 % of the measured value of the HRR for fires larger than 400 kW.

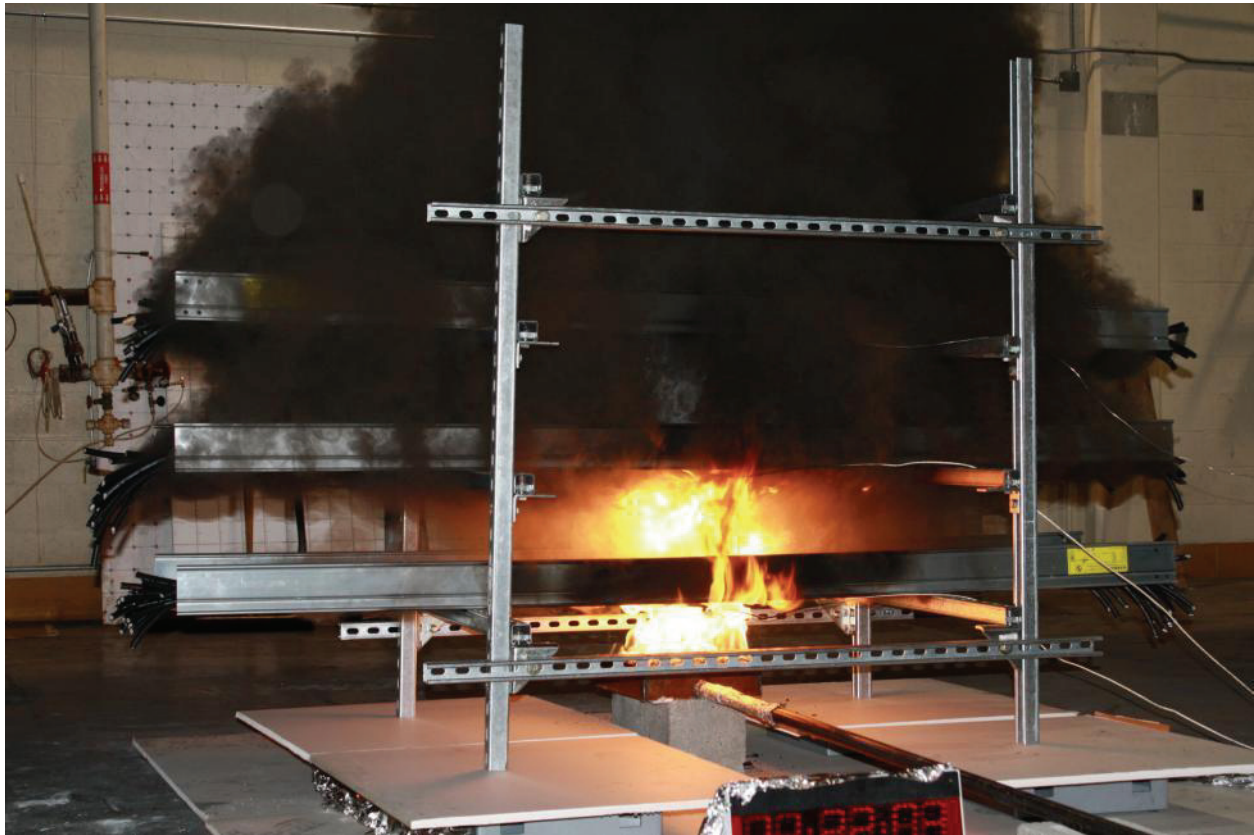


Figure 8-1. Multiple Tray (MT) cable test apparatus.

8.2 Results, Multiple Tray Experiments, Series 1

Sixteen Multiple Tray Experiments were conducted with the number of trays ranging from 1 to 7 in May, 2009. Two lengths of tray were used – 2.4 m (8 ft) and 3.6 m (12 ft). The smaller trays were supported by a steel rack whose vertical supports were 1.2 m (4 ft) apart, and the larger trays were supported by a rack with supports 1.8 m (6 ft) apart. Each rack spaced the trays 30 cm (1 ft) apart vertically. The measurements consisted of the following:

- Heat Release Rate. The heat release rate was measured using oxygen consumption calorimetry under one of two large hoods. Using the HRR and estimates of the area of burning tray, the heat release rate per unit area (HRRPUA) could be estimated.
- Mass Loss Rate. The trays and support rig were placed on four scales. The mass loss rate was calculated by taking the first derivative of the measured mass loss curve. The ratio of the HRR to the mass loss rate is the effective heat of combustion. This value changes over the course of the experiment. Towards the end of the experiment, when there is little flaming combustion but the cables continue to smolder in the trays, there is still an appreciable HRR measured via oxygen consumption calorimetry but a relatively low mass loss rate. For this

reason, oxygen consumption calorimetry was used as the primary HRR measurement because it is a better indicator of the energy release rate from the fire.

Note that for the multiple tray experiments, there was no calculation performed to determine how much of the non-metallic components of the cable were consumed because it was difficult to assess how much of the cable in each tray had actually burned following the experiment.

- Adiabatic Surface Temperature. Plate thermometers (EN 1363-1) were positioned on the underside of each tray along the centerline. They were used to monitor the “exposing” temperature of the fire below the tray.
- Videotape. Each experiment was videotaped from a single location that viewed the stack of cables broadside. Every five minutes during the experiment an estimate was made of the area of burning cables. The heat release rate measurement divided by the estimated area produced a time-history of the average heat release rate per unit area of burning cable tray. These results are plotted on the following pages.

8.2.1 Multiple Tray Test 1 (MT-1)

This experiment consisted of 3 trays, one above the other with a spacing of 30 cm (1 ft). Each tray was 2.4 m (8 ft) long, and each was filled with 32 cables (#23) neatly arranged in a single row. The burner under the bottom tray was maintained at about 40 kW for most of the experiment.

The heat release rate as a function of time is shown in Figure 8-2. The black curve is the HRR obtained via oxygen consumption calorimetry; the red was inferred from the measured mass loss rate and the estimated effective heat of combustion. The times when each tray became involved in the fire were estimated from visual observations during the experiment.

The damage to the cables was largely confined within the volume spanned by the 4 vertical support columns. The columns were 1.2 m (4 ft) apart.

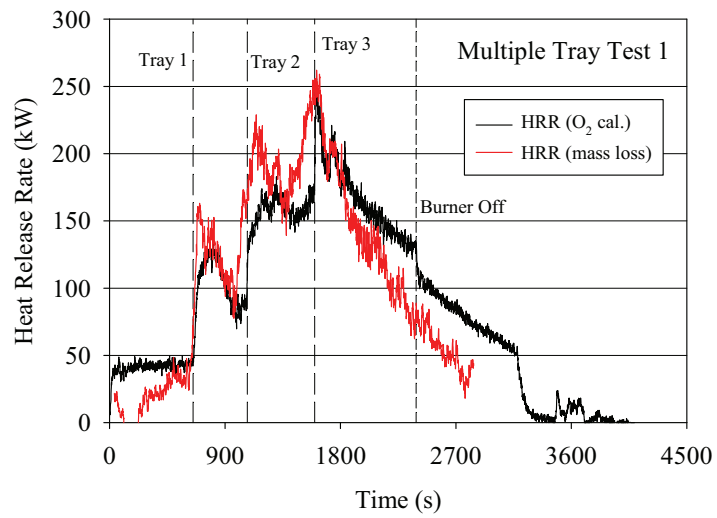


Figure 8-2. Multiple Tray Experiment 1

8.2.2 Multiple Tray Test 2 (MT-2)

This experiment consisted of 3 trays, one above the other with a spacing of 30 cm (1 ft). Each tray was 2.4 m (8 ft) long, and each was filled with 44 cables (#701) neatly arranged in a single row. The burner under the bottom tray was maintained at about 40 kW for the entire experiment.

The heat release rate as a function of time is shown in Figure 8-3. The black curve is the HRR obtained via oxygen consumption calorimetry; the red was inferred from the measured mass loss rate and the estimated effective heat of combustion. The times when each tray became involved in the fire were estimated (to the nearest minute) from the video tape.

The fire spread to the ends of each tray, following a V-pattern by which the cables in front of the flames were pre-heated by the fire in the tray above.

There was virtually no solid residue left after the experiment, only the copper conductors remained.

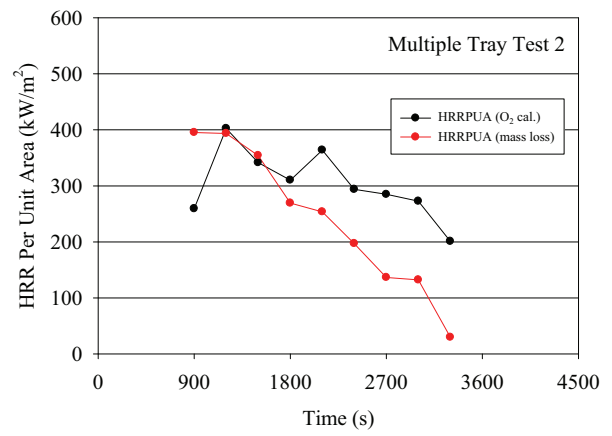
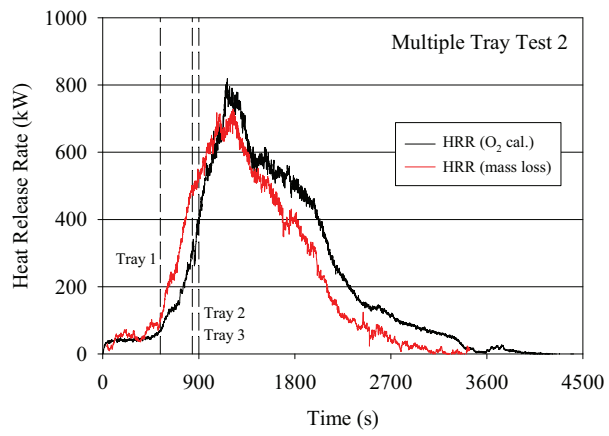


Figure 8-3. Multiple Tray Experiment 2.

8.2.3 Multiple Tray Test 3 (MT-3)

This experiment consisted of 3 trays, one above the other with a spacing of 30 cm (1 ft). Each tray was 2.4 m (8 ft) long, and each was filled with 32 cables (#219) neatly arranged in a single row. The burner under the bottom tray was maintained at about 40 kW for 10 min.

The heat release rate as a function of time is shown in Figure 8-4. The black curve is the HRR obtained via oxygen consumption calorimetry; the red was inferred from the measured mass loss rate and the estimated effective heat of combustion. The times when each tray became involved in the fire were estimated (to the nearest minute) from the video tape.

The damage to the cables was largely confined within the volume spanned by the 4 vertical support columns. The columns were 1.2 m (4 ft) apart.

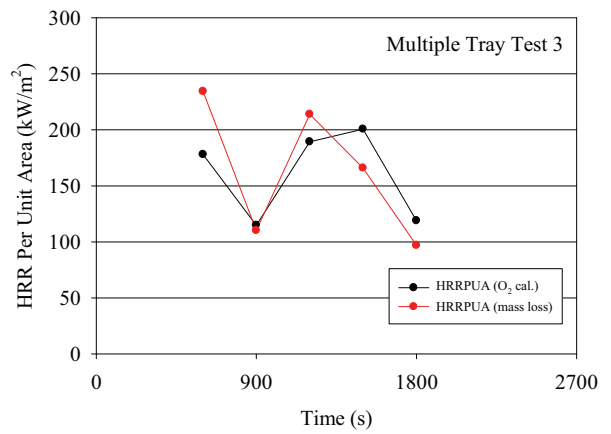
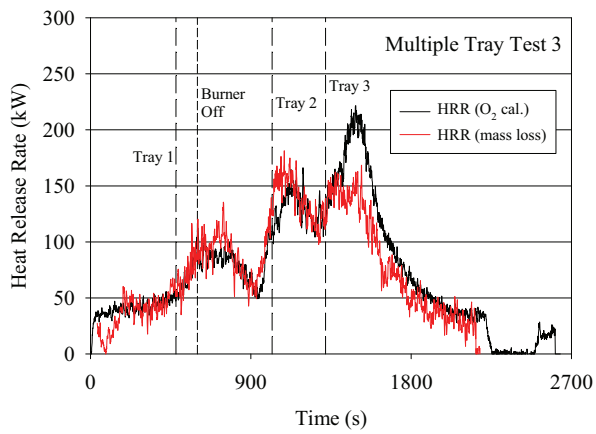


Figure 8-4. Multiple Tray Experiment 3

8.2.4 Multiple Tray Test 4 (MT-4)

This experiment consisted of 4 trays, one above the other with a spacing of 30 cm (1 ft). Each tray was 2.4 m (8 ft) long. Tray 1 (bottom tray) was filled with 28 cables (#43). Tray 2 was filled with 18 #43 cables and 10 #21 cables. Tray 3 was filled with 28 #21 cables. Tray 4 was filled with 23 #21 cables and 5 #20 cables. All of the cables were from the same manufacturer with very similar properties. All of the cables were densely packed neatly in a single row.

The burner under the bottom tray was maintained at about 40 kW for nearly 48 min. The reason the burner was left on for such a long time was that the fire did not spread readily from tray to tray. In fact, Tray 1 did not begin burning on its top side until after a gap was opened up in the cables to allow flame to break through. The neatly packed cables afforded no means for a piloting flame to ignite flammable vapors that had been accumulating on the top side of the tray due to the heating from below. Tray to tray upward spread was achieved for all trays by “picking” a gap in the cables with a fireman’s pick ax. The time of this action is noted on the plot in Figure 8-5.

The heat release rate as a function of time is shown in Figure 8-5. Note that because the cable trays were touched during the experiment by the pick ax, the mass loss data could not be used to estimate the heat release rate. The times when each tray became involved in the fire were estimated (to the nearest minute) from the video tape. Tray 4 never became fully involved, and Trays 1, 2 and 3 required “picking” to achieve ignition on the top sides.

The damage to the cables was largely confined to a relatively short length of Trays 1, 2 and 3, roughly 1 m (3 ft).

Following the conclusion of Test 4, it was decided to no longer tightly pack the cables into the trays because it was clear that such an arrangement might lead to spurious test results. Had no manual intervention taken place in Test 4, the result might have been no cable damage except for the area just above the burner on the underside of the tray. In an actual cable installation, it cannot be assumed whether or not the cables are laid in the tray in such a way as to prevent even a small flame from piloting a fire in the tray.

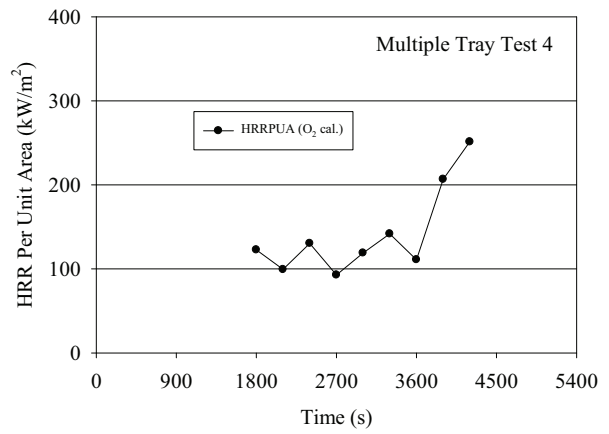
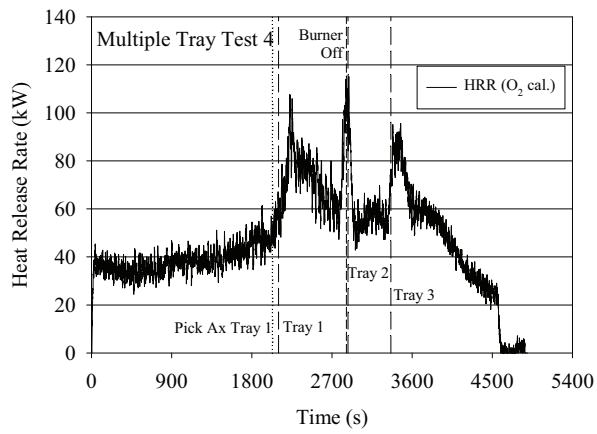


Figure 8-5. Multiple Tray Experiment 4

8.2.5 Multiple Tray Test 5 (MT-5)

This experiment consisted of 3 trays, one above the other with a spacing of 30 cm (1 ft). Each tray was 2.4 m (8 ft) long. Tray 1 (bottom tray) was filled with 26 of cable #21 and 2 of cable #23. Tray 2 was filled with 14 of cable #23 and 16 of cable #15. Tray 3 was filled with 25 of cable #13. The cables were packed loosely.

The burner under the bottom tray was maintained at about 40 kW and turned off following the observation of sustained burning in Tray 1.

The heat release rate as a function of time is shown in Figure 8-6. The black curve is the HRR obtained via oxygen consumption calorimetry; the red was inferred from the measured mass loss rate and the estimated effective heat of combustion. The times when each tray became involved in the fire were estimated (to the nearest minute) from the video tape.

The damage to the cables was relatively minor. The cables in each tray burned over roughly 1 m (3 ft) in length.

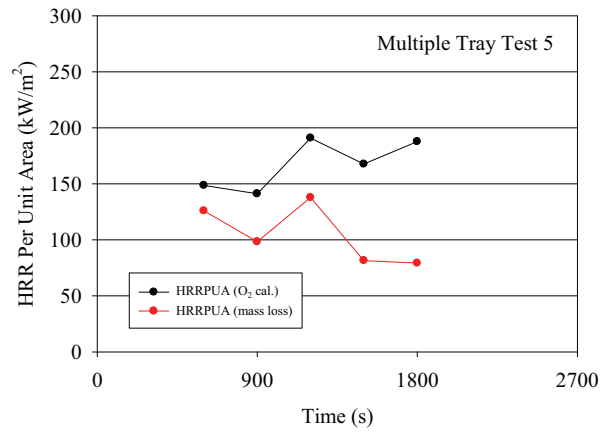
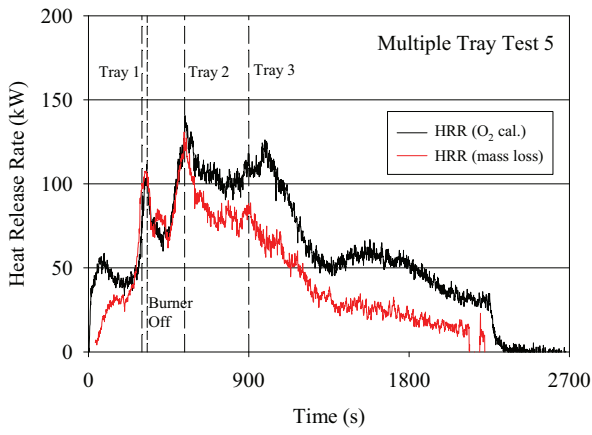


Figure 8-6. Multiple Tray Experiment 5

8.2.6 Multiple Tray Test 6 (MT-6)

This experiment consisted of 4 trays, one above the other with a spacing of 30 cm (1 ft). Each tray was 2.4 m (8 ft) long. Each tray contained 24 cables, all #13. The cables were packed loosely.

The burner under the bottom tray was maintained at about 40 kW and turned off following the observation of sustained burning in Tray 1. However, shortly thereafter, the fire's HRR dropped fairly quickly and it appeared that the fire would shortly go out. It was decided at this point to re-light the burner, and the fire grew once again.

The heat release rate as a function of time is shown in Figure 8-7. The black curve is the HRR obtained via oxygen consumption calorimetry; the red was inferred from the measured mass loss rate and the estimated effective heat of combustion. The times when each tray became involved in the fire were estimated (to the nearest minute) from the video tape.

The damage to the cables was relatively minor. The cables in each tray burned over roughly 1 m (3 ft) in length.

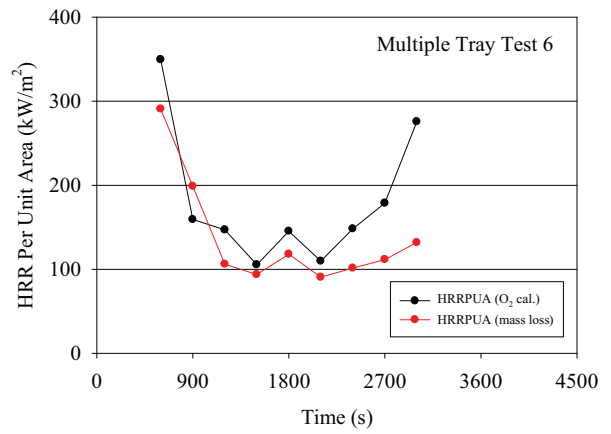
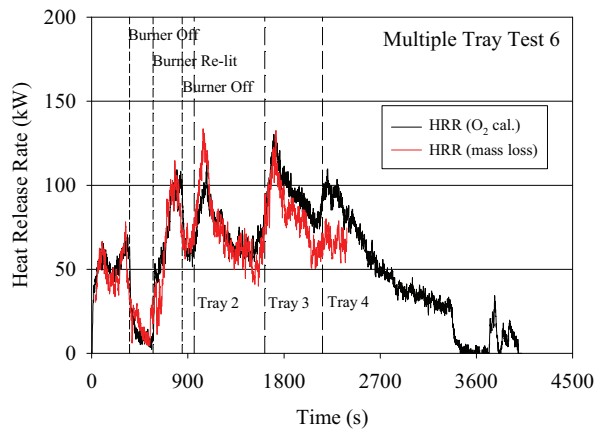
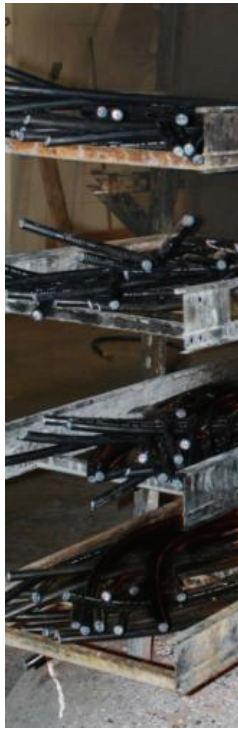


Figure 8-7. Multiple Tray Experiment 6

8.2.7 Multiple Tray Test 7 (MT-7)

This experiment consisted of 7 trays, one above the other with a spacing of 30 cm (1 ft). The bottom 4 trays were each 2.4 m (8 ft) long, while the top 3 trays were each 3.6 m (12 ft) long. Each tray contained 36 cables, all #13. This represented a 50 % increase in loading over Test 6. The cables were packed loosely.

The burner under the bottom tray was maintained at about 40 kW, but it was not turned off following the observation of sustained burning in Tray 1 to prevent the decrease in HRR that was observed after the burner was turned off in previous experiments.

The heat release rate as a function of time is shown in Figure 8-8. The black curve is the HRR obtained via oxygen consumption calorimetry; the red was inferred from the measured mass loss rate and the estimated effective heat of combustion. The times when each tray became involved in the fire were estimated (to the nearest minute) from the video tape.

There was a dramatically different outcome in Test 7 compared to Test 6. The fire grew to over 1 MW and spread to the end of nearly every tray.

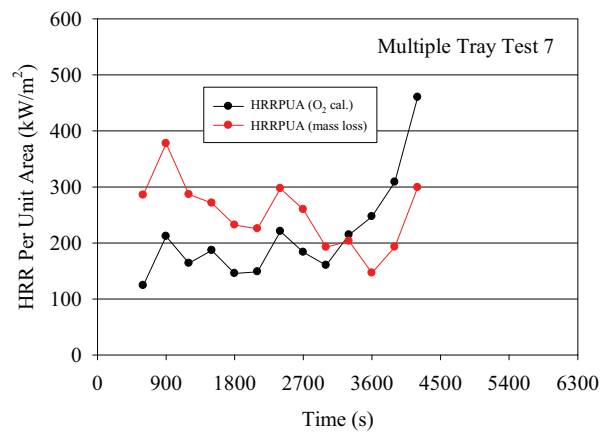
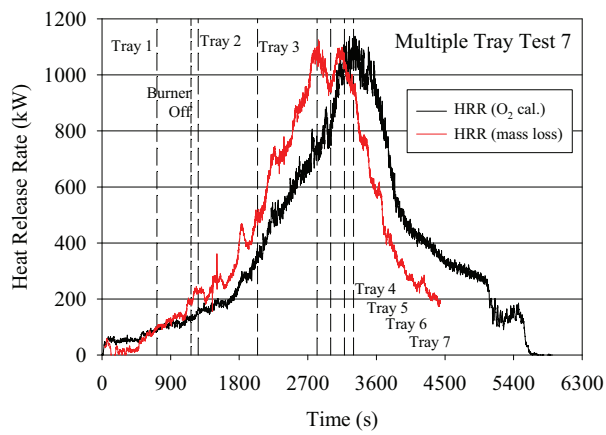


Figure 8-8. Multiple Tray Experiment 7

8.2.8 Multiple Tray Test 8 (MT-8)

This experiment consisted of 4 trays, one above the other with a spacing of 30 cm (1 ft). Each tray was 3.6 m (12 ft) long. Each tray contained 44 cables, all #701. The cables were packed loosely.

The burner under the bottom tray was maintained at about 40 kW, and it was turned off just after the fire was observed to have spread to the bottom tray.

The heat release rate as a function of time is shown in Figure 8-9. The black curve is the HRR obtained via oxygen consumption calorimetry; the red was inferred from the measured mass loss rate and the estimated effective heat of combustion. The times when each tray became involved in the fire were estimated (to the nearest minute) from the video tape.

The fire spread to the ends of each tray, following a V-pattern by which the cables in front of the flames were pre-heated by the fire in the tray above.

There was virtually no solid residue left after the experiment, only the copper conductors remained.

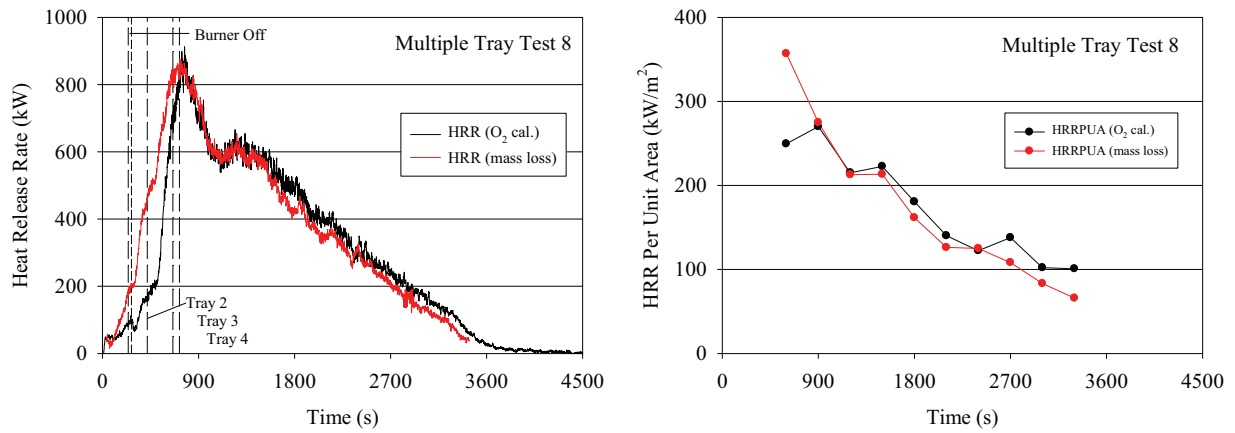


Figure 8-9. Multiple Tray Experiment 8

8.2.9 Multiple Tray Test 9 (MT-9)

This experiment had the exact same set-up as Test 8, only with half as many cables in each tray. This experiment consisted of 4 trays, one above the other with a spacing of 30 cm (1 ft). Each tray was 3.6 m (12 ft) long. Each tray contained 22 cables, all #701. The cables were packed loosely.

The burner under the bottom tray was maintained at about 40 kW, and it was turned off just after the fire was observed to have spread to the second tray from the bottom.

The heat release rate as a function of time is shown in Figure 8-10. The black curve is the HRR obtained via oxygen consumption calorimetry; the red was inferred from the measured mass loss rate and the estimated effective heat of combustion. The times when each tray became involved in the fire were estimated (to the nearest minute) from the video tape.

Unlike Test 8, the fire did not spread to the ends of each tray. In fact, there was relatively light damage to the cables, all confined within about a meter from the burner.

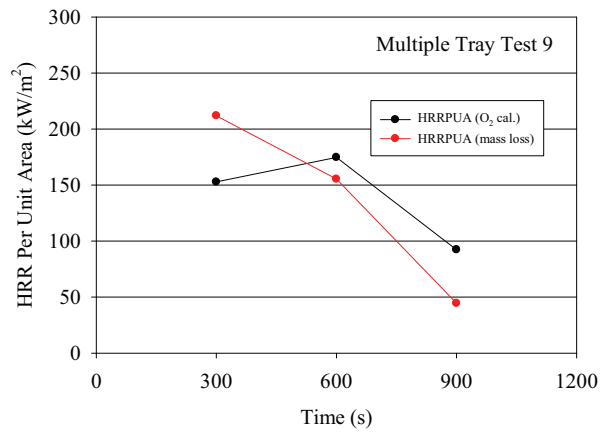
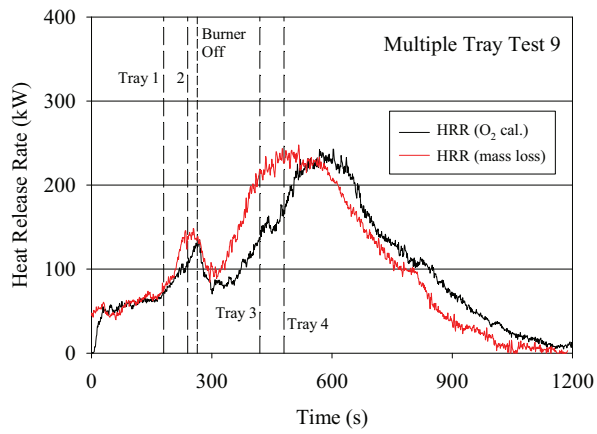


Figure 8-10. Multiple Tray Experiment 9

8.2.10 Multiple Tray Test 10 (MT-10)

This experiment consisted of 3 trays, one above the other with a spacing of 30 cm (1 ft). Each tray was 2.4 m (8 ft) long, and each was filled with 14 cables (#11). This was a large diameter, 37 conductor cable. In the Radiant Panel Apparatus the cables were packed fairly tightly in a single row. However, in the multiple tray experiment, the cables were arranged loosely, forming approximately two rows within each tray.

The burner under the bottom tray was maintained at about 40 kW until the bottom tray was ignited.

The heat release rate as a function of time is shown in Figure 8-11. The black curve is the HRR obtained via oxygen consumption calorimetry; the red was inferred from the measured mass loss rate and the estimated effective heat of combustion. The times when each tray became involved in the fire were estimated from visual observations during the experiment.

The damage to the cables was largely confined within the volume spanned by the 4 vertical support columns. The columns were 1.2 m (4 ft) apart.

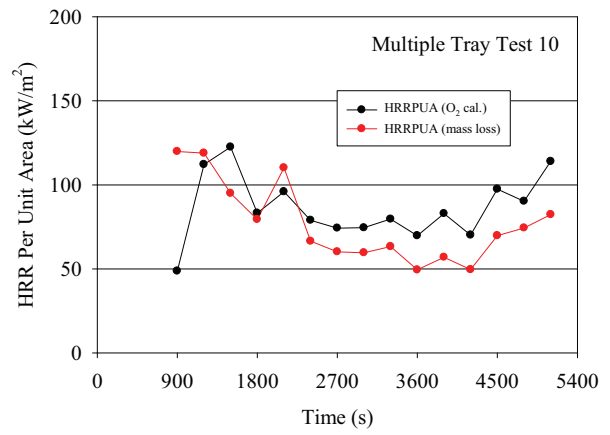
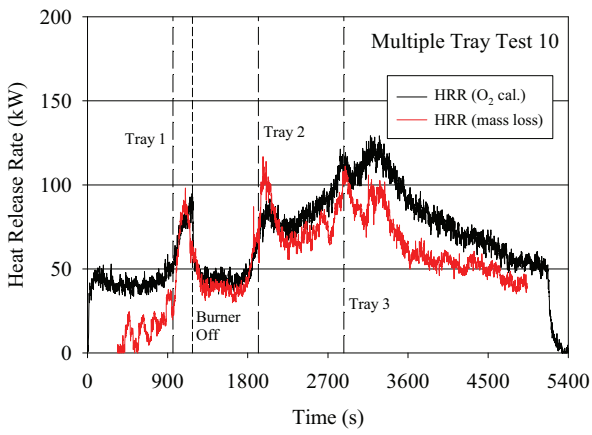


Figure 8-11. Multiple Tray Experiment 10

8.2.11 Multiple Tray Test 11 (MT-11)

This experiment was a replicate of Test 8. The results are similar, but there are noticeable differences in the HRR.

This experiment consisted of 4 trays, one above the other with a spacing of 30 cm (1 ft). Each tray was 3.6 m (12 ft) long. Each tray contained 44 cables, all #701. The cables were packed loosely.

The burner under the bottom tray was maintained at about 40 kW, and it was turned off just after the fire was observed to have spread to the bottom tray.

The heat release rate as a function of time is shown in Figure 8-12. The black curve is the HRR obtained via oxygen consumption calorimetry; the red was inferred from the measured mass loss rate and the estimated effective heat of combustion. The times when each tray became involved in the fire were estimated (to the nearest minute) from the video tape.

The fire spread to the ends of each tray, following a V-pattern by which the cables in front of the flames were pre-heated by the fire in the tray above.

There was virtually no solid residue left after the experiment, only the copper conductors remained.

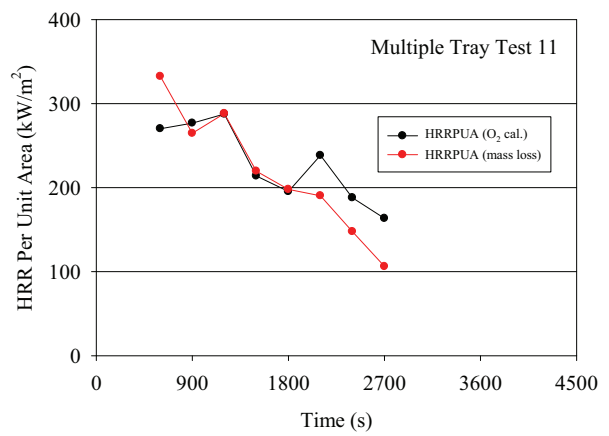
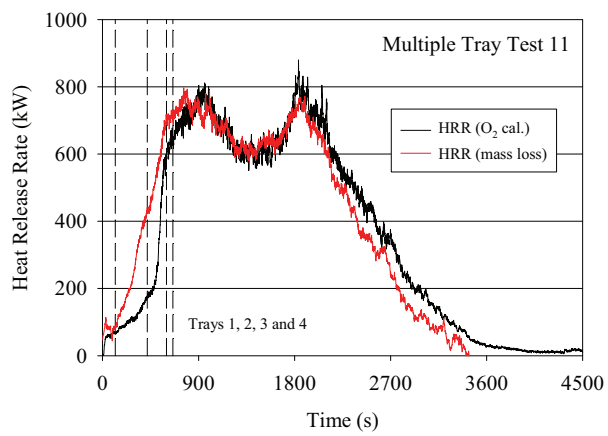


Figure 8-12. Multiple Tray Experiment 11

8.2.12 Multiple Tray Test 12 (MT-12)

This experiment consisted of 3 trays, one above the other with a spacing of 30 cm (1 ft). Each tray was 2.4 m (8 ft) long. Each tray contained 40 cables, all #700. The cables were packed loosely.

The burner under the bottom tray was maintained at about 40 kW and turned off following the observation of sustained burning in Tray 2.

The heat release rate as a function of time is shown in Figure 8-13. The black curve is the HRR obtained via oxygen consumption calorimetry; the red was inferred from the measured mass loss rate and the estimated effective heat of combustion. The times when each tray became involved in the fire were estimated (to the nearest minute) from the video tape.

The damage to the cables was relatively minor. The cables in each tray burned over roughly 1 m (3 ft) in length.

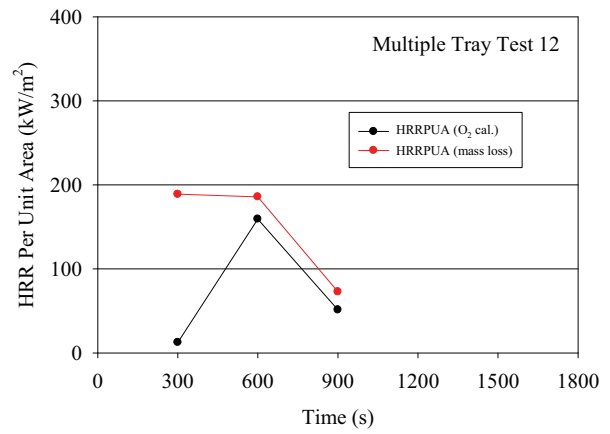
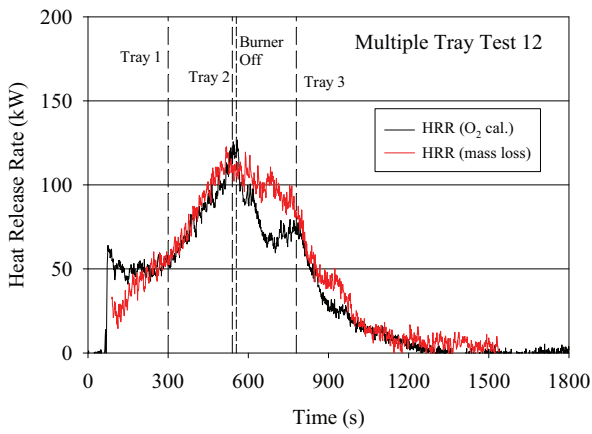


Figure 8-13. Multiple Tray Experiment 12

8.2.13 Multiple Tray Test 13 (MT-13)

This experiment did not actually involve multiple trays. Rather, a single 2.4 m (8 ft) tray was positioned the same way as the bottom tray in all the other experiments of this series. The tray was loaded the same way as in Test 11 – 44 cables (#701), loosely packed.

Following the ignition of the fire in the tray, the burner was turned off. However, the heat release rate dropped down towards zero and by 15 min the fire was almost out and had not spread beyond the vicinity of the burner. It was decided that the burner should be re-lit at 20 min and left on to see if the burner could support the fire long enough to allow it to spread to the ends of the tray as it had with this same loading in Tests 2, 8 and 11. It did not spread after about an hour beyond columns of the support rig.

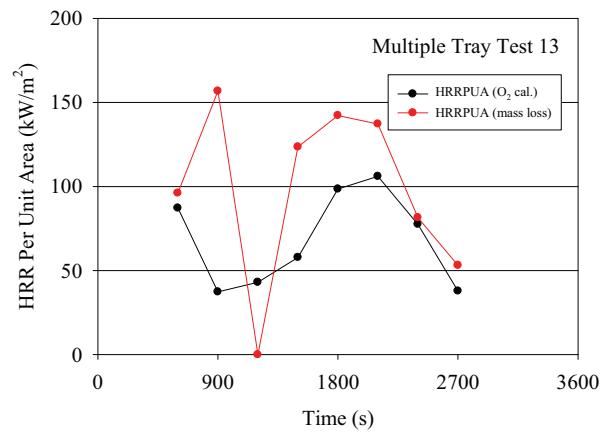
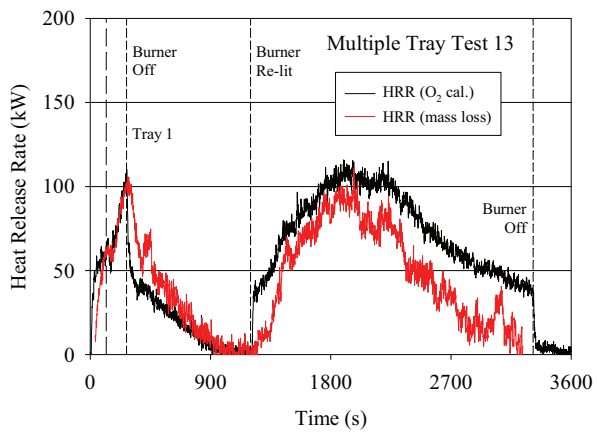


Figure 8-14. Multiple Tray Experiment 13

8.2.14 Multiple Tray Test 14 (MT-14)

This experiment consisted of 4 trays, one above the other with a spacing of 30 cm (1 ft). Each tray was 2.4 m (8 ft) long. Tray 1 (bottom tray) contained 24 #220 cables. Tray 2 contained 36 #220 cables. Tray 3 contained 32 #219 cables. Tray 4 contained 42 #219 cables. All trays were loosely packed.

The burner under the bottom tray was maintained at about 40 kW until the bottom tray was ignited. After it was turned off, the fire slowly spread to Tray 2 and then Tray 3, but the fires within each tray were fairly weak and it appeared that the fire would have died out unless something were done. Thus, it was decided to re-light the burner at 30 min, after which the fire grew considerably.

The heat release rate as a function of time is shown in Figure 8-16. The black curve is the HRR obtained via oxygen consumption calorimetry; the red was inferred from the measured mass loss rate and the estimated effective heat of combustion. The times when each tray became involved in the fire were estimated from visual observations during the experiment.

The damaged cables formed a V-pattern as seen in Figure 8-15.



Figure 8-15. Damage to cables following Multiple Tray Test 14.

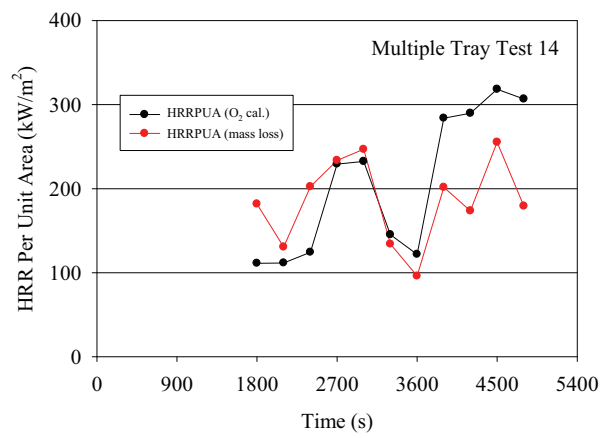
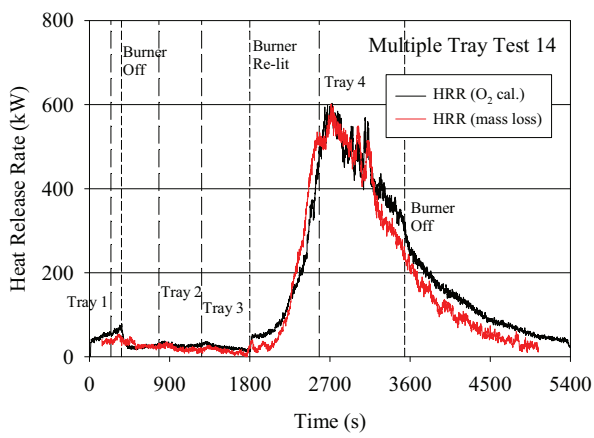


Figure 8-16. Multiple Tray Experiment 14

8.2.15 Multiple Tray Test 15 (MT-15)

This experiment consisted of 3 trays, one above the other with a spacing of 30 cm (1 ft). Each tray was 2.4 m (8 ft) long. Tray 1 (bottom tray) contained 25 #16 cables. Tray 2 contained 14 #12 cables. Tray 3 contained 36 #367 cables. All trays were packed loosely. The objective of this experiment was to observe the behavior of cable #367. The first two trays were loaded only to produce a fire under Tray 3.

The burner under the bottom tray was maintained at about 40 kW until all the trays were ignited. The reason for this is that the growth of the fire in Trays 1 and 2 was fairly sluggish, and as the intent of the experiment was to evaluate the cables in Tray 3, the burner was left on until those cables were involved.

The heat release rate as a function of time is shown in Figure 8-18. The black curve is the HRR obtained via oxygen consumption calorimetry; the red was inferred from the measured mass loss rate and the estimated effective heat of combustion. The times when each tray became involved in the fire were estimated from visual observations during the experiment.

The fire spread to the ends of Tray 3, but the fire in Trays 1 and 2 stopped just beyond the columns of the support rig, as seen in Figure 8-17.



Figure 8-17. Fire spread to the ends of Tray 3, Multiple Tray Test 15.

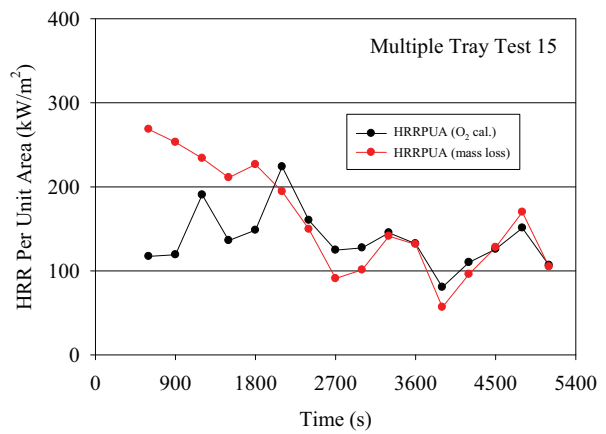
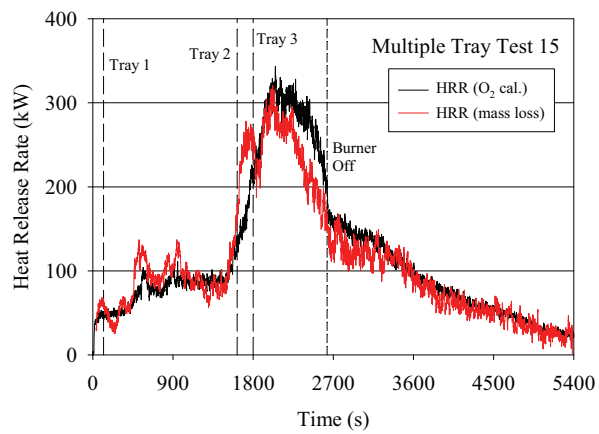


Figure 8-18. Multiple Tray Experiment 15

8.2.16 Multiple Tray Test 16 (MT-16)

This experiment consisted of 3 trays, one above the other with a spacing of 30 cm (1 ft). Each tray was 2.4 m (8 ft) long. Tray 1 (bottom tray) contained 80 #270 cables. Tray 2 contained 30 #270 cables and 50 #269 cables. Tray 3 contained 80 #269 cables. All trays were packed loosely. Both cable #269 and #270 were very similar in construction. Both were double shielded co-axial cable.

The burner under the bottom tray was maintained at about 40 kW until the fire had spread to Tray 2.

The heat release rate as a function of time is shown in Figure 8-20. The black curve is the HRR obtained via oxygen consumption calorimetry; the red was inferred from the measured mass loss rate and the estimated effective heat of combustion. The times when each tray became involved in the fire were estimated from visual observations during the experiment.

The damage to the cables extended about to the columns of the support rig, as shown in Figure 8-19.



Figure 8-19. Damage to cables, Multiple Tray Test 16.

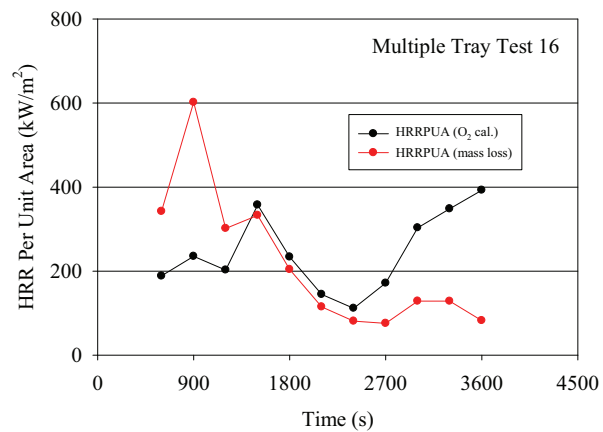
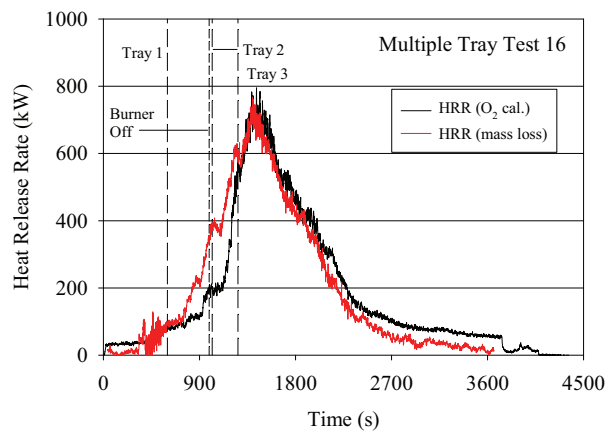


Figure 8-20. Multiple Tray Experiment 16

Table 8-A. Summary of Multiple Tray Experiments, Series 1.

Test No.	Cable #	Trays	Cables per Tray	Loading	Fill (Note 1) (% of NEC max)	Comments/Damage
MT-1	23	3 x 8 ft	32	Tight	36	Damage confined to 4 ft inner bay (Note 2)
MT-2	701	3 x 8 ft	44	Tight	50	Fire spread to ends, all trays
MT-3	219	3 x 8 ft	32	Tight	36	Damage confined to 4 ft inner bay (Note 2)
MT-4	43, 21, 20	4 x 8 ft	28	Tight	37	Pick ax required to aid upward spread Damage confined to 2 ft
MT-5	21, 23, 15, 13	3 x 8 ft	28	Loose	32, 34, 29	Damage confined to 2 ft
MT-6	13	4 x 8 ft	24	Loose	27	Damage confined to 2 ft
MT-7	13	4 x 8 ft 3 x 12 ft	36	Loose	41	50 % more cable than MT-6 Fire spread to ends, all trays
MT-8	701	4 x 12 ft	44	Loose	41	Fire spread to ends except lowest tray
MT-9	701	4 x 12 ft	22	Loose	25	50 % less cable than MT-8 Damage confined to 6 ft inner bay (Note 2)
MT-10	11	4 x 8 ft	14	Loose	83	Damage confined to 4 ft inner bay (Note 2)
MT-11	701	4 x 12 ft	44	Loose	50	Replicate of MT-8 Fire spread to ends, all trays
MT-12	700	3 x 8 ft	40	Loose	34	Light Damage above burner

Test No.	Cable #	Trays	Cables per Tray	Loading	Fill (Note 1) (% of NEC max)	Comments/Damage
MT-13	701	1 x 8 ft	44	Loose	50	Test to see if spread can occur for only one tray. Damage only in vicinity of burner
MT-14	219, 220	4 x 8 ft	Tray 1: 24 #220 Tray 2: 36 #220 Tray 3: 32 #219 Tray 4: 42 #219	Loose	45, 68, 36, 48	Slow vertical spread to 3 rd tray; substantial spread after relight of burner. Spread nearly to end of trays
MT-15	12, 16, 367	3 x 8 ft	Tray 1: 25 #16 Tray 2: 14 #12 Tray 3: 36 #367	Loose	53, 83, 54	Test of Kerite cable in the 3 rd tray Tray 3 burns to the end
MT-16	269, 270	3 x 8 ft	80	Loose	67	Shielded, triaxial cable Fire spread nearly to end of Tray 3

Notes:

- 1 The column entitled “% of NEC max” indicates the volume of the tray occupied by cables as a fraction of the limit imposed by the National Electric Code (NFPA 70 2008).
- 2 The “inner bay” of the rack is the area between the support columns.

8.3 Results, Multiple Tray Experiments, Series 2

A second series of Multiple Tray Experiments was conducted in January and February, 2010. Unlike the first series, conducted in May, 2009, these experiments consisted of mixtures of cables because there was not enough of any given type of cable to conduct an extensive parameter study. Table 8-B lists the number and type of cable used in each tray for each experiment.

Also, these experiments were intended to assess the effect of tray width, tray spacing, and tray fill. The first series of Multiple Tray Experiments involved only one tray width (0.45 m, 18 in) and one tray spacing (0.30 m, 12 in).

Table 8-B. Summary of Multiple Tray Experiments, Series 2

Test No.	Tray Spacing (in)	Tray Width (in)	Tray Loading (%)	Cable 2	Cable 3	Cable 7	Cable 17	Cable 22	Cable 25	Cable 34	Cable 45	Cable 47	Cable 212	Cable 261	Cable 272	Cable 273	Cable 312	Cable 327	Cable 337	Cable 503	Cable 505	Cable 612	Cable 700	Cable 701
MT-17	12	18	50	2	3	4	2	4			2			3	2						3			3
MT-18	12	36	50	4	6	8	4	8			4			6	4						6			6
MT-19	12	18	50	2	3	4	2	4			2			3	2						3			3
MT-20	12	36	25	2	3	4	2	4			2			3	2						3			3
MT-21	18	18	50	2	3	4	2	4			2			3	2						3			3
MT-22	15	36	50	4	6	8	4	8			4			6	4						6			6
MT-23	9	18	50	2	3	4	2	4			2			3	2						3			3
MT-24	9	36	25	2	3	4	2	4			2			3	2						3			3
MT-25	12	18	50						3	2		6	2			1	3	5	3	5		4	4	
MT-26	12	12	75						3	2		6	2			1	3	5	3	5		4	4	

Notes:

1. The numbers in the columns labeled “Cable *n*” indicate the number of that particular cable used in the test.
2. MT-22 was the last test conducted, and because of the lack of cables it was necessary to make a few substitutions to maintain the same approximate composition of cable as the other experiments.

8.3.1 Multiple Tray Test MT-17 and MT-18

Tests 17 and 18 were designed to assess the effect of doubling the width of the tray from 0.45 m (18 in) to 0.90 m (36 in). In both experiments, the trays were loaded to 50 % of the NEC limit, which means that the wider tray contained twice as much cable as the narrower. Each test used seven trays stacked 0.3 m (12 in) apart. The trays were 12 ft (3.6 m) long, but to save cable for the rest of the series, only 3 ft of cable was used in the lowest tray, followed by 4 ft, 5 ft, 7 ft, 8 ft, 9 ft, and 12 ft at the top. The intent of this loading arrangement was to capture the so-called V-pattern of upward spread without wasting an excessive amount of cable in the lower trays. However, because the fire spread to the ends of the loaded portion of each tray, it was decided in subsequent experiments to include greater lengths of cable in the lower trays.

Figure 8-21 displays the HRR of both experiments. The doubling of the cable mass (by way of doubling the horizontal surface area) more than doubles the HRR. The total burning time of the two tests is comparable.

Figure 8-22 and Figure 8-23 are photographs of Tests MT-17 and MT-18, respectively. Figure 8-23 demonstrates the increased burning area of the wider trays.

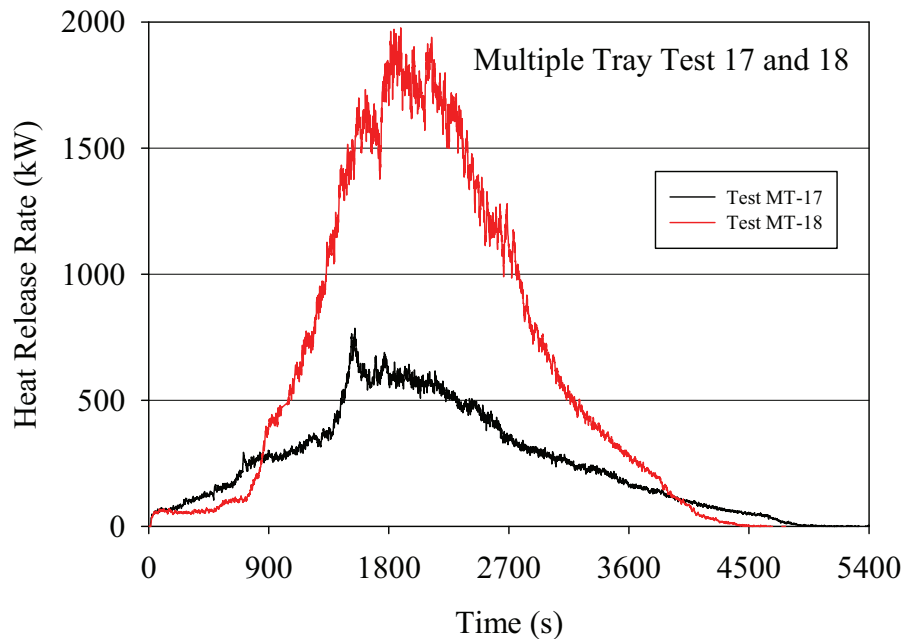


Figure 8-21. Heat Release Rates for MT-17 and MT-18.



Figure 8-22. Multiple Tray Test 17 after 25 min.



Figure 8-23. Multiple Tray Test 18 after approximately 20 min.

8.3.2 Multiple Tray Test MT-19 and MT-20

Tests MT-19 and MT-20 were designed to assess the effect of doubling the size of the tray while maintaining the same cable mass. Test MT-19 involved a stack of 7 trays, 0.45 m (18 in) in width and loaded to 50 % of the NEC limit. Test MT-20 involved the same amount of cable, only now spread out in a 0.90 m (36 in) wide tray. The trays were spaced 0.3 m (12 in) apart in both tests. The lowest tray contained 5 ft (out of 12) of cable, the next tray contained 7 ft, and the five trays above contained the full length of 12 ft of cable.

Figure 8-24 shows the HRR of both experiments. The total amount of cable burned in each test is comparable, as evidenced by the comparable areas under both curves, but the burn time for the MT-19 is roughly twice as great as MT-20. This clearly demonstrates that the upward spread and burning rate of the cables are influenced by the higher relative loading of the trays in MT-19. In MT-20, the fire spread rapidly upward because the cables were spaced far enough apart in the tray that the flames were able to pass through, rather than around, the cables.

The photographs shown in Figure 8-25 and Figure 8-26 demonstrate that the wider trays enable the fire to reach its peak in roughly half the time, and because more trays are burning simultaneously, the peak HRR is more than double.

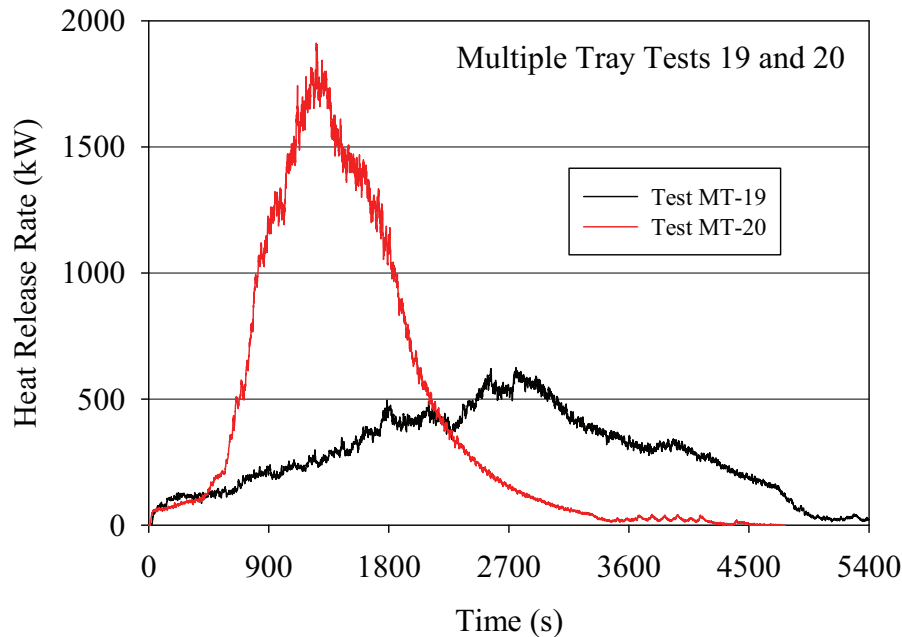


Figure 8-24. Heat Release Rates for Tests MT-19 and MT-20.



Figure 8-25. Photograph of Multiple Tray Test MT-19.



Figure 8-26. Photograph of Multiple Tray Test MT-20.

8.3.3 Multiple Tray Test MT-21 and MT-22

Tests MT-21 and MT-22 were originally intended to assess the impact of increasing the vertical cable spacing from 0.3 m (12 in) to 0.45 m (18 in). However, during Test MT-21, the fire did not spread beyond the second tray. The tray width in this test was 0.3 m (12 in). The 40 kW burner was left on for 45 min (instead of the usual 15), and still the fire burned only weakly in the second tray and more or less burned out within the area just above the burner in the lowest tray. Because of this, it was decided not to use the 18 in spacing in Test MT-22, but rather 15 in (0.38 m) spacing with 0.90 m (36 in) wide trays, loaded to 50 % of the NEC limit.

The HRR of MT-21 and MT-22 are shown together in Figure 8-27 even though the two experiments are not easily compared. The photographs on the following page show the dramatically different outcomes of the two experiments.

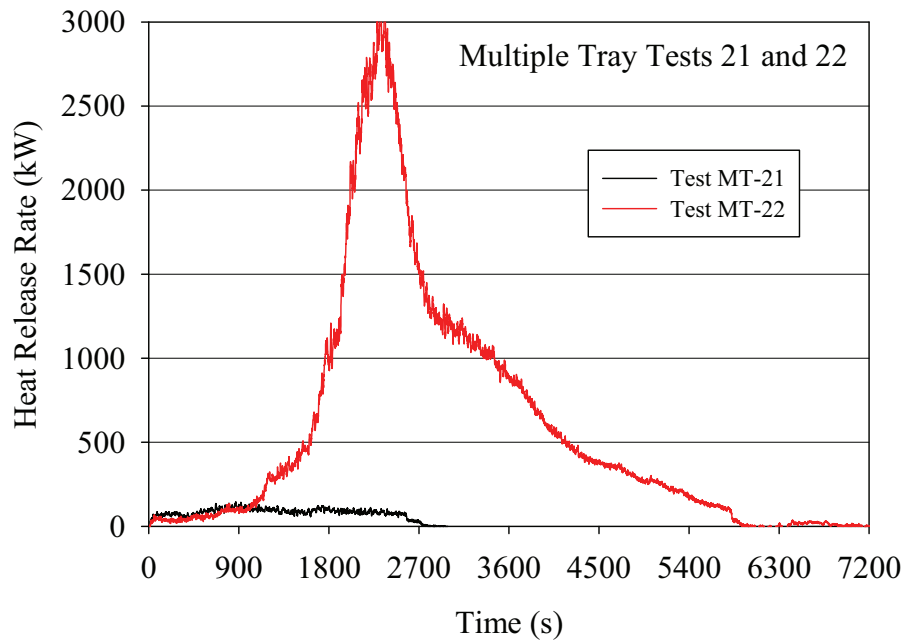


Figure 8-27. Heat Release Rates for Multiple Tray Tests MT-21 and MT-22.



Figure 8-28. Photograph of Multiple Tray Test MT-21.



Figure 8-29. Photograph of Multiple Tray Test MT-22.

8.3.4 Multiple Tray Tests MT-23 and MT-24

Tests MT-23 and MT-24 were designed to assess the effect of decreasing the vertical tray spacing from 0.3 m (12 in) to 0.23 m (9 in). At the same time, these experiments demonstrated that spreading out cables over a wider tray (36 in in Test 24) leads to more rapid growth and a higher peak HRR. The same type and number of cables were used in both tests.

Figure 8-30 displays the HRR for MT-23 and MT-24. Photographs of the experiments are shown in Figure 8-31 and Figure 8-32, respectively. It is important to note that the fire in the 36 in wide trays (MT-24) spread to both ends of all of the trays, while the fire in the 18 in wide trays only spread to one end due to a slight breeze in the test building caused by an asymmetric arrangement of air intake ducts.

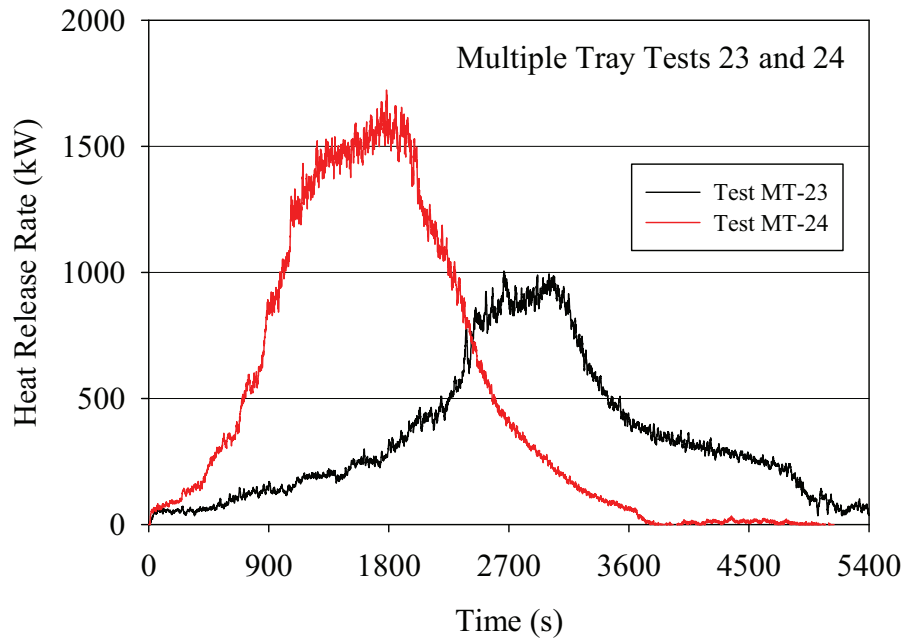


Figure 8-30. Heat Release Rates for Multiple Tray Tests MT-23 and MT-24.



Figure 8-31. Photograph of Multiple Tray Test MT-23.



Figure 8-32. Photograph of Multiple Tray Test MT-24.

8.3.5 Multiple Tray Tests MT-25 and MT-26

Tests MT-25 and MT-26 were conducted with a different mixture of cables than Tests MT-17 through MT-24. Table 8-B provides the make-up of each tray. Also, MT-25 and MT-26 used only five trays each, spaced 0.3 m (12 in) apart. The lowest tray contained 5 ft of cable (out of 12), the next tray contained 7 ft, and the next three trays contained 12 ft each. Both tests used the same amount of cable, but in Test MT-25 the cables were spread in a 0.45 m (18 in) tray while in MT-26, the cables were spread in a 0.3 m (12 in) wide tray. The objective of the test was to see if the change in tray width would lead to a similar result as for the wider trays.

Figure 8-33 shows the HRR for MT-25 and MT-26. The results demonstrate that spreading the same mass of cable within a tray that is 1.5 times as wide leads to more rapid upward spread and a higher peak HRR. The photograph of MT-25 shown in Figure 8-34 shows that burning is nearly complete in the wider tray test at 48 min whereas the fire in the narrower tray is still burning near its peak after 1 h (Figure 8-35). A slight breeze in the test lab caused the fire to spread to the left.

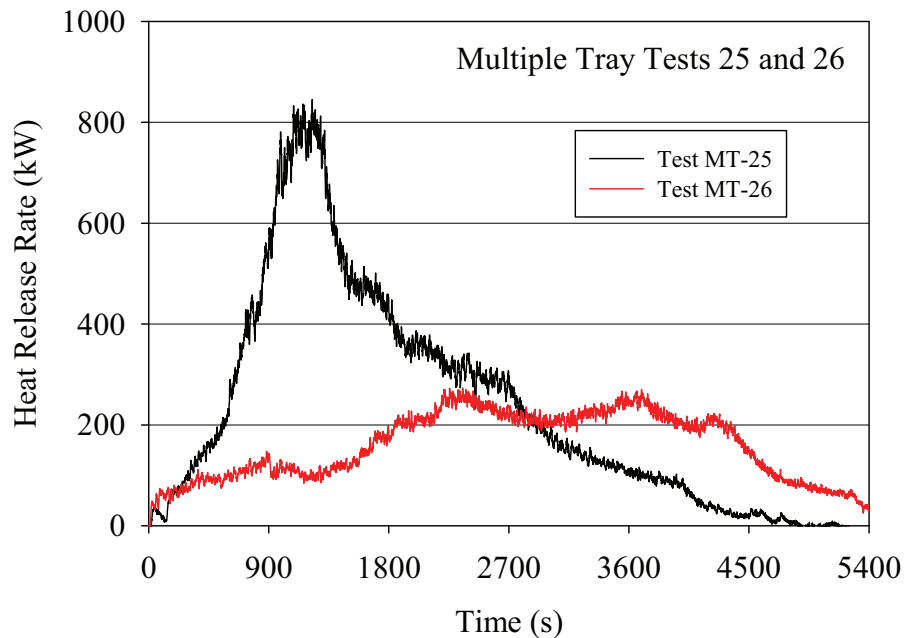


Figure 8-33. Heat Release Rates for Multiple Tray Tests MT-25 and MT-26.



Figure 8-34. Photograph of Multiple Tray Test MT-25.



Figure 8-35. Photograph of Multiple Tray Test MT-26.

9 MODELING

The goal of the CHRISTIFIRE program is to gather data to support the development of methods to model cable fires. This chapter describes a relatively simple model that can be used to predict the heat release rate from a vertical stack of horizontal cable trays. The relative simplicity of the model is a direct result of the fact that the data collected during this and other cable fire projects is subject to considerable uncertainty based on the test method, scale, and cable type. Before introducing the model, a summary of the data collected during this phase of the project is discussed.

9.1 Summary of Data Collection for Modeling

The preceding chapters present a considerable amount of information about the burning of electrical cables, but it is difficult to use the data directly in a fire model because the most important properties that have been measured, such as the heat release rate per unit area (HRRPUA), the heat of combustion, and the char/residue yield, are effective properties that depend significantly on the particular test configuration. For example, the HRRPUA that is determined from the Radiant Panel Apparatus and the Cone Calorimeter is dependent on the size of the sample, the imposed heat flux, and the heat fed back from the fire itself. As another example, the heat of combustion that is extracted from the Micro-Calorimeter (MCC) data is different from that which is extracted from the Radiant Panel Apparatus or Cone Calorimeter because the MCC makes use of an oxygen-depleted environment.

Table 9-A lists some important parameters for modeling cable fires. Of these, only the bulk physical properties like Outer Diameter (OD), Mass/Length, and Plastic Mass Fraction can be measured with a degree of accuracy that would warrant a detailed description within a model. The other properties are significantly affected by the specific test configuration, and, thus, models employing these parameters cannot include a detailed treatment of the physical phenomena.

Another problem with the measurements of thermo-physical properties of the cables is that there are literally hundreds of different types of cables currently installed in NPPs in the U.S., manufactured over a span of approximately 40 years under a changing regulatory framework. Compiling a comprehensive database of material properties for the purpose of fire modeling would be an enormous undertaking. Given the uncertainty associated with the various bench-scale measurements, it would be of questionable value as well. Archibald Tewarson of FM Global (Factory Mutual) has compiled an extensive list of heats and products of combustion for a wide variety of materials, including those used in cables (SFPE, 2008). However, the list includes mostly effective properties of materials that are in general dependent on the details of the measurement apparatus. In addition, it is difficult to combine the properties of the individual materials that make up a cable because these materials burn in stages; first the jacket, followed by the insulation material and filler.

Table 9-A. Summary of measured properties of the cables used in CHRISTIFIRE.

Cable No.	OD (mm)	Mass/Length (kg/m)	Plastic Mass Fraction	Residue Yield			Heat of Combustion (MJ/kg)		HRRPUA (kW/m ²)	
				Tube Furnace	MCC	Radiant Panel	Cone	Radiant Panel	Cone	Radiant Panel
11	32	1.985	0.45	--	0.28	0.2	16.4	16.7	127	160
16	19	0.671	0.48	0.09	0.32	0.5	23.8	15.0	173	100
23	14	0.253	0.69	0.33	0.43	0.4	13.2	12.2	135	100
43	15	0.357	0.62	--	0.35	0.3	17.0	--	169	110
46	15	0.437	0.52	0.20	0.38	0.5	16.2	15.9	172	80
219	14	0.296	0.61	0.27	0.47	0.3	20.5	19.3	187	200
220	18	0.560	0.62	0.33	0.46	0.4	22.5	17.3	--	200
269	12	0.240	0.53	--	0.24	0.0	18.1	13.9	510	270
271	10	0.123	0.70	0.18	0.27	0.1	28.1	16.0	199	180
367	16	0.441	0.73	0.40	0.44	0.3	23.3	18.0	169	210
700	12	0.322	0.33	0.30	0.31	0.5	22.5	19.2	--	150
701	14	0.366	0.42	0.15	0.25	0.0	18.0	16.1	266	250

Note: The precision of the measurement is indicated by the number of significant figures.

9.2 The FLASH-CAT Model

This section describes a relatively simple model for predicting the growth and spread of a fire within a vertical stack of horizontal cable trays. The model is referred to as FLASH-CAT, short for Flame Spread over Horizontal Cable Trays. The basic assumptions are taken from Appendix R of NUREG/CR-6850, with some additional information provided by the small and intermediate-scale experiments described in this report. Following the description of the model, the results of the 26 Multiple Tray Experiments are compared with the predictions of the model.

9.2.1 Model Overview

The FLASH-CAT model makes use of the following assumptions:

- The cable trays are horizontal and stacked vertically.
- There are no barriers separating the trays, and the tray tops and bottoms are open.
- The cables are not protected with coatings, armor shielding, or thermal blankets of any kind.
- There is a fire beneath the lowest tray.
- Each tray has at least a single row of cables, or roughly 25 % of the NEC limit.

Under these assumptions, the fire is assumed to propagate upwards through the array of cable trays according to an empirically determined timing sequence. In other words, the time for the fire to spread from one tray to the tray above is a function only of its order in the stack, not the thermal properties of the cables. The length of cables within a given tray that ignite initially increases as the fire spreads upwards. Lateral spread of the fire begins as soon as the cables within the tray ignite. This produces a solid V-shaped burning pattern that expands laterally with time. As the mass of combustible material within the center of the V is consumed, the V-shape becomes an expanding, open wedge of burning cable. The fires in each tray continue to spread until the end of the tray is reached.

Burning Rate: Once a given tray has ignited, the model assumes that the cables burn over a length that is greater than that of the tray below. The length increases according to the formula:

$$L_{i+1} = L_i + 2 h_i \tan(35^\circ) \quad (9.1)$$

Here, h_i is the vertical distance between the two trays. The value of 35° is based on observations of cable fire experiments performed at Sandia National Laboratories and documented in NUREG/CR-6850. The fire is assumed to span the width, W , of the tray. The heat release rate of the fire within the tray is initially equal to the length times the width times the specified heat release rate per unit area (HRRPUA). This last parameter is described below.

Vertical Spread Rate: NUREG/CR-6850 suggests that a fire propagates upward through the stack of trays as follows. The lowest (first) tray ignites after 5 min of exposure to the ignition source. The second tray ignites 4 min following the ignition of the first tray. The third tray ignites 3 min after the second. The fourth tray ignites 2 min after the third. The fifth tray ignites

1 min after the fourth. It is assumed that each subsequent ignition occurs 1 min apart.

Horizontal Spread Rate (S): NUREG/CR-6850 provides estimates of horizontal spread rates for a typical thermoset (XPL) and thermoplastic (PVC) cable. The values are 1.1 m/h (3.5 ft/h) and 3.2 m/h (10.6 ft/h), respectively. It is assumed that the fire in a given tray spreads laterally at this rate until the end of the tray is reached.

Fire Duration: NUREG/CR-6850 does not discuss fire duration. However, given a known combustible mass and a specified heat release rate, the duration of the fire, Δt , at a given location is calculated:

$$\Delta t = \frac{m_c'' \Delta H}{5 \dot{q}_{avg}'' / 6} \quad (9.2)$$

where m_c'' is the combustible mass per unit area, ΔH is the heat of combustion, and \dot{q}_{avg}'' is the heat release rate per unit area (HRRPUA)⁸. The combustible mass per unit area can be found by calculating:

$$m_c'' = \frac{n Y_p (1 - v) m'}{W} \quad (9.3)$$

where n is the number of cables per tray, Y_p is the mass fraction of non-metallic material, v is the char yield, m' is the mass per unit length of cable, and W is the width of the tray. Note that not all of the non-metallic materials in a cable will burn. There is almost always some solid residue or char left behind. The mass of this residue divided by the mass of the original combustible material is designated by v .

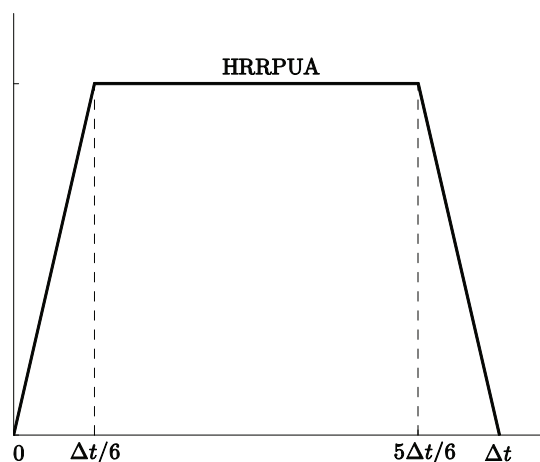


Figure 9-1. Idealized time history of the local heat release rate per unit area.

⁸ Note that the fraction 5/6 is a result of the fact that the average heat release rate per unit area is based on 80 % of the total energy release.

Heat Release Rate: The total heat release rate of the fire is calculated from the following formula:

$$\dot{Q}(t) = \dot{Q}_{\text{burner}} + W \sum_{i=1}^{N_{\text{trays}}} \left[\int_{-L/2}^{L/2} \dot{q}''(t - t_{\text{ign},i}(x)) dx \right] \quad (9.4)$$

The time of ignition for the point, x , of the i -th tray is:

$$t_{\text{ign},i}(x) = t_{\text{ign},i,0} + \max \left(0, \frac{|x| - L_i/2}{S} \right) \quad (9.5)$$

The time, $t_{\text{ign},i,0}$, is the time when the tray first ignites, whereas $t_{\text{ign},i}(x)$, is the time when the cables located at the point x first ignite. If this point is within the original section of cable that first ignites, the two ignition times are the same.

Model Output: The primary output of the FLASH-CAT model is the time history of the heat release rate, $\dot{Q}(t)$. In addition, it is possible to create a simple animation showing the progression of the fire upwards and outwards as a function of time. Figure 9-2 shows the evolution of Multiple Tray Test 17 as predicted by FLASH-CAT.

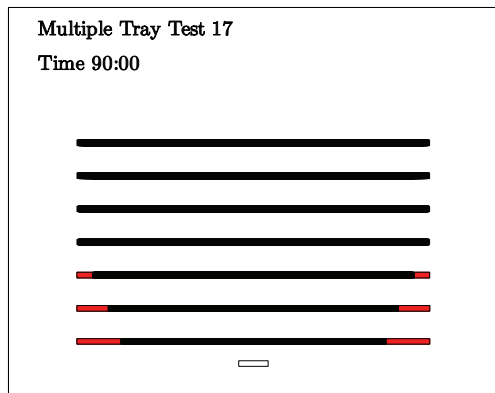
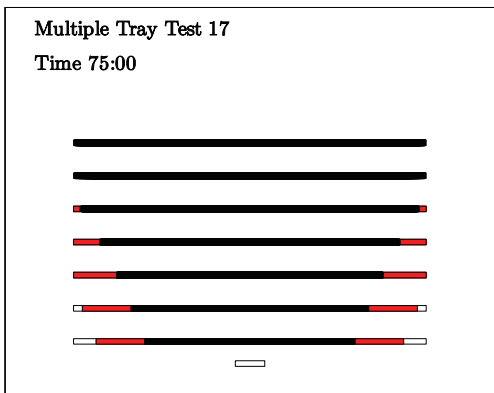
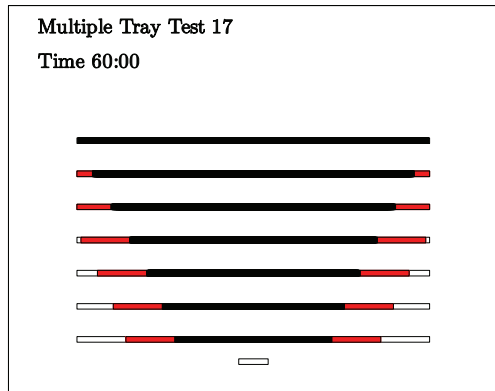
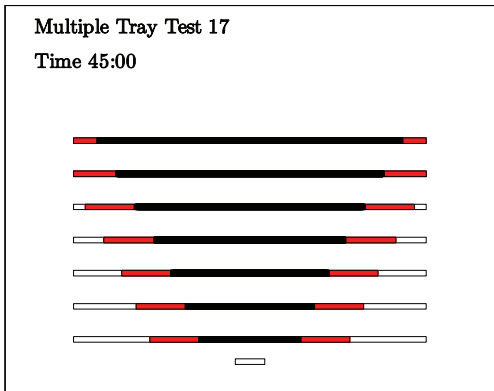
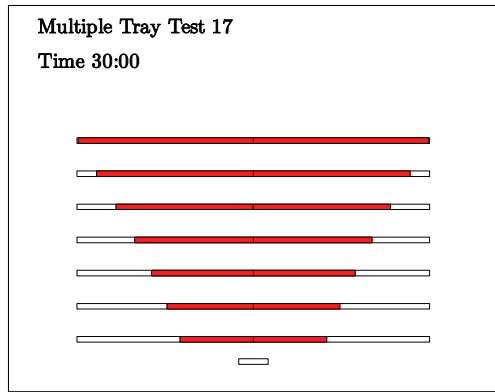
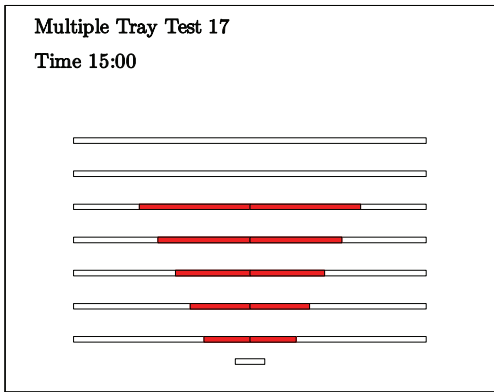


Figure 9-2. FLASH-CAT model results for Multiple Tray Test 17.

9.2.2 FLASH-CAT Model Input Parameters

This section describes the information needed by the FLASH-CAT model to predict the heat release rate from a vertical stack of horizontal ladder-back cable trays. The parameters for all 26 full-scale experiments are listed in Table 9-B.

Test #: There were 26 experiments involving multiple horizontal ladder-back trays, denoted by the abbreviation MT for Multiple Tray. Tests 1-16 were conducted in May, 2009, and Tests 17-26 were conducted in January and February, 2010.

Cable ID: Each spool of cable used in CHRISTIFIRE was assigned a number for tracking purposes. It has no other meaning other than to identify it. Note that each of Tests 1-16 made use of only a few different cables. These cables had been tested in the Radiant Panel Apparatus, the Cone Calorimeter, the Tube Furnace, and the Micro-Calorimeter, as well. Tests 17-26 used fixed combinations of cables. Tests 17-24 all used the same cables mixed together in the same ratio. Tests 25 and 26 used a different mixture.

No. Cables (n): This parameter indicates the number of cables in each tray.

No. Trays (N_{trays}): The number of horizontal trays used in the test.

Tray Spacing (h_i): The vertical distance from the bottom of tray i to the bottom of tray $(i+1)$. The various racks used to support the trays used 3 inch spacing increments. The vertical spacing ranged from 9 in to 18 in. In Test 13, only one tray was used in order to determine if the fire would spread over a single tray.

Tray Length: Only two tray lengths were used in the series, 8 ft (2.4 m) and 12 ft (3.6 m). Note that in Tests 1-16, each tray was filled with cables along its entire length. In Tests 17-26, some of the trays contained shortened cables near the bottom of the stack to save on supply.

Tray Width (W): Three tray widths were used in the series, 12 in (0.3 m), 18 in (0.45 m), and 36 in (0.90 m). Most tests involved 18 in trays, a common size in the United States.

Mass/Length (m'): The mass per unit length of a single cable, accurate to roughly 1 g/m.

Plastic Mass Fraction (Y_p): The fraction of the cable's mass that is not metal. The Plastic Mass Fraction can be measured easily by disassembling a 10 to 20 cm length of cable into its constituent parts and weighing each with a scale that has an accuracy of plus or minus 1 mg, in which case the value can be reliably determined with an accuracy of $\pm 1\%$. In cases where there is a mixture of cables, the plastic mass fraction for each type can be determined and an average value can be computed using the formula:

$$\bar{Y}_p = \frac{\sum_{i=1}^n Y_{p,i} m'_i}{\sum_{i=1}^n m'_i} \quad (9.6)$$

Char Yield (v): The (mass) fraction of the non-metallic (plastic) part of the cable that is left behind after the fire. This quantity can be determined from any of the bench-scale tests, but its value is dependent on the test configuration and procedure. For this reason, a value of 0.25 has been chosen for all thermoset cables, and a value of 0 for thermoplastics. In the former case, the cables have been observed to form a char, and the char yield ranges from about 0.1 to 0.5. In the latter case, almost all of the combustible material melts and then burns away.

HRRPUA (\dot{q}''_{avg}): Heat Release Rate Per Unit Area (of tray). Correlated values of HRRPUA are listed in NUREG/CR-6850, Appendix R.3, "Heat Release Rate from Cable Tray Fires." The lowest value listed is $0.45 \times 178 = 80 \text{ kW/m}^2$ for an XPE/XPE (thermoset) cable. The highest value is $0.45 \times 589 = 265 \text{ kW/m}^2$ for a PE/PVC (thermoplastic) cable. The measured values from the Cone Calorimeter (Table 6-A) and the Radiant Panel Apparatus (Figure 7-22) for a variety of cables used in CHRISTIFIRE fall within this range.

For FLASH-CAT, the recommended value of HRRPUA is 150 kW/m^2 for thermoset cables and 250 kW/m^2 for thermoplastics. If there is a mixture of thermoset and thermoplastic materials within the cables and/or within the tray, the HRRPUA can be expressed as a mass-weighted average of the two recommended values. For example, if 30 % of the combustible mass is composed of thermoset materials and 70 % of thermoplastic, the HRRPUA can be taken as

$$\text{HRRPUA} = (0.3 \times 150) + (0.7 \times 250) = 220 \text{ kW/m}^2$$

Heat of Combustion (ΔH): The energy released per unit mass of fuel consumed. This is the value used to convert the mass loss rate to the heat release rate. It is only an effective value, found by averaging over (usually) the steady burning phase of the fire. Its value is subject to considerable uncertainty because each of the cable components has a different heat of combustion, and the value is not necessarily a constant over the entire burning period. This is especially true of charring materials. For this reason, a single value of 16 MJ/kg has been selected for all cable types in the FLASH-CAT model. Measured values from the Radiant Panel Apparatus, Cone Calorimeter, and Micro-Combustion Calorimeter are inconsistent. The values change from test to test, and device to device. If more reliable data can be found in the future, it can easily be used in the model.

Burner Length, Width, HRR, Duration, and Offset: These parameters merely establish the fire of origin. In CHRISTIFIRE, a $40 \text{ kW} \pm 5 \text{ kW}$ natural gas burner was positioned approximately 20 cm (8 in) below the bottom tray. It was typically not extinguished until the fire had established itself in the first two trays.

Spread Rate (S): None of the bench-scale or intermediate-scale experiments performed in CHRISTIFIRE could be used to determine the horizontal rate of fire spread over a tray filled with cables. Instead, NUREG/CR-6850, Appendix R, contains a formula for spread rate based on theoretical arguments and scaling laws. Rates are suggested for horizontal spread of both thermoplastic (3.2 m/h) and thermoset (1.1 m/h) cables. As with HRRPUA, if there is a mixture

of thermoset and thermoplastic materials within the cable and/or tray, the spread rate should be taken as a mass-weighted average of the two recommended spread rates.

Table 9-B. 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		HRRPVA		Heat of Combustion		Burner Length		Burner Width		Burner HRR		Burner Duration		Burner Offset		Spread Rate	
				m	m	m	m	kg/m	kg/kg	kg/kg	kg/kg	kg/kg	kg/m ²	kw/m ²	kJ/kg	m	m	kw	s	m	m/h										
1	23	32	3	0.3	2.4	0.45	0.253	0.69	0.25	150	16000	0.3	0.3	40	2400	0.2	1.1														
2	701	44	3	0.3	2.4	0.45	0.366	0.42	0	250	16000	0.3	0.3	40	3600	0.2	3.2														
3	219	32	3	0.3	2.4	0.45	0.296	0.61	0.25	150	16000	0.3	0.3	40	650	0.2	1.1														
4	43	28	4	0.3	3.6	0.45	0.357	0.62	0.25	150	16000	0.3	0.3	40	2800	0.2	1.1														
5	16	28	3	0.3	2.4	0.45	0.671	0.48	0.25	150	16000	0.3	0.3	40	400	0.2	1.1														
6	16	24	4	0.3	3.6	0.45	0.671	0.48	0.25	150	16000	0.3	0.3	40	900	0.2	1.1														
7	16	36	7	0.3	3.6	0.45	0.671	0.48	0.25	150	16000	0.3	0.3	40	1100	0.2	1.1														
8	701	44	4	0.3	3.6	0.45	0.366	0.42	0	250	16000	0.3	0.3	40	250	0.2	3.2														
9	701	22	4	0.3	3.6	0.45	0.366	0.42	0	250	16000	0.3	0.3	40	260	0.2	3.2														
10	11	14	3	0.3	2.4	0.45	1.985	0.45	0.25	150	16000	0.3	0.3	40	1200	0.2	1.1														
11	701	44	4	0.3	3.6	0.45	0.366	0.42	0	250	16000	0.3	0.3	40	100	0.2	3.2														
12	700	40	3	0.3	2.4	0.45	0.322	0.33	0.25	150	16000	0.3	0.3	40	550	0.2	1.1														
13	701	44	1	N/A	2.4	0.45	0.366	0.42	0	250	16000	0.3	0.3	40	3300	0.2	3.2														
14	219	35	4	0.3	2.4	0.45	0.296	0.61	0.25	150	16000	0.3	0.3	40	3600	0.2	1.1														
15	367	36	3	0.3	2.4	0.45	0.441	0.73	0.25	150	16000	0.3	0.3	40	2700	0.2	1.1														
16	269	80	3	0.3	2.4	0.45	0.24	0.53	0	250	16000	0.3	0.3	40	1000	0.2	1.1														
17	N/A	28	7	0.3	3.6	0.45	0.52	0.53	0.25	150	16000	0.3	0.3	40	900	0.2	1.1														
18	N/A	56	7	0.3	3.6	0.90	0.52	0.53	0.25	150	16000	0.3	0.3	40	900	0.2	1.1														
19	N/A	28	7	0.3	3.6	0.45	0.52	0.53	0.25	150	16000	0.3	0.3	40	900	0.2	1.1														
20	N/A	28	7	0.3	3.6	0.90	0.52	0.53	0.25	150	16000	0.3	0.3	40	900	0.2	1.1														
21	N/A	28	7	0.45	3.6	0.45	0.52	0.53	0.25	150	16000	0.3	0.3	40	900	0.2	1.1														
22	N/A	56	7	0.38	3.6	0.90	0.52	0.53	0.25	150	16000	0.3	0.3	40	900	0.2	1.1														
23	N/A	28	7	0.23	3.6	0.45	0.52	0.53	0.25	150	16000	0.3	0.3	40	900	0.2	1.1														
24	N/A	28	7	0.23	3.6	0.90	0.52	0.53	0.25	150	16000	0.3	0.3	40	900	0.2	1.1														
25	N/A	38	5	0.3	3.6	0.45	0.39	0.49	0.25	150	16000	0.3	0.3	40	900	0.2	1.1														
26	N/A	38	5	0.3	3.6	0.30	0.39	0.49	0.25	150	16000	0.3	0.3	40	900	0.2	1.1														

9.2.3 Model Validation

The following pages present results comparing the measured HRR from the 26 Multiple Tray Experiments with predictions of the FLASH-CAT model. The predictions have been made using only information obtained by dissecting a few tens of centimeters worth of cable. The information that could not be obtained directly from inspection of the cable has been taken from NUREG/CR-6850 or from effective averages of the bench-scale experiments in CHRISTIFIRE, as explained in the previous section.

It is important to note that these 26 experiments were not used in any way to calibrate the model. The basic model formulation is based on the guidance set forth in NUREG/CR-6850, and the input parameters were obtained either by direct measurement of the cables or from 6850. As such, this exercise constitutes model *validation*, not *calibration*.

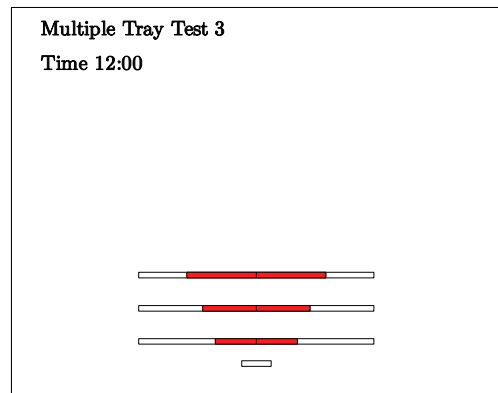
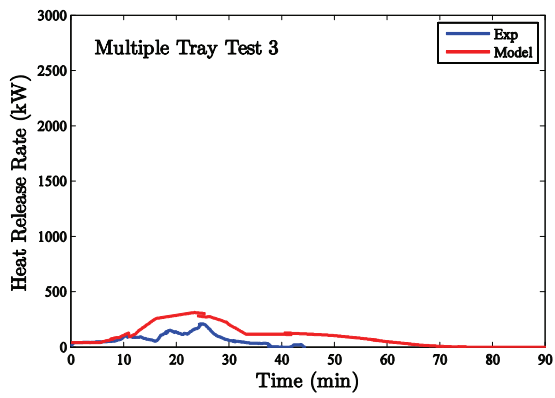
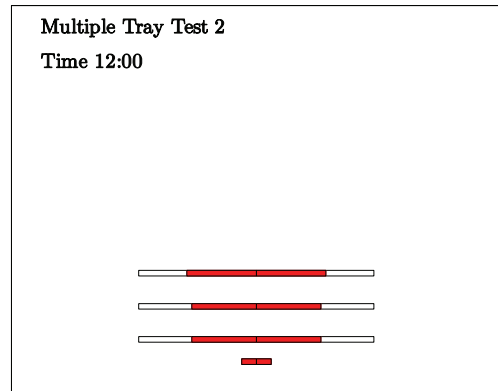
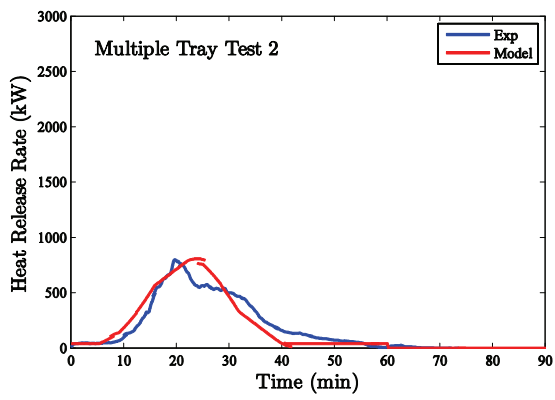
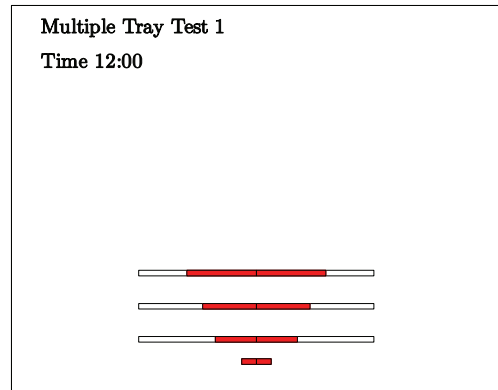
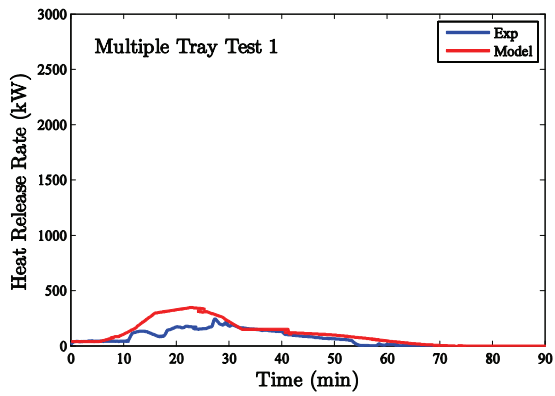


Figure 9-3. Comparison of predicted and measured HRR for Multiple Tray Tests 1-3.

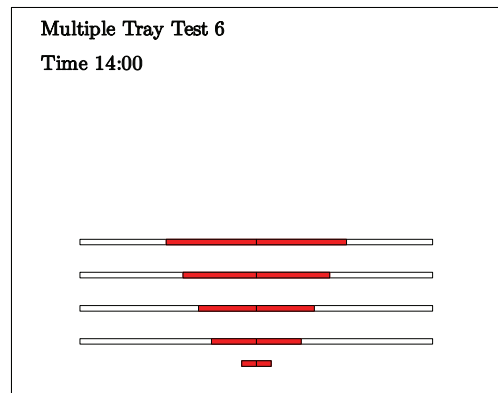
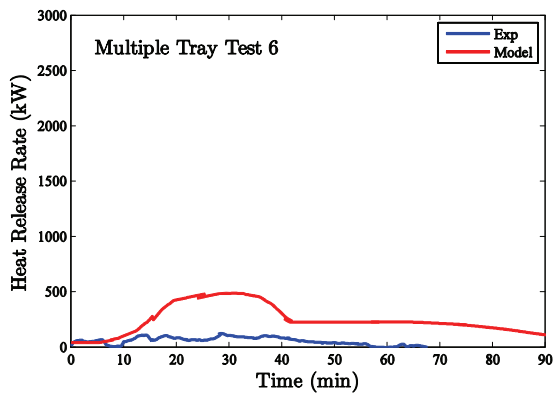
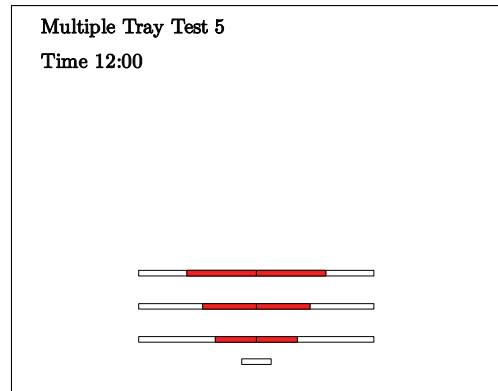
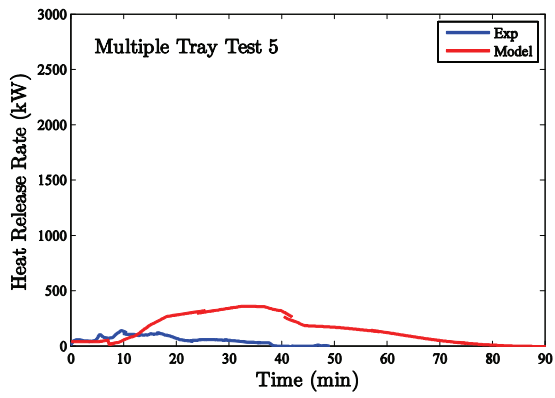
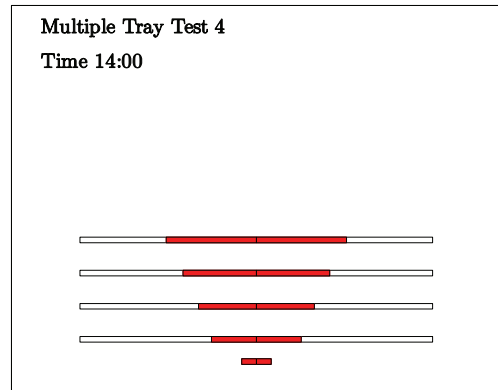
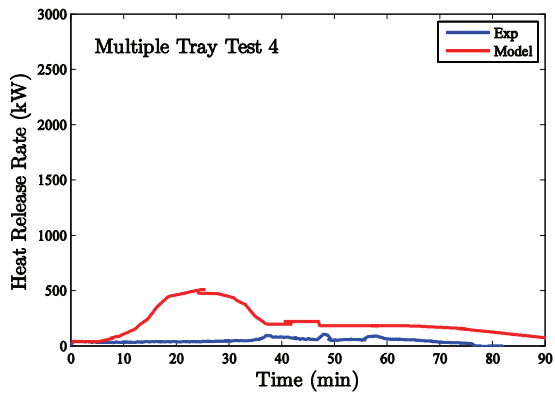


Figure 9-4. Comparison of predicted and measured HRR for Multiple Tray Tests 4-6.

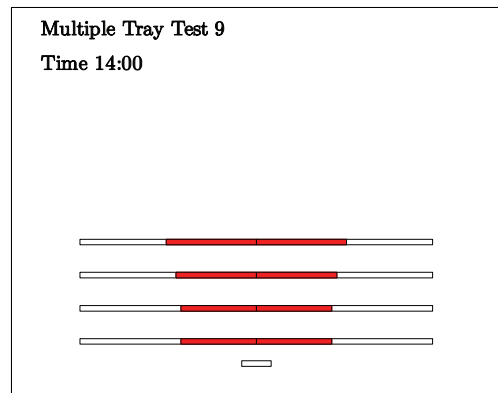
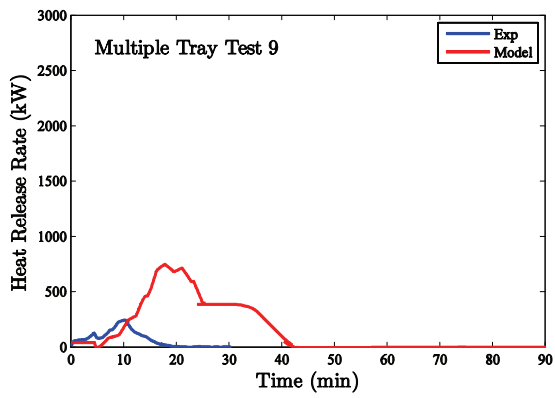
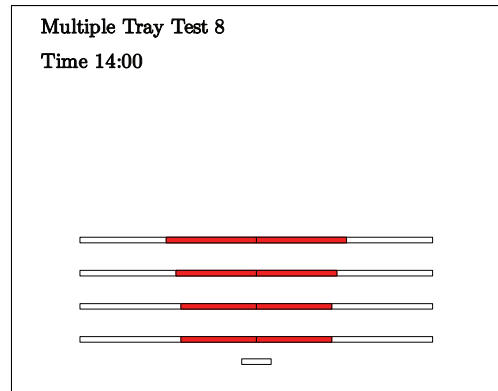
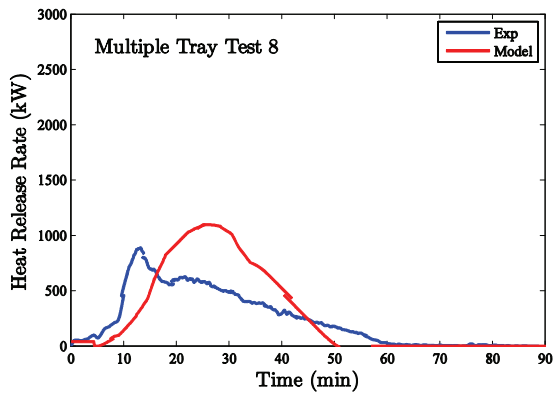
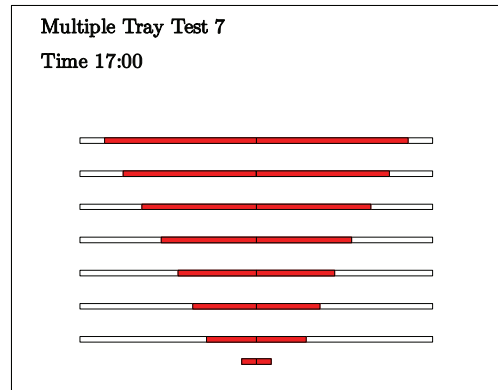
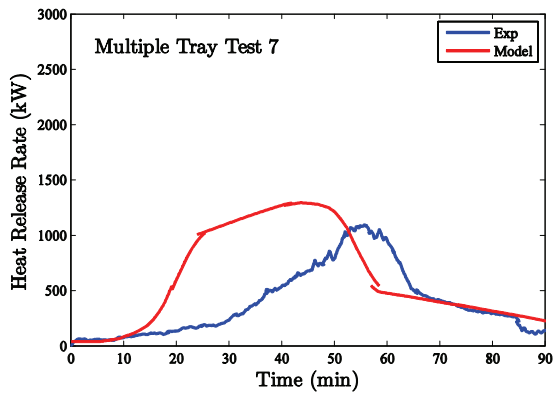


Figure 9-5. Comparison of predicted and measured HRR for Multiple Tray Tests 7-9.

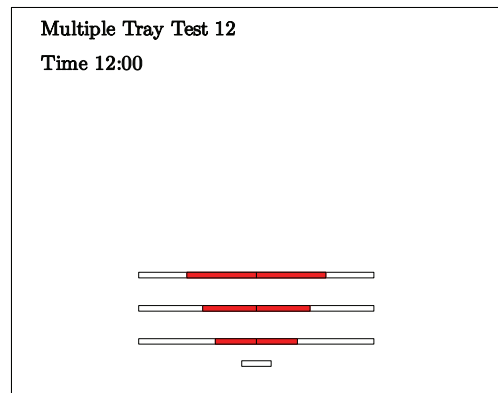
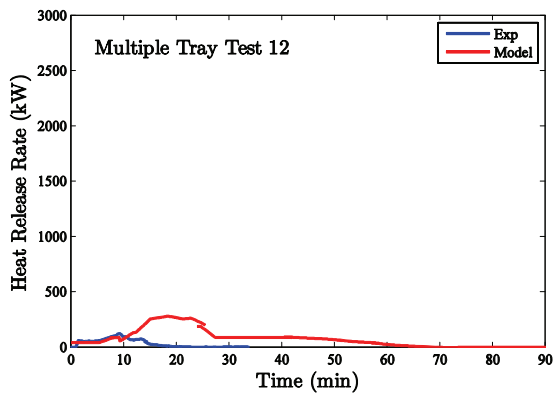
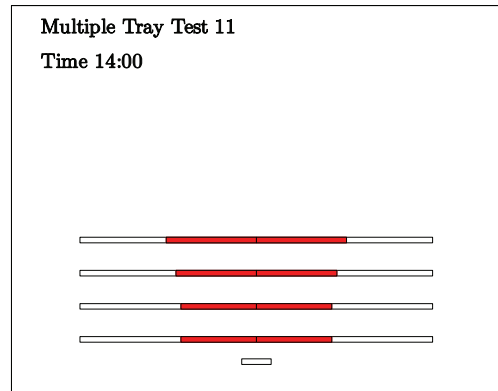
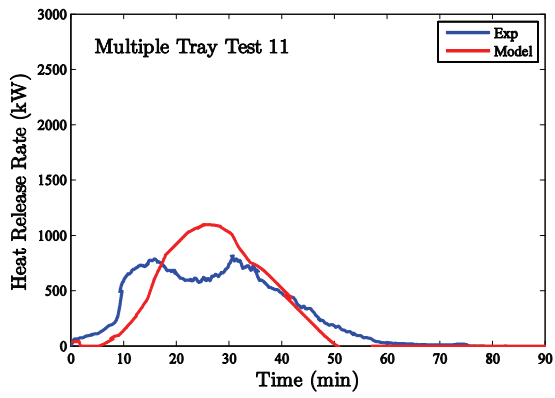
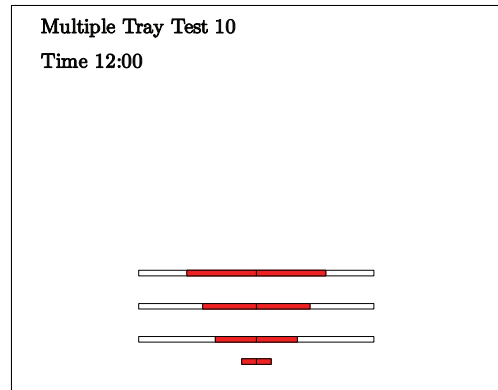
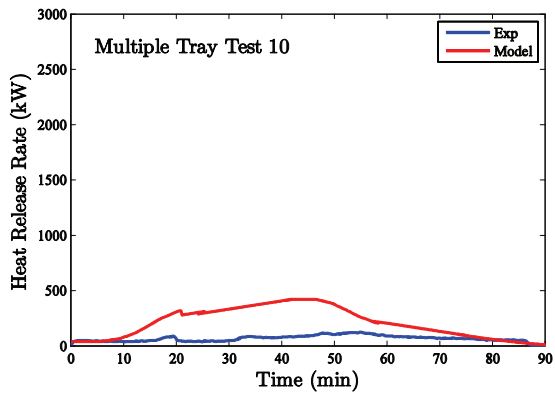


Figure 9-6. Comparison of predicted and measured HRR for Multiple Tray Tests 10-12.

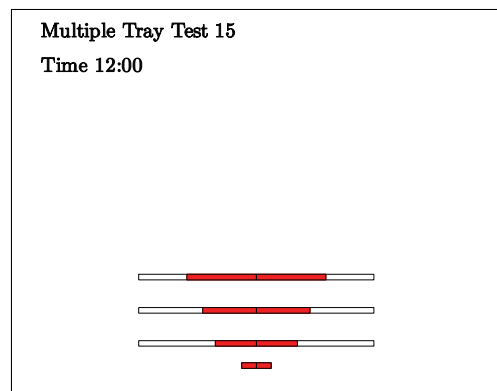
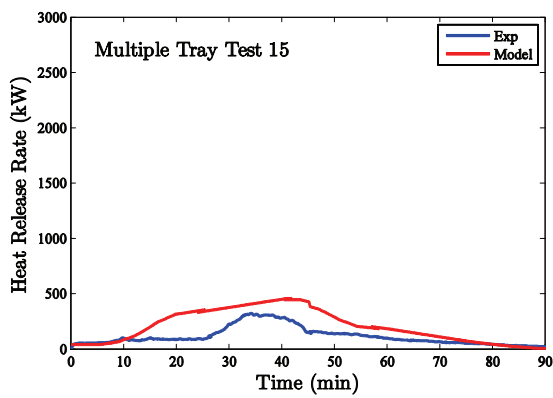
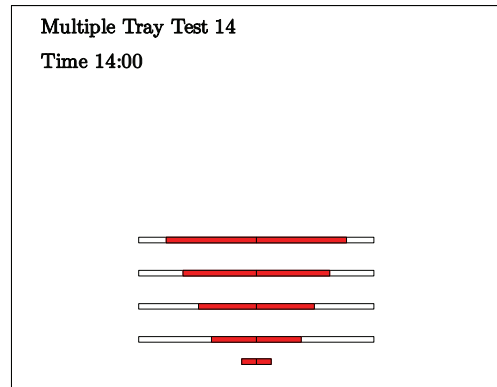
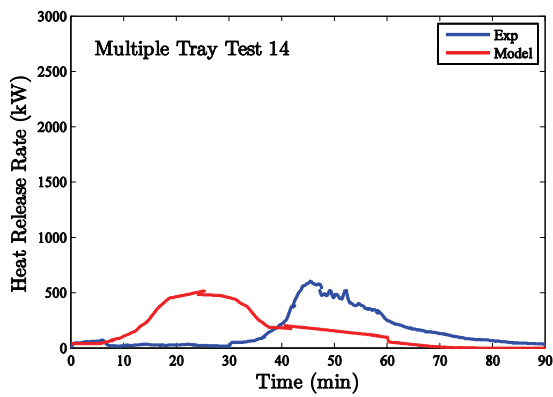
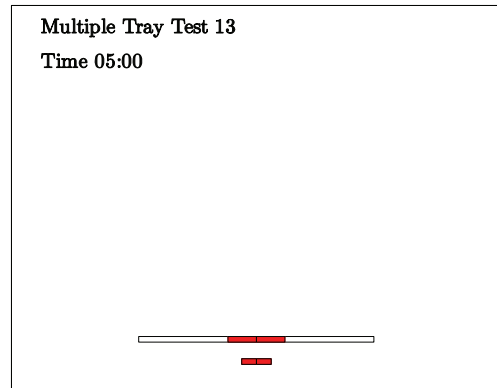
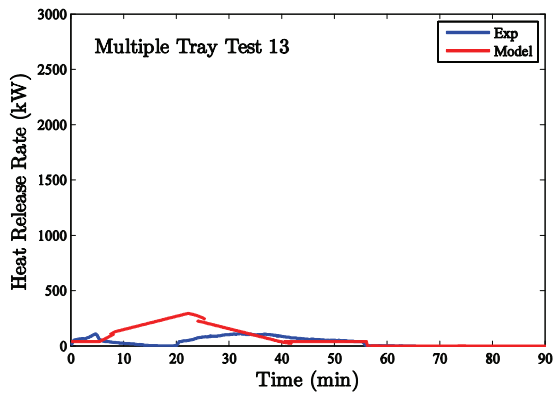


Figure 9-7. Comparison of predicted and measured HRR for Multiple Tray Tests 13-15.

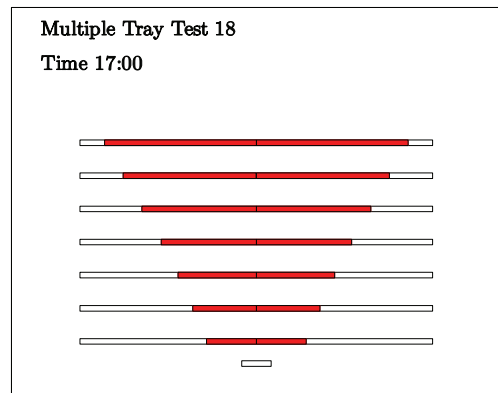
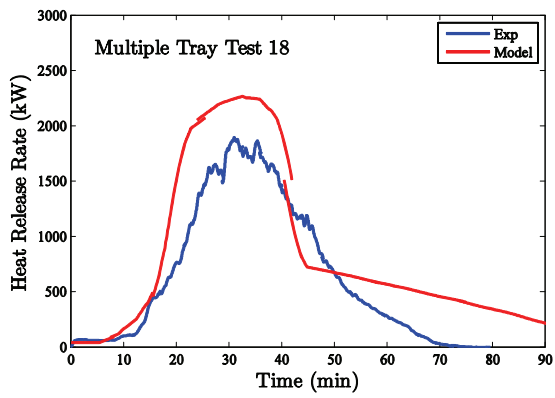
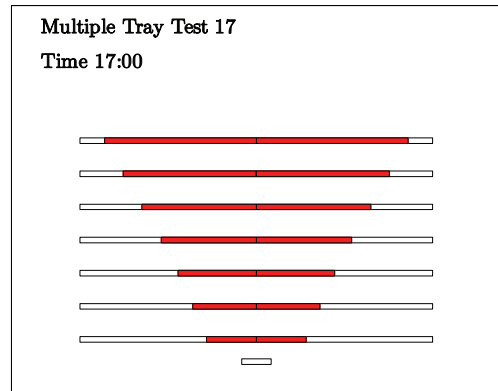
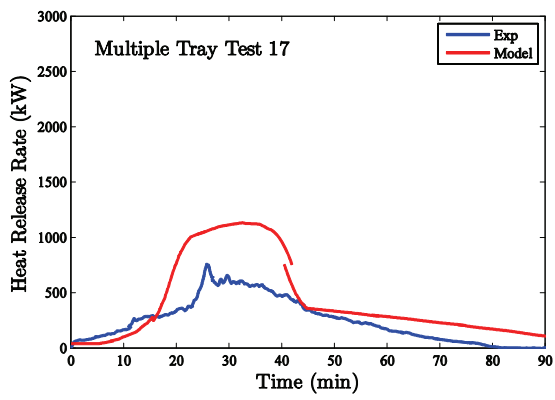
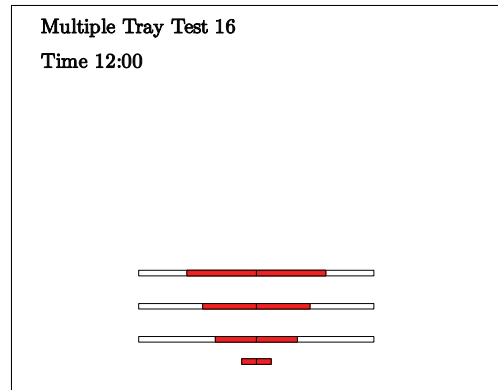
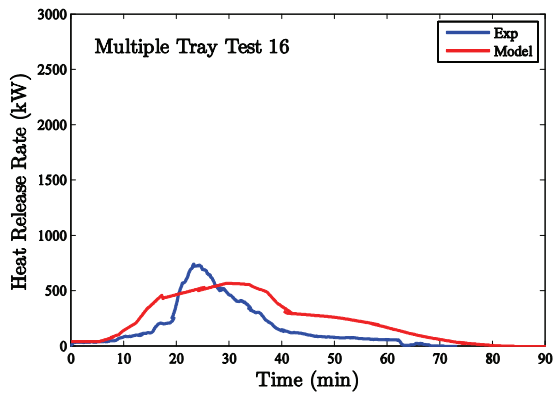


Figure 9-8. Comparison of predicted and measured HRR for Multiple Tray Tests 16-18.

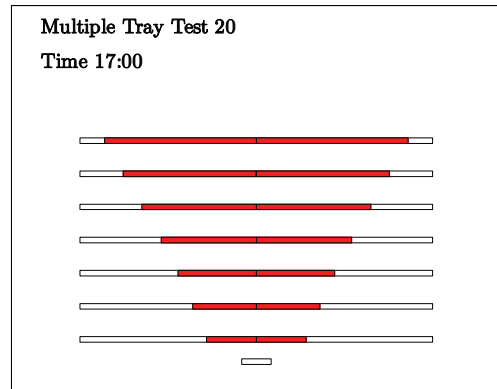
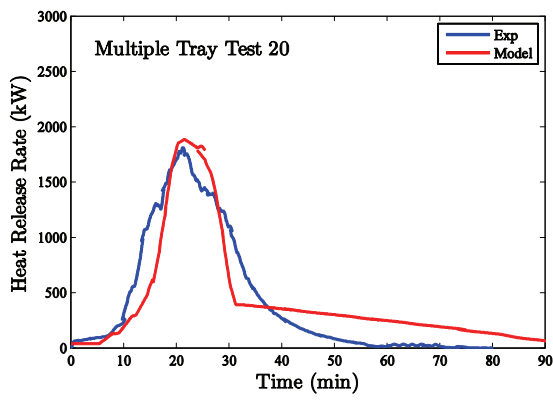
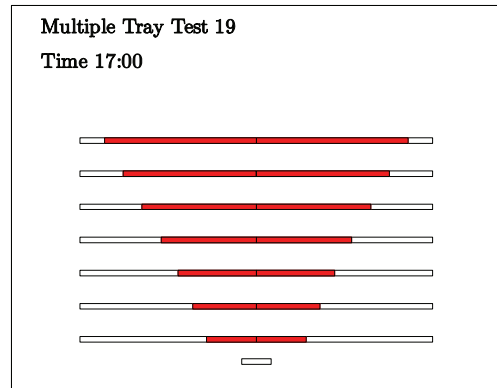
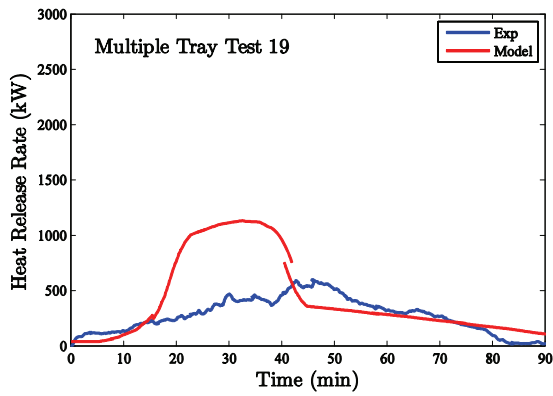


Figure 9-9. Comparison of predicted and measured HRR for Multiple Tray Tests 19-20.

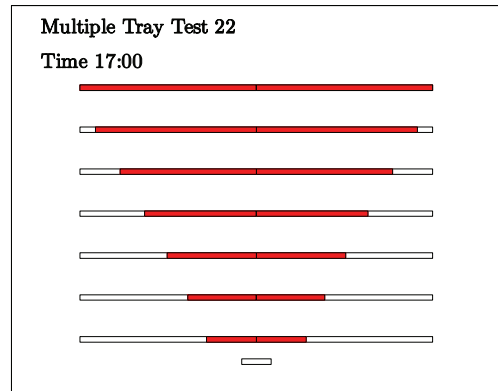
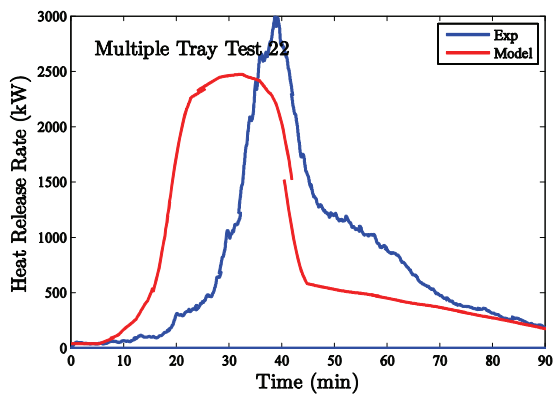
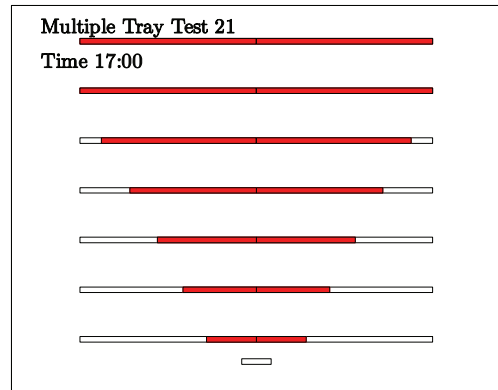
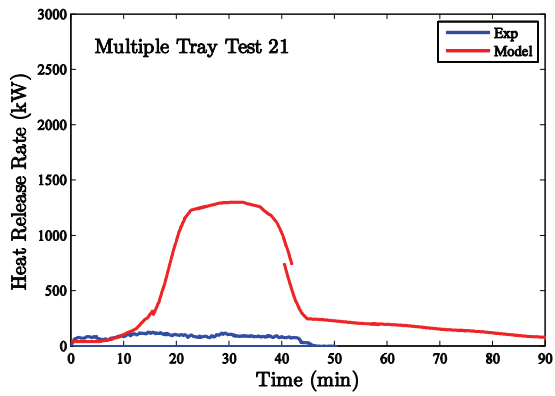


Figure 9-10. Comparison of predicted and measured HRR for Multiple Tray Tests 21-22.

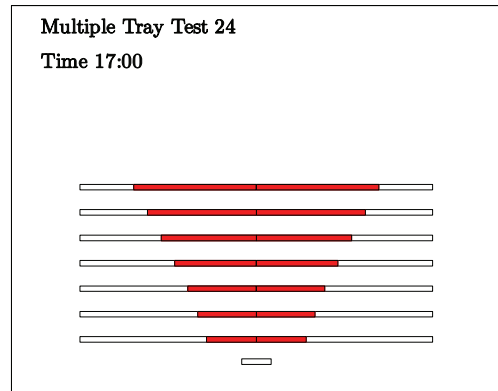
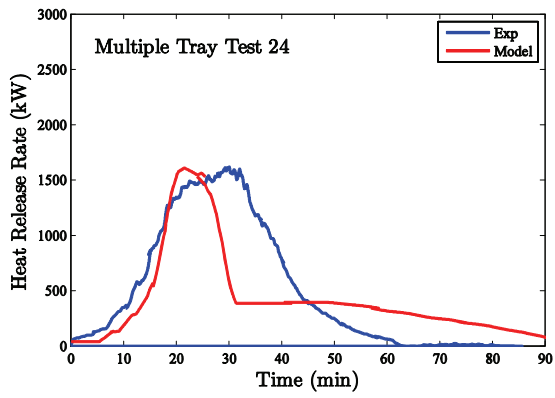
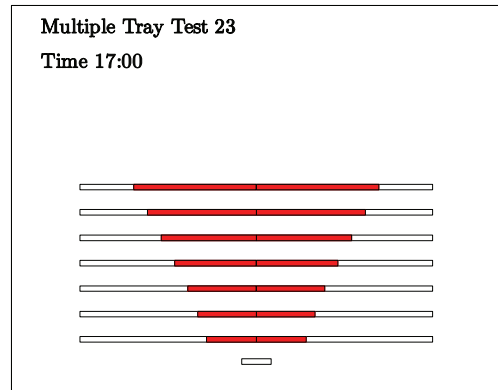
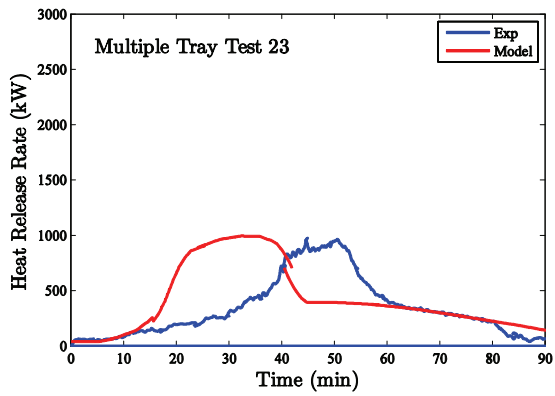


Figure 9-11. Comparison of predicted and measured HRR for Multiple Tray Tests 23-24.

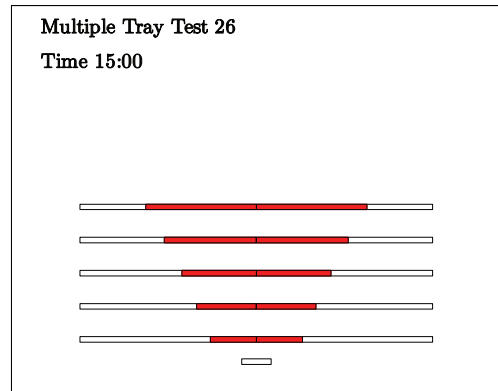
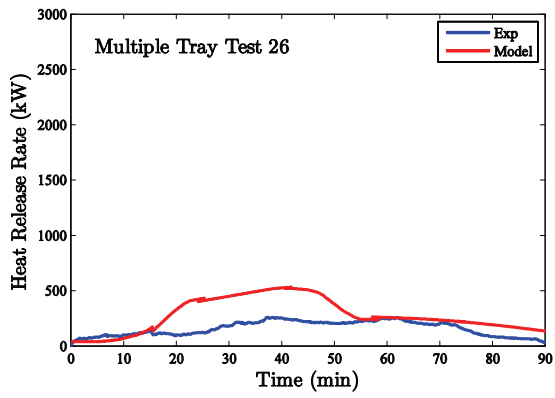
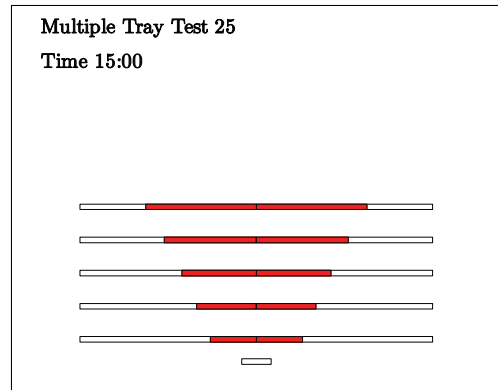
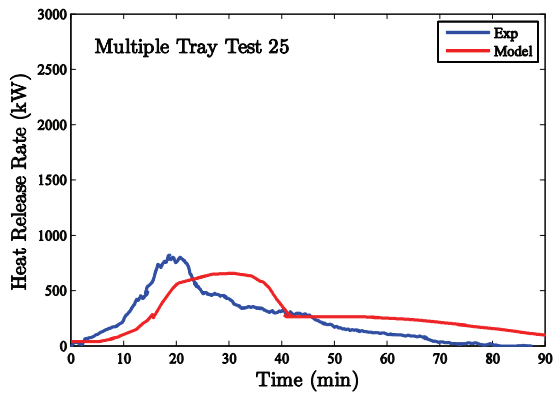


Figure 9-12. Comparison of predicted and measured HRR for Multiple Tray Tests 25-26.

9.2.4 Discussion of Model Results

The FLASH-CAT model captures general features of the experiments, including variations in tray width, loading and cable type. The model has no mechanism for distinguishing the vertical spacing. With a few exceptions, the model tends to over-predict the peak HRR and the total energy release (see Figure 9-13). This is a desirable feature in light of the fact that no information about a particular cable is required of the model user other than its bulk properties which can be measured easily with nothing more than a ruler and a scale. The other inputs to the model are characteristic values taken from sources like NUREG/CR-6850.

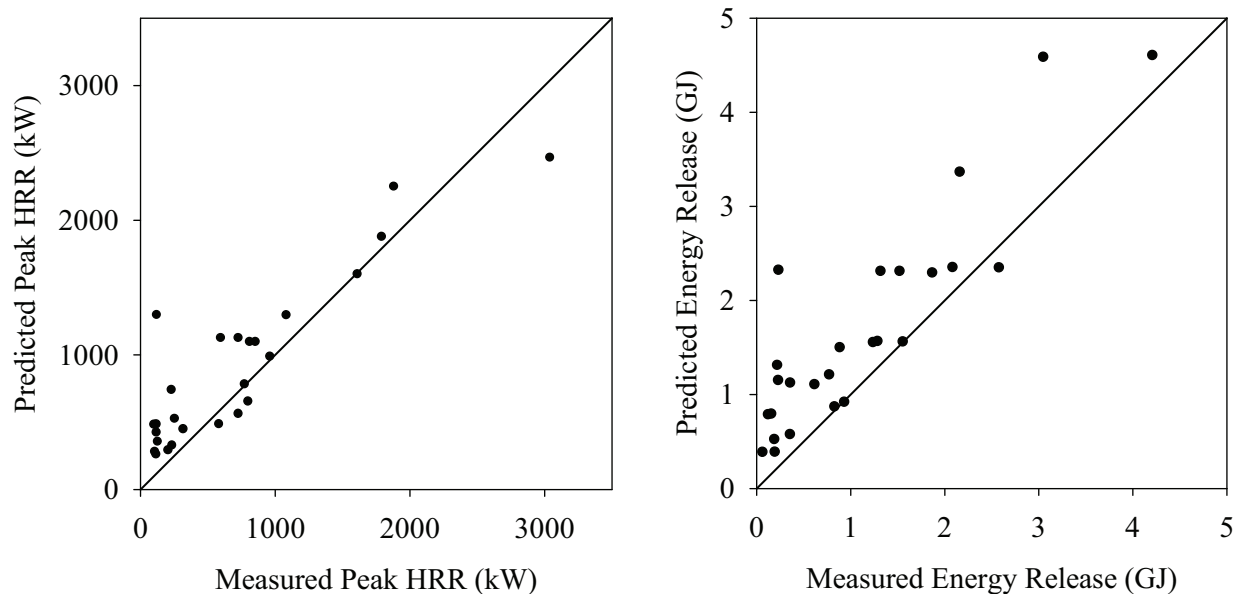


Figure 9-13. Comparison of peak HRR and total energy release for FLASH-CAT.

A key assumption in the FLASH-CAT model is that the fire will spread laterally until all of the cable is consumed. In many of the multiple tray experiments, this did not happen, and damage was confined to the initial V-shaped region above the ignition point. For this reason, the FLASH-CAT model in many cases over-predicts the HRR and the total consumption of cable. The lateral spread rates for thermoplastic and thermoset cables that are listed in NUREG/CR-6850 are based on estimates of the thermo-physical properties of “typical” TP and TS cables. As can be seen in Figure 9-14, it is very difficult to predict from first principles if the fire is going to spread laterally at all, and if it does, at what rate. For example, during Multiple Tray Test 19, there was a slight breeze (on the order of 0.1 m/s) in the laboratory that caused the fire to spread to the left. The fire did not spread to the right beyond its initial V-pattern. The breeze was created by an asymmetric layout of air intake ducts, but nevertheless was strong enough to affect the progression of the fire. Rather than try to fine-tune the model, it has been decided to use the spread rates suggested in NUREG/CR-6850 because there is no evidence that these rates led to an under-prediction of the fire spread in any experiment. In addition, the breeze in the test lab is

typical of air movement in any industrial facility, including NPPs. As with any model, such physical phenomena can be added, but this level of detail is unwarranted given the other uncertainties of the model.



Figure 9-14. Photograph of MT-19 compared to the FLASH-CAT model prediction.

The following notes apply to specific experiments:

Test 4: In the experiment, the cables were packed tightly together within the trays. As a result, the fire did not spread upward as expected because the flames were not able to penetrate the densely packed cables. In fact, a pick axe was used by the technicians to open up gaps in the cable through which the fire could spread upwards. An assumption of the model is that the fire will propagate upwards according to an empirical timing sequence (5-4-3-2-1 minutes). This implies that no barrier, including densely packed cables, inhibits the upward spread.

Test 7: In the experiment, there was a relatively high loading of cables in the tray. As a result, the time to the fire's peak HRR was somewhat lagging the fixed time sequence of the model.

Test 9: This experiment used a relatively light load of thermoplastic cable. The model assumes a relatively high HRRPUA and spread rate for this type of cable, but in the experiment the fire did not spread laterally.

Test 14: In the experiment, the burner below the lowest tray was extinguished before the fire in the lowest tray had established itself. The burner was turned back on 30 min after the start of the test in order to give the fire a chance to spread to the top of the stack. There is no mechanism in the simple timing sequence of the model to account for the on-off-on operation of the burner.

Test 21: In the experiment, the trays were separated by 18 in (0.45 m), and as a result, the fire did not spread beyond the second tray. The model always assumes that the fire will spread upwards, and as a result over-predicts the HRR of this test.

10 CONCLUSION AND FUTURE WORK

This report documents Phase 1 of the CHRISTIFIRE (Cable Heat Release, Ignition, Spread in Tray Installations during Fire) Project. The goal of the project is to collect data to support the development of predictive fire models that can estimate the growth and spread of fires within cable trays. This first phase of the project has addressed horizontal, ladder-back trays filled with unshielded cables in fairly open configurations.

Phase 1 of CHRISTIFIRE involved measurements of various thermo-physical properties for several dozen different types of cables from micro- to full-scale, plus mathematical modeling. Notable results of the experimental measurements are as follows:

- Effective fire properties of cables, including heat of combustion, heat release rate per unit area, and char yield depend significantly on the test configuration.
- The amount of combustible mass in a cable is an easily obtained and important parameter for predicting the duration of a fire.
- The measured heat release rate per unit area (HRRPUA) of a burning cable tray ranges roughly between 100 kW/m^2 and 200 kW/m^2 for thermoset cables, and it ranges between 200 kW/m^2 and 300 kW/m^2 for thermoplastics. These values are consistent with the data listed in NUREG/CR-6850.

Notable results of the modeling effort are as follows:

- The guidance for modeling horizontal cable tray fires that is put forth in Appendix R of NUREG/CR-6850 has been codified in a simple model called FLASH-CAT (Flame Spread over Horizontal Cable Trays). This model has been compared to 26 full-scale experiments involving one to seven horizontal trays. The predicted heat release rates in almost all cases are comparable to or greater than the measured rates.
- Effective values of the heat release rate per unit area of cable tray (HRRPUA) of 150 kW/m^2 for thermosets and 250 kW/m^2 for thermoplastics were used in the FLASH-CAT model.
- Effective values of the lateral spread rate of 1.1 m/h for thermoset cables and 3.2 m/h for thermoplastic cables were used in the FLASH-CAT model.
- Effective values of the char yield of 0.25 for thermosets and 0 for thermoplastics were used in the FLASH-CAT model.
- A single effective heat of combustion of 16 MJ/kg provided reasonable results for all cable types in the FLASH-CAT model.
- The effective input values produce conservative estimates of the HRR for 26 full-scale experiments.

Some recommendations:

- Given the variability in the measurements of the heat of combustion, heat release rate per unit area, and char yield, it does not benefit the overall modeling effort to compile an exhaustive

“database” of properties for the hundreds of different cable types currently installed in NPPs. Simple models like FLASH-CAT do not warrant detailed estimates of cable properties because of the built-in conservatism and assumed effective values of parameters. Detailed models would typically require a given cable of interest to be specially tested and would not be able to make use of a generic list of material properties.

- For the purpose of estimating the burning rates of unshielded cables in horizontal tray configurations, it is sufficient to know the mass per unit length and combustible mass fraction. These parameters can all be obtained with a ruler, scale, pocket knife, and a few tens of centimeters of cable. Parameters like the heat release rate per unit area (HRRPUA), char yield, and heat of combustion can be assumed based on representative values for thermoset and thermoplastic cables.

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A TESTING STANDARDS FOR CABLES

This Appendix has been extracted from the letter report entitled, “Response to NRR FAQ 06-0022, Guidance on Standards and Flame Propagation Tests,” June 21, 2007, prepared by Felix E. Gonzalez and Jason Dreisbach, US NRC RES Fire Research Branch. Its purpose was to provide a response to an FAQ (Frequently Asked Question) concerning flame propagation (spread) tests for electrical cables. The response evaluates current flame propagation tests compared to the IEEE 383-1974 standard. This standard had been previously referenced as the US NRC minimum test standard and acceptance criteria for cable flame propagation tests.

Table A-1 provides a summary of various test methods designed to assess the fire performance of electrical cables. The follow-on discussion compares these methods with IEEE 383-1974. Tests with lower burner heat outputs than the IEEE 383-1974 standard are difficult to compare due to the difference in test sample size. These low heat exposure tests are discussed but are not directly compared to IEEE 383-1974.

Note that a flame propagation test procedure in one standard could be included or referenced in another. This does not mean that the two standards are the same. Rather, it means that the standard uses the same testing procedure for flame propagation testing. A standard might have other sections that have nothing to do with flame propagation, like smoke and aging test procedures, materials of construction, or markings. For this reason, the data was organized in terms of flame tests instead of individual standards.

Table A-1: Standard Fire Tests for Electrical Cables

Title	Number	Standard Title
FT-6 / Flame Travel Test (horizontal)	NFPA 262	Standard Method of Test for Flame Travel and Smoke of Wires and Cables for Use in Air-Handling Spaces (2007 Ed)
	CSA 22.2 No. 0.3	Test Methods for Electrical Wires and Cables (Jan 2005)
Fire Test (Riser/vertical)	UL 1666	Test for Flame Propagation Height of electrical and Optical-Fiber Cables Installed Vertically in Shafts (4 th Ed Nov 2000 Revisions thru Jul 2002)
FT-4 / Vertical Flame Test (vertical)	UL 1581	Reference Standard for Electrical Wires, Cables, and Flexible Cords (4 th Ed Oct 2001 Revisions thru Aug 2006)
	UL 1685	Vertical-Tray Fire-Propagation and Smoke-Release Test for Electrical and Optical-Fiber Cables (2 nd Ed Feb1997 Revisions thru Nov 2000)
	UL 83	Thermoplastic-Insulated Wires and Cables (13 th Ed Nov 2003 Revisions thru Apr 2006)
	UL 44	Thermoset-Insulated Wires and Cables (16 th Ed July2005 Revisions thru Nov 2005)
	CSA 22.2 No. 0.3	Test Methods for Electrical Wires and Cables (Jan 2005)
	IEEE 1202-1991	IEEE Standard for Flame Testing of Cables for Use in Cable Tray in Industrial and Commercial Occupancies (1991)
Flame test qualification (vertical)	IEEE 383-2003	IEEE Standard for Qualifying Class 1E Electric Cables and Field Splices for Nuclear Power Generating Stations (2003; Revision of IEEE 383-1974)

Title	Number	Standard Title
Vertical Cable Tray Flame Test (vertical)	ICEA T-29-520	Conducting Vertical Cable Tray Flame Tests with Theoretical Heat Input Rate of 210000 Btu/hr (Sep 1986)
Vertical Flame Spread (vertical)	IEC 60332-3-21	Tests on Electric Cables Under Fire Conditions Parts 3-21 to 23: Test for Vertical Flame Spread of Vertically-Mounted Bunched Wires or Cables: Category A (F/R), A & B (Oct 2000)
	IEC 60332-3-22	
	IEC 60332-3-23	
Vertical Tray Flame Test (vertical)	UL 1581	Reference Standard for Electrical Wires, Cables, and Flexible Cords (4 th Ed Oct 2001 Revisions thru Aug 2006)
	UL 83	Thermoplastic-Insulated Wires and Cables (13 th Ed Nov2003 Revisions thru Apr 2006)
	UL 44	Thermoset-Insulated Wires and Cables (16 th Ed July2005 Revisions thru Nov2005)
	UL 1685	Vertical-Tray Fire-Propagation and Smoke-Release Test for Electrical and Optical-Fiber Cables (2 nd Ed Feb 1997 Revisions thru Nov 2000)
Vertical Cable Tray Flame Test (vertical)	ICEA T-30-520	Guide for Conducting Vertical Cable Tray Flame Tests with Theoretical Heat Input of 70000 Btu/hr (Sep 1986)
Flame test (vertical)	IEEE 383-1974	IEEE Standard for Type Test of Class 1E Electric Cables, Field Splices, and Connections for Nuclear Power Generating Stations (1974)
Flame test (vertical)	IEEE 817-1993	IEEE Standard Test Procedure for Flame-Retardant Coatings Applied to Insulated Cables in Cable Trays (1993)
Vertical Flame Spread (vertical)	IEC 60332-3-24	Tests on Electric Cables Under Fire Conditions Parts 3-21 to 23: Test for Vertical Flame Spread of Vertically-Mounted Bunched Wires or Cables: Category C (Oct 2000)
Vertical Flame Propagation (vertical)	IEC 60332-1-2	Test for vertical flame propagation for a single insulated wire or cable - Procedure for 1 kW pre-mixed flame (2004-07)
Vertical Flame Propagation (vertical)	IEC 60332-1-3	Test for vertical flame propagation for a single insulated wire or cable - Procedure for determination of flaming droplets/particles (2004-07)
VW-1 Vertical Wire Flame Test (vertical)	UL 1581	Reference Standard for Electrical Wires, Cables, and Flexible Cords (4 th Ed Oct 2001 Revisions thru Aug 2006)
	UL 83	Thermoplastic-Insulated Wires and Cables (13 th Ed Nov 2003 Revisions thru Apr 2006)
	UL 44	Thermoset-Insulated Wires and Cables (16 th Ed July 2005 Revisions thru Nov 2005)
	CSA 22.2 No. 0.3	Test Methods for Electrical Wires and Cables (Jan 2005)
FT-1 Vertical Flame Test (vertical)	UL 1581	Reference Standard for Electrical Wires, Cables, and Flexible Cords (4 th Ed Oct 2001 Revisions thru Aug 2006)
	UL 83	Thermoplastic-Insulated Wires and Cables (13 th Ed Nov 2003 Revisions thru Apr 2006)
	UL 44	Thermoset-Insulated Wires and Cables (16 th Ed July 2005 Revisions thru Nov 2005)
	CSA 22.2 No. 0.3	Test Methods for Electrical Wires and Cables (Jan 2005)
Flame test (vertical)	IPCEA S-61-402	Thermoplastic-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy (Oct 1994)
FT-2 Horizontal Flame Test (horizontal)	UL 1581	Reference Standard for Electrical Wires, Cables, and Flexible Cords (4 th Ed Oct 2001 Revisions thru Aug 2006)
	UL 83	Thermoplastic-Insulated Wires and Cables (13 th Ed Nov 2003 Revisions thru Apr 2006)
	UL 44	Thermoset-Insulated Wires and Cables (16 th Ed July2005 Revisions thru Nov 2005)

Title	Number	Standard Title
	CSA 22.2 No. 0.3	Test Methods for Electrical Wires and Cables (Jan 2005)
Standard Test Method for Flame Spread (vertical)	ASTM D5537-03	Standard Test Method for Heat Release, Flame Spread, Smoke Obscuration, and Mass Loss testing of Insulating Materials Contained in electrical or Optical Fiber Cables When Burning in a Vertical Cable Tray Configuration (Dec 2003)
Fire Propagation Test	FM 3972	Test Standard for Cable Fire Propagation (Mar 1994)

Discussion

IEEE 383-1974 is the baseline test with which the other tests will be compared. It is a 20 kW (70000 BTU/h) heat exposure, vertical test. As in all the 20 kW tests discussed below, it has a 20 minute exposure time. This test requires cables to self extinguish before reaching the top of the tray (8 ft or 2.4 m) to pass the test.

One of the most severe flame tests is the FT-6 Horizontal Flame Test included in the NFPA 262 and CSA C22.2 No. 0.3 standards. It is a horizontal flame test used for cables in plenum applications. This test uses a burner heat output of 86 kW (294000 BTU/h). This test has one of the lowest acceptable damage lengths, the second highest heat output, and uses a high air flow in its chamber during testing to increase flame spread.

The UL 1666 Fire Riser Test is another of the more severe flame tests. It is a vertical test used for cables in riser shaft applications. It has the highest heat output of all the tests (154.5 kW), second highest exposure time (30 min) and high air flow in its chamber during testing. This test has an acceptable cable damage length of 12 ft (3.66 m). Even though the damage criteria is less severe than the IEEE 383-1974 (12 ft vs 10 ft), the higher exposed heat and time makes this test more severe.

The FT-4/Vertical Flame Test, included in standards IEEE 1202-1991, CSA C22.2 No. 0.3, UL 1685, and referenced in UL 1581, UL 44, and UL 83, is the most rigorous of the 20 kW tests. The testing conditions and equipment in all of the 20 kW tests are essentially the same. What makes this test the most difficult to pass of the 20 kW tests is its low acceptable damage length of 4.9 ft (1.5 m).

The ICEA T-29-520 standard is essentially the same as the 20 kW IEEE 383-1974 tests except with a burner heat output of 62 kW. The distance acceptance criterion is the same as IEEE 383-1974. Cables passing this test meet or exceed the performance of IEEE 383-1974 tested cables, and could have similar cable performance to tests like the FT-4/Vertical Flame Test.

The Vertical Flame Spread test (IEC 60332-3-21, IEC 60332-3-22 and IEC 60332-3-23) uses a 20 kW burner. In these tests, the recommended acceptance length of damage is 10.2 ft (3.1 m) which is less rigorous than the 8 ft (2.44 m) of acceptable damage of the IEEE 383-1974 standard, but the heat exposure time is 40 min, twice the time exposed in IEEE 383-1974.

The Vertical Tray Flame Test (UL 1581, 1685, 83, and 44) and Vertical Cable Tray Flame Test

(ICEA T-30-520) both use a 20 kW burner. These two tests are very similar to the IEEE 383-1974. The three have the same acceptable damage length of 8 ft (2.44 m) and require cables to self extinguish before reaching the top of the tray. Also, the heat exposure time is 20 min. These tests have minor variations in procedure and equipment used.

IEEE 817-1993 Flame Test is mainly used to determine whether cables need to be coated or not. It does not have pass/fail criteria. If cable damage reaches the top of the tray, the cable is recommended to be coated.

The IEC 60332-3-24 standard is very similar to IEEE 383-1974 but has less strict acceptance criteria. This test has the same burner heat output and exposure time as IEEE 383-1974 but has an acceptable damage length of 10.2 ft (3.1 m) making the test less severe.

Note that the IEC 60332-3-10 standard is the description of the apparatus used in the IEC 60332-3-21, IEC 60332-3-22, IEC 60332-3-23, and IEC 60332-3-24 standards discussed above and not an actual test.

Low Intensity Test Methods

The tests discussed below have burner heat outputs equal or lower than 1 kW. It is not appropriate to compare these methods to IEEE 383-1974 due to the vast difference in test samples and burner heat outputs. These low heat exposure tests will be discussed for completeness, but will not be directly compared to the IEEE 383-1974 baseline standard.

Vertical Flame Propagation Tests (IEC 60332-1-2 and IEC 60332-1-3) are both 1 kW burner tests. Both exposure times vary from 1 to 8 minutes, depending on the sample diameter. IEC 60332-1-2 requires more than 50 mm (1.97 in) of distance between the lower edge of the top support and the onset of charring and less than 540 mm (21.26 in) from the lower edge to the top support. IEC 60332-1-3 requires that the filter paper used as indicator does not ignite during the test.

The four 500 W tests are very similar in terms of heat exposure time and passing criteria. These tests are: the VW-1 Vertical Wire Flame Test (UL 1581 and CSA C22.2 No.0.3, and referenced in UL 83 and UL 44), the FT-1 Vertical Flame Test (UL 1581 and CSA 22.2 No.0.3 and referenced in UL83 and UL44), Flame Test (ICEA S-61-402), and the FT-2 Horizontal Flame Test (UL 1581 and CSA 22.2 No.0.3, and referenced in UL 83, and UL 44). The first three are vertical flame tests and have exposure times of 75 seconds total with different time intervals between heat applications. The three are very similar and require that samples do not burn more than 60 seconds or burn less than 25 % of the indicator and/or cotton batting. The FT-2 test is a horizontal test with a heat exposure time of 30 seconds and requires that the cable self-extinguish and that no flaming particles ignite cotton under specimen.

The ASTM D5537-03 *Standard Test Method for Flame Spread* is used to determine the heat release rate by measuring gas concentrations and flow. It also measures Flame Propagation by

blistering and char length. This test does not have any acceptance criteria.

The FM 3972 *Test Standard for Cable Fire Propagation* is used to calculate a Fire Propagation Index to classify cable fire propagation characteristics. In the test procedure, a pilot flame is used to ignite the cables. After that, the flame is extinguished and heaters are used until the cable self-extinguishes. Measurements of the combustion gas concentrations and flow, time, and heat release rate are used to calculate the Fire Propagation Index. This test does not have any acceptance criteria.

NRC FORM 335 (9-2004) NRCMD 3.7	U.S. NUCLEAR REGULATORY COMMISSION	1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)
BIBLIOGRAPHIC DATA SHEET		NUREG/CR-7010, Vol. 1
<i>(See instructions on the reverse)</i>		
2. TITLE AND SUBTITLE	Cable Heat Release, Ignition, and Spread in Tray Installations During FIRE (CHRISTIFIRE) Volume 1: Horizontal Trays	3. DATE REPORT PUBLISHED
		MONTH YEAR
		October 2010
5. AUTHOR(S)	K. McGrattan (NIST), A. Lock (NIST), N. Marsh (NIST), M. Nyden (NIST), M. Price (NIST), A. Morgan (University of Dayton Research Institute), M. Galaska (University of Dayton Research Institute), K. Schenck (University of Dayton Research Institute)	4. FIN OR GRANT NUMBER
		N6549
		6. TYPE OF REPORT
		Draft
		7. PERIOD COVERED <i>(Inclusive Dates)</i>
		Oct. 2008 to June 2010
8. PERFORMING ORGANIZATION - NAME AND ADDRESS <i>(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)</i>		
National Institute of Standards and Technology Building and Fire Research Laboratory Gaithersburg, MD 20899		
9. SPONSORING ORGANIZATION - NAME AND ADDRESS <i>(If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)</i>		
Division of Risk Analysis Office of Nuclear Regulatory Research U.S. Nuclear Regulatory Commission Washington, DC 20555-0001		
10. SUPPLEMENTARY NOTES		
D. Stroup, NRC Project Manager		
11. ABSTRACT <i>(200 words or less)</i>		
<p>This report documents the first 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. The first phase of the program focuses on horizontal tray configurations. The experiments conducted range from micro-scale, in which very small (5 mg) samples of cable materials were burned in a calorimeter to determine their heat of combustion and other properties; to full-scale, in which horizontal, ladder-back trays loaded with varying amounts of cable were burned under a large oxygen-depletion calorimeter. Other experiments include cone calorimetry, smoke and effluent characterization in a small test furnace, and intermediate-scale calorimetry involving a single tray of cables underneath a bank of radiant panels. The results of the small-scale experiments are to serve as input data for fire models; while the results of the full-scale experiments are to serve as validation data for the models.</p>		
12. KEY WORDS/DESCRIPTORS <i>(List words or phrases that will assist researchers in locating the report.)</i>		13. AVAILABILITY STATEMENT
Cable fires, fire experiments		unlimited
		14. SECURITY CLASSIFICATION
		<i>(This Page)</i> unclassified
		<i>(This Report)</i> unclassified
		15. NUMBER OF PAGES
		16. PRICE



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