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# RESPONSE BIAS OF ELECTRICAL CABLE COATINGS AT FIRE CONDITIONS

Volume 2
Fire Properties of Cables

Final Report

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**Research Information Letter**
**Office of Nuclear Regulatory Research**

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# ABSTRACT

This report contains the results of an experimental research program on the performance of fire-retardant cable coatings. The program is sponsored by the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research, and the experiments were performed at Sandia National Laboratories and the National Institute of Standards and Technology. The goal of the experiments was to assess the effects of commercially available fire-retardant cable coating materials on the thermal and electrical responses of cables exposed to fire conditions.

This research is being conducted in several phases. Phase 1 consists of developing a fundamental understanding of the use and performance of fire-retardant cable coatings and is documented in Volumes 1–3 of this research information letter. Volume 1 traces the history and use of fire-retardant electrical cable coatings. Volumes 2 and 3 provide empirical data on the performance of selected cable coatings, with Volume 2 discussing fire resistance properties and Volume 3 covering electrical cable functionality.

The experiments performed in Phase 1 ranged from bench scale to full scale. Different types of thermal exposures were used to evaluate cable coating performance, including radiant heat, vertical and horizontal flame impingement, horizontal fire plume, and hot gas layer exposures. Experiments included both uncoated cables (as a control) and cables with a fire-retardant cable coating material applied. The variables evaluated included coating material, coating thickness, cable system mass, cable type, exposure conditions, cable orientation, and cable construction. Recommendations and conclusions based on these results have been compiled but are being withheld until Phase 2 of the project is complete, to ensure that guidance is not issued prematurely.

The goal of Phase 2 is to evaluate the effects of aging on the performance of fire-retardant cable coatings. Phase 2 has already started and is expected to be completed by the end of fiscal year 2027. In Phase 3, the final phase of the project, the NRC will work with the Electric Power Research Institute to develop updated guidance and recommendations for performance-based applications. The Phase 3 work is planned to be performed concurrently with the completion of Phase 2.

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# EXECUTIVE SUMMARY

**PRIMARY AUDIENCE:** Fire protection engineers and fire probabilistic risk assessment (PRA) analysts conducting or reviewing fire modeling that supports analysis related to fire characteristics and fire-induced circuit damage associated with fire-retardant cable coatings.

**SECONDARY AUDIENCE:** Engineers, reviewers, utility managers, and other stakeholders who conduct, review, or manage fire protection programs and need to understand the underlying technical basis for the performance of fire-retardant cable coatings.

## KEY RESEARCH QUESTIONS

What are the origins of the fire-retardant cable coatings used in U.S. nuclear power plants, how well do various types of coatings perform, what are some issues related to their performance, and how does aging affect their performance?

## RESEARCH OVERVIEW

The goal of this experimental research program is to better understand how the use of fire-retardant cable coatings affects flame spread, heat release rate, ignition, and loss of function. This research is needed because some of the guidance in NUREG/CR-6850, “EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities,” issued September 2005, is unclear or uncertain, primarily because empirical data to support it are lacking.

Previous research programs have provided considerable information on the fire characteristics and electrical response of electrical cables damaged by fire conditions. How the use of fire-retardant cable coatings changes these characteristics is less well understood. This research program focuses on developing an empirically based dataset to support fire modeling and fire PRA assumptions about the performance of fire-retardant cable coatings.

The research was performed in several stages at multiple fire testing laboratories, using both standardized and non-standardized experimental techniques. Initial screening experiments at Sandia National Laboratories provided insight into the ignition and circuit functionality of electrical cables covered with fire-retardant coatings. Subsequent experiments at the National Institute of Standards and Technology focused on flame spread, heat release rate, ignition, and circuit functionality, through both bench-scale and large-scale tests.

Another important question is how aging affects the performance of fire-retardant cable coatings. In several instances, U.S. Nuclear Regulatory Commission (NRC) regional inspection personnel have identified changes in the appearance of cable coating materials. Currently, little to no information is available about how age-related degradation may affect the performance of cable coatings. Further research to investigate this question is being planned.

## KEY FINDINGS

This research program has yielded significant data on the fire characteristics of electrical cables with fire-retardant coatings, as well as the impact of such coatings on circuit functionality. The results significantly advance scientific understanding of cable coating performance and will be used to update the guidance in NUREG/CR-6850. The guidance updates will be incorporated into Phase 2 of the project and issued during Phase 3.

## WHY THIS MATTERS

This report provides empirical evidence to assist the NRC staff and nuclear power plant engineers performing and reviewing fire modeling analyses and fire PRAs.

## HOW TO APPLY RESULTS

Engineers performing and reviewing fire modeling analyses and fire PRAs should focus on the results in Volumes 2 and 3 of this report. The results should be applied with caution, however, as the NRC anticipates updating the fire PRA methodology in Phase 3 of the project. Conclusions are intentionally omitted from Volumes 1–3, as additional testing is forthcoming. Volume 4 will document the conclusions when all testing is complete.

## LEARNING AND ENGAGEMENT OPPORTUNITIES

On July 14, 2025, NRC staff conducted a public meeting with members of the public and interested stakeholders. This was a comment-gathering meeting, with allotted time to allow for members of the public and interested stakeholders to ask questions and comment on Volumes 1–3 of the draft cable coating RIL and the aged cable coating project plan.

The meeting summary and presentation slides from the public meeting can be found in the NRC Agencywide Documents Access and Management System (ADAMS) under accession numbers ML25210A426 and ML25191A208, respectively.

The attendees asked questions, made comments, and participated in the topics covered by the NRC staff. Even though the NRC will not make any regulatory decisions from this meeting, this meeting was a way to facilitate feedback on the cable coating research and the aged cable coating project plan. NRC Staff considered all stakeholder comments and after review, no changes were made to the draft reports. However, stakeholder feedback provided valuable information and will be considered when completing the next phases of this project.

# ACKNOWLEDGMENTS

The authors wish to thank the following individuals for their contributions to this project: Kent W. Brown for providing extensive insight into and history of the use of fire-retardant cable coatings in the nuclear industry, and the tribulations associated with the development of experiment standards; the current and former U.S. Nuclear Regulatory Commission (NRC) staff from the Office of Nuclear Reactor Regulation for sponsoring this work and providing detailed comments on the draft documents; current and former staff members of the National Institute of Standards and Technology, including Kevin McGrattan, Scott Bareham, Laurean DeLauter, Doris Rinehart, Artur Chernovsky, Ed Hnetkovsky, and Mike Selepak, who directly supported the completion of this work; and current and former staff members of Sandia National Laboratories, including Jason Brown, Chris LaFleur, and Steven Nowlan.

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Furthermore, we thank the Tennessee Valley Authority (TVA) for donating vintage cables from the 1970s for testing. We also thank Brenda Simril and Robert Egli from the TVA for providing information on fuel load calculations.

Lastly, we would like to recognize our colleague and friend Doug DePriest of the TVA. Doug always provided valuable advice, insights, and support for researchers. His passion for his work and his desire to promote safety were exemplary. Doug was instrumental in many industry initiatives to provide technically sound resolutions of regulatory concerns, and his support of cable coating research is just one of many examples of his invaluable contributions. He will be dearly missed.

# ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| °C | degrees Celsius |
| °F | degrees Fahrenheit |
| AWG | American Wire Gauge |
| CAROLFIRE | Cable Response to Live Fire |
| CDRS | conductors |
| CHRISTIFIRE | Cable Heat Release, Ignition, and Spread in Tray Installations |
| cm | centimeter(s) |
| CSPE | chlorosulfonated polyethylene |
| CVTC | continuous vulcanization tray cable |
| DEG C | degrees Celsius |
| DIR BUR | direct burial |
| EPR | ethylene-propylene rubber |
| EPRI | Electric Power Research Institute |
| FLASH-CAT | flame spread over horizontal cable trays (model) |
| FMRC | Factory Mutual Research Corporation |
| FR | flame retardant |
| FT4 | Flame Test 4 |
| FR-XLP | flame retardant cross-linked polyethylene |
| FMRC GP-1 | Factory Mutual Research Corporation Group 1 |
| HRR | heat release rate |
| HRRPUA | heat release rate per unit area |
| IEEE | Institute of Electrical and Electronics Engineers |
| IEC | International Electrotechnical Commission |
| in. | inch(es) |
| ISO | International Organization for Standardization |
| kg | kilogram(s) |
| km | kilometer(s) |
| kW | kilowatt(s) |
| L | liter(s) |
| lb | pound(s) |
| LSZH | low smoke zero halogen |
| m | meter(s) |
| MCC | microcombustion calorimetry |
| mi | mile(s) |
| min | minute(s) |
| MJ | megajoule(s) |
| NEC | National Electric Code |
| NIST | National Institute of Standards and Technology |
| NPP | nuclear power plant |
| NRC | U.S. Nuclear Regulatory Commission |
| OIL RES | oil resistant |
| PE | polyethylene |

| | |
|---|---|
| PRA | probabilistic risk assessment |
| PVC | polyvinyl chloride |
| RES | Office of Nuclear Regulatory Research (NRC) |
| RIL | research information letter |
| ROHS | restriction of hazardous substances |
| s | second(s) |
| SIS | safety instrumented system |
| SNL | Sandia National Laboratories |
| SR | silicone rubber |
| SUN RES | sun resistant |
| TC | thermocouple |
| TC-ER | tray cable—exposed run |
| TC/NCC | tray cable/nickel coated copper |
| Tefzel® | DuPont Ethylene-Tetrafluoroethylene (ETFE) Resin |
| TFN | thermoplastic fixture wire nylon jacketed |
| TGA | thermogravimetric analysis |
| THHN | thermoplastic high-heat-resistant nylon coated |
| THWN | thermoplastic heat- and water-resistant nylon coated |
| THIEF | thermally induced electrical failure |
| TP | thermoplastic |
| TS | thermoset |
| TVA | Tennessee Valley Authority |
| UL | Underwriters Laboratories |
| VNTC | vinyl nylon tray cable |
| XHHW | cross-linked high heat water resistant |
| XLPE or XLP | cross-linked polyethylene |
| XLPO | cross-linked polyolefin |

# 1. INTRODUCTION

Electrical cables perform numerous functions in nuclear power plants (NPPs). Power cables supply electricity to motors, transformers, heaters, light fixtures, fire suppression equipment, and reactor cooling equipment. Control cables connect plant equipment such as motor-operated valves and motor starters to remote initiating devices (e.g., switches, relays, and contacts). Instrumentation cables transmit low-voltage signals between input devices and display panels. NPPs typically contain hundreds of miles of electrical cables. A typical boiling-water reactor requires approximately 100 kilometers (km) (60 miles (mi)) of power cable, 80 km (50 mi) of control cable, and 400 km (250 mi) of instrument cable. A pressurized-water reactor may require even more cables. The containment building of Waterford Steam Electric Generating Station, Unit 3, contains nearly 1,600 km (1,000 mi) of cable (Lofaro, et al. 1996).

Electrical cable insulating materials dominate the in situ fire fuel load in most areas of an NPP. These materials are found both in the cable routing raceways throughout the plant and in the electrical control cabinets. In a postulated fire scenario, they may be an ignition source or an intervening combustible, and they may also themselves lose functionality. Electrical 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, number of conductors, conductor size, and combustible mass ratio.

Electrical cables have been involved in several fires in NPPs over the years. In March 1975, a serious fire involving electrical cables occurred at the Browns Ferry Nuclear Plant (BFN), operated by the Tennessee Valley Authority (Collins, et al. 1976). The fire damaged more than 1,600 cables, resulting in loss of all emergency core cooling system equipment in Unit 1 and much of it in Unit 2. The damage was extensive because of the flammability of the cables, including their ease of ignition, flame spread, and heat release rate (HRR).

The experimental evidence and analytical tools available to calculate the development and effects of cable tray fires are relatively limited when compared to the vast number of possible fire scenarios that can be postulated for NPPs. Many of the large-scale fire experiments conducted on cables are qualification experiments in which the materials are experimented with in a relatively large-scale configuration and qualitatively ranked on a comparative basis. APPENDIX A to NUREG/CR-7010, “Cable Heat Release, Ignition and Spread in Tray Installations during Fire (CHRISTIFIRE), Phase 1: Horizontal Trays,” Volume 1, issued July 2012 (McGrattan, Lock, et al. 2012), summarizes these experiments. While providing a relative ranking of cables, this type of experiment typically does not address the details of fire growth and spread and does not provide any useful data for model calculations.

A variety of studies have focused on small-scale material characterization experiments. Many investigators have questioned the degree to which small-scale experiment results reflect full-scale fire behavior, especially for plastic materials. Until these small-scale experiment results have been more fully evaluated through larger scale experiment data, caution must be exercised in using small-scale experiment results to predict full-scale fire behavior.

The need for data about the fire hazards of cables also relates to the methods described in NUREG/CR-6850, “EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities,” (U.S. NRC and Electric Power Research Institute (EPRI) 2005). The fire probabilistic risk assessment (PRA) method requires data on cable flame spread and HRRs and fire spread from cable tray to cable tray. As mentioned above, the currently available data are limited. More data are needed to reduce the uncertainty associated with the PRA methods.

## 1.1 Review of Past Experimental Programs

Two past experimental programs are important forerunners of the current study.

The CAROLFIRE (Cable Response to Live Fire) project described in NUREG/CR-6931, Volumes 1 and 2, issued April 2008 (Nowlen and Wyant 2008b) (Nowlen and Wyant 2008a), 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.

The CHRISTIFIRE (Cable Heat Release, Ignition, and Spread in Tray Installations during Fire) program, described in NUREG/CR-7010 (McGrattan, Lock, et al. 2012), focused on the burning behavior of unprotected cables. Experiments were performed at a variety of scales. Bench-scale and medium-scale experiments were performed to gather basic thermo-physical property data for a variety of models. Full-scale experiments were performed to provide data to validate the models. One result of the program was a validated model, FLASH-CAT, whose purpose is to predict the flame spread over horizontal cable trays. Additional experiments performed as part of the CHRISTIFIRE program extended this simple model to vertical configurations.

# 2. TECHNICAL APPROACH

This volume of the research program report focuses on the burning behavior of coated cables.

## 2.1 Basic Thermal Properties of Cable Coating

The thermal conductivity, specific heat, and density of four different cable coatings were measured. This information is needed to incorporate a coating in a thermal penetration calculation like the THIEF model described in NUREG/CR-6931, “Cable Response to Live Fire (CAROLFIRE),” Volume 3, “Thermally-Induced Electrical Failure (THIEF) Model,” issued April 2008 (McGrattan 2008).

In addition to these basic thermal properties, additional experiments were conducted to determine the burning behavior. These experiments include thermogravimetric analysis (TGA) and microcombustion calorimetry (MCC). Both measurement techniques indicate the temperature at which the materials pyrolyze. This information cannot be used in a simple thermal conduction calculation like THIEF, but it does indicate when the materials begin to thermally degrade.

## 2.2 Cone Calorimetry

During the CHRISTIFIRE program, cone calorimetry was performed for the various types of cables that were included in larger scale experiments. The purpose was to determine if a simple bench-scale measurement could reliably predict larger scale behavior. In the current study, the burning rates of coated cables have been measured in the cone calorimeter to determine the effect of the coating on ignition times, peak burning rate, burning duration, and total energy release.

## 2.3 Cable Ignition

Guidance documents like NUREG/CR-6850 suggest that the ignition temperature of an electrical cable is the same as the temperature at which the cable fails electrically. This assumption is based on circuit experiments performed in the CAROLFIRE program (Nowlen and Wyant 2008a) (Nowlen and Wyant 2008b). It has been observed that heated, energized cables sometimes ignite at nearly the same instant that the cables malfunction electrically. It is speculated that the spark from the electrical failure ignites the flammable gases. Generally, it is not necessarily true that the electrical failure temperature is the same as the ignition temperature. In fact, there is no single value for either, because electrical failure and flaming ignition are influenced by other factors besides temperature. Putting these other factors aside, electrical failure results from either melting or some other physical breakdown of the cable’s insulation material, but this does not necessarily occur at temperatures high enough to invoke ignition or sustain burning.

The oven experiments focused exclusively on ignition temperature. The cable samples were unenergized and suspended in a convection oven and heated until ignited.

## 2.4 Vertical Flame Spread Experiments

A key component of electrical cable qualification is the vertical flame spread test as described in Institute of Electrical and Electronics Engineers (IEEE) Standard 1202, “Standard for Flame Testing of Cables for Use in Cable Tray in Industrial and Commercial Occupancies,” issued 1991 (IEEE 1991). A modified version of this test has been performed at the National Institute of

Standards and Technology (NIST) using three different cables protected by four different coatings. Two series of experiments have been performed, the first involving unenergized cables; the second involved energized and thermally monitored cables. The objectives of the experiments were to determine the effect of cable coatings on upward flame spread.

## 2.5 Bench-Scale and Full-Scale Circuit Integrity Experiments

An important question about cable coatings is how long they maintain circuit integrity. The answer depends on the heating rate, which is typically determined by the location of the cables relative to the fire. Experiments are performed at both bench and full scale to measure the time to electrical failure and the cable temperature at the time of failure.

# 3. CABLE AND COATING PROPERTIES

This section describes the electrical cables and the coatings that have been used in the experiments.

## 3.1 Properties of Cables Used in the Experiments

The tables on the following pages contain a general description of the cables used in the experiments. Note that "Cable No." is merely an identifier and has no relevance beyond this project. Figure 3-1 and Figure 3-2 show photographs of the cables. The cable markings are listed in Table 3-1, while the cable properties are listed in Table 3-2. The reported cable diameter and layer thickness measurements have a combined standard uncertainty of 0.2 millimeters (mm) (0.008-inch (in.)). The mass fraction measurements were obtained by dissecting 20-centimeter (cm) (8 in.) cable segments into their constituent parts—jacket, filler, insulators, and conductors. The reported mass fraction measurements have a combined standard uncertainty of 0.01. Taylor and Kuyatt (Taylor and Kuyatt 1994) give NIST guidelines for expressing measurement uncertainty.

Table 3-1 presents a cross-reference of the cables used in CAROLFIRE (Nowlen and Wyant 2008a) (Nowlen and Wyant 2008b) and those purchased and those left over from previous NRC-sponsored experiments at Brookhaven National Laboratory.


Figure 3-1. Photograph of cables 800–811.

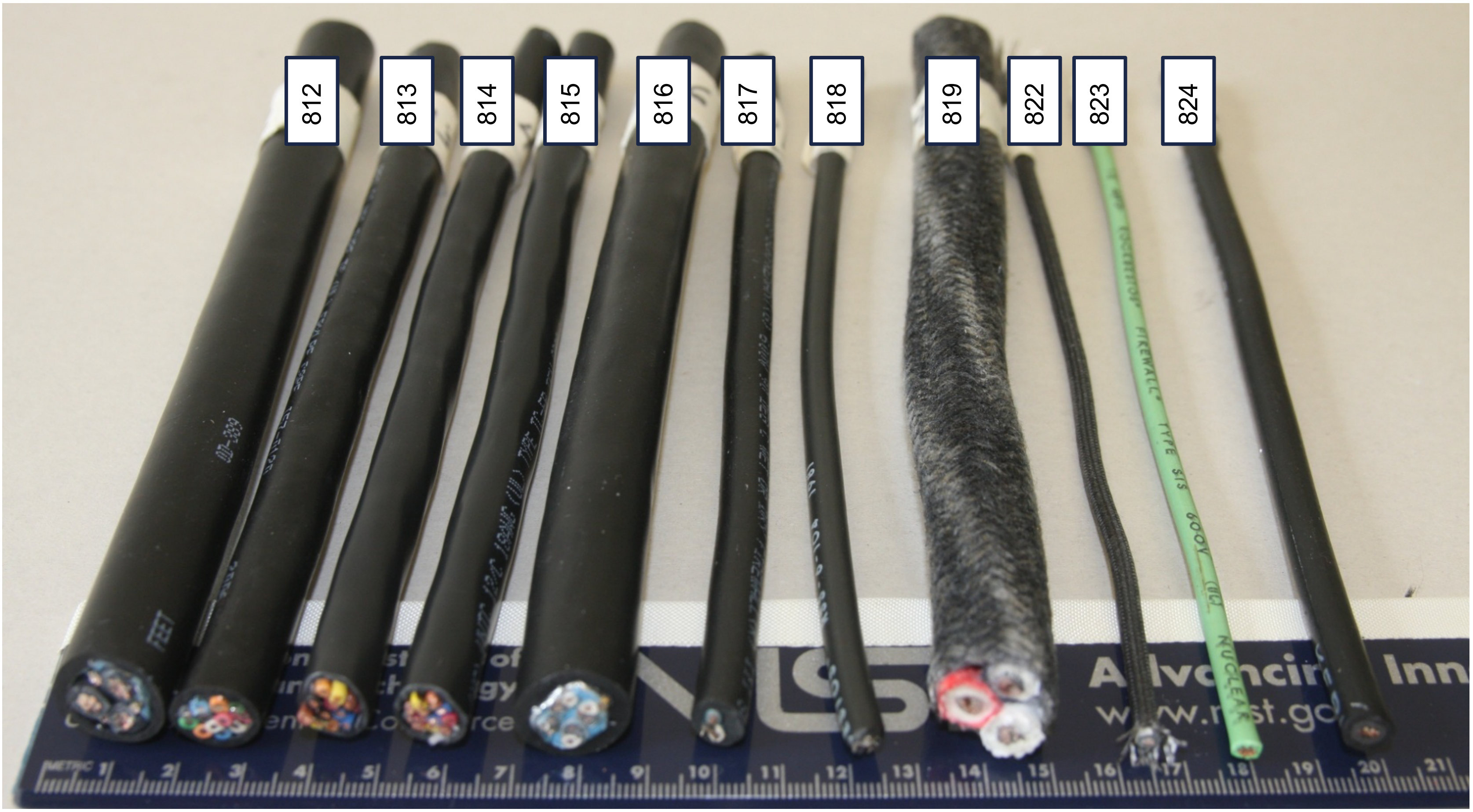



**Figure 3-2. Photograph of cables 812–824.**

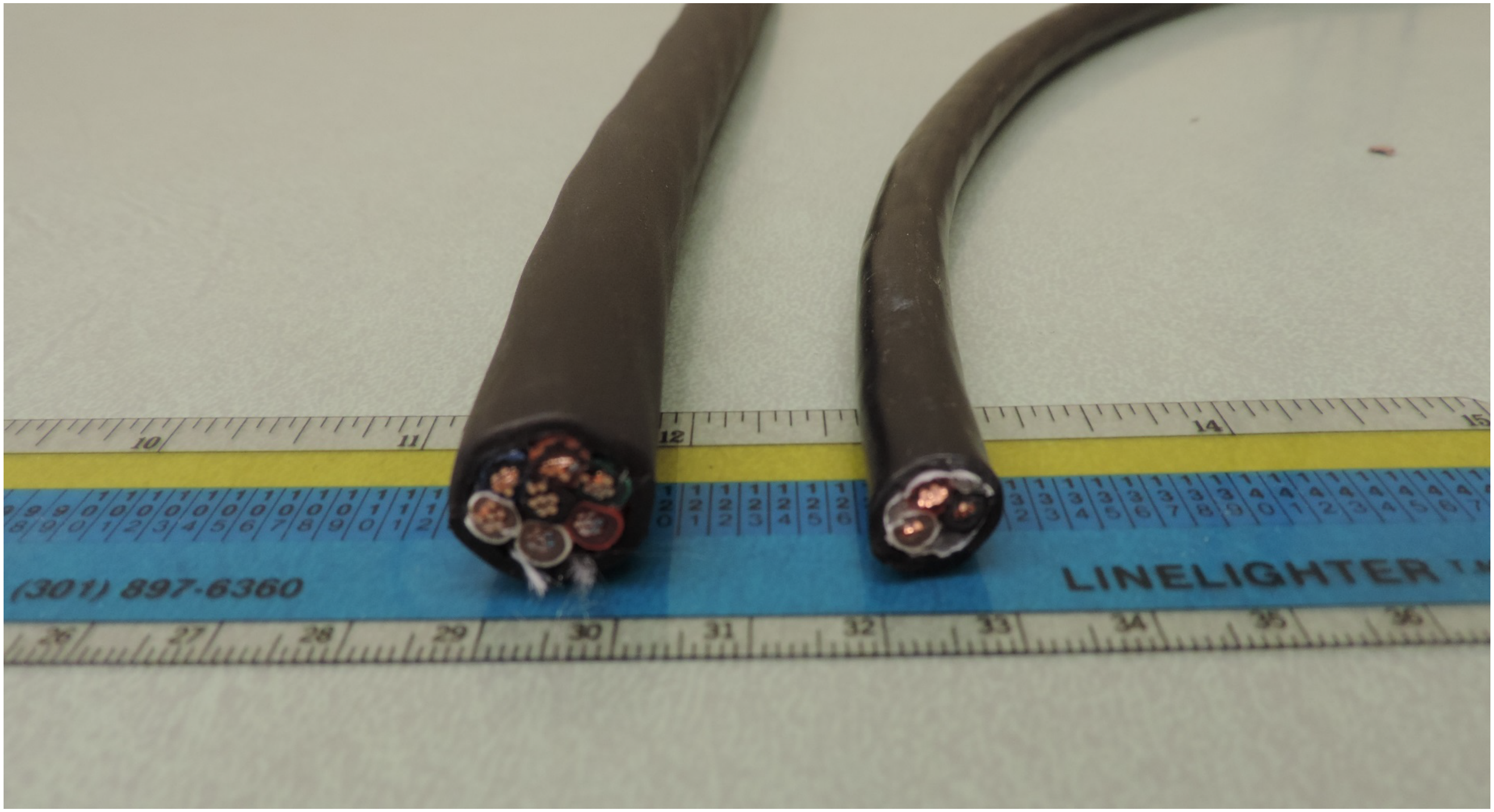



**Figure 3-3. Photograph of cables 900 (left) and 902 (right).**

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

| Cable No. | SOURCE | MANUFACTURER* | DATE | CABLE MARKINGS |
|---|---|---|---|---|
| 800 | CAROLFIRE #1 | GENERAL CABLE | 2006 | GENERAL CABLE® BICC® BRAND (WC) VNTC 7/C 12 AWG (UL) TYPE TC-ER THHN/THWN CDRS DIR BUR SUN RES 600 V 03 FEB 2006 |
| 801 | PURCHASED | GENERAL CABLE | 2011 | GENERAL CABLE® (WC) VNTC 7/C 12AWG (UL) TYPE TC-ER THHN/THWN CDRS DIR BUR SUN RES 600 V ROHS 03/FEB/2011 |
| 802 | CAROLFIRE #10 | ROCKBESTOS | 2006 | 7/C 12 AWG COPPER ROCKBESTOS-SURPRENANT (G) 600 V 90DEG C FIREWALL(R) III XHHW-2 SUN RES DIR BUR OIL RES II NEC TYPE TC (UL) XLPE CSPE FT4 C52-0070 2006 6C-326 |
| 803 | PURCHASED | ROCKBESTOS | 2011 | 7/C 12 AWG COPPER ROCKBESTOS-SURPRENANT (G) 600 V 90 DEG C FIREWALL(R) III XHHW-2 SUN RES DIR BUR OIL RES II NEC TYPE TC (UL) XLPE CSPE FT4 C52-0070 2011 1C-136 |
| 804 | CAROLFIRE #3 | GENERAL CABLE | 2006 | GENERAL CABLE® BICC® BRAND (WC) CVTC 7C 12AWG FR-XLP/PVC (UL) TYPE TC-ER XHHW-2 CDRS DIR BUR SUN RES 90C WET OR DRY 600 V 08 MAR 2006 |
| 805 | CAROLFIRE #12 | CABLE USA | UNKNOWN | NO MARKINGS |
| 806 | CAROLFIRE #8 | ROCKBESTOS | 2005 | 7/C 12 AWG COPPER ROCKBESTOS-SURPRENANT (G) X-LINK(R) TC 600 V 90 DEG C WET OR DRY SUN RES DIR BUR NEC TYPE TC (UL) FMRC GP-1 K2 COLOR CODE FRXLPE LSZH-XLPO C12-0070 2005 5 D-880 |
| 807 | CAROLFIRE #15 | GENERAL CABLE | 2006 | GENERAL CABLE® BICC® BRAND SUBSTATION CONTROL CABLE 7/C #12AWG 600 V 30 MAY 2006 |
| 808 | CAROLFIRE #11 | ROCKBESTOS | 2005 | 7/C 14 AWG ROCKBESTOS-SURPRENANT (G) VITA-LINK(R) TC/NCC 600 V 90 DEG C (UL) TYPE TC SUN RES FT-4 FIRE-RESISTANT SILICONE LSZH C65-0070 2005 5F-052 |
| 809 | CAROLFIRE #9 | FIRST CAPITOL | | NO MARKINGS |
| 810 | PURCHASED | GENERAL CABLE | 2011 | GENERAL CABLE® (WC) VNTC 3/C 8AWG WITH GRND (UL) TYPE TC-ER THHN/THWN CDRS DIR BUR SUN RES 600 V ROHS 10/FEB/2011 |
| 811 | CAROLFIRE #14 | ROCKBESTOS | 2006 | 3/C 8 AWG ROCKBESTOS-SURPRENANT (G) 600 V FIREWALL(R) III XHHW-2 90 DEG C SUN RES DIR BUR OIL RES II NEC TYPE TC (UL) FRXLPE CSPE FT4 P62-0084 2006 6C-399 |
| 812 | PURCHASED | ROCKBESTOS | 2010 | 3/C 8 AWG COPPER ROCKBESTOS-SURPRENANT (G) 600 V FIREWALL(R) III XHHW-2 90 DEG C SUN RES DIR BUR OIL RES II NEC TYPE TC (UL) FRXLPE CSPE FT4 P62-0084 2010 0 D-389 |
| 813 | CAROLFIRE #13 | ROCKBESTOS | 2006 | 12/C 18 AWG COPPER ROCKBESTOS-SURPRENANT(G) 600 V 90 DEG C WET OR DRY FIREWALL(R) III SUN RES DIR BUR OIL RES II NEC TYPE TC (UL) FRXLPE CSPE I57-0120 2006 6C-399 |

| Cable No. | SOURCE | MANUFACTURER* | DATE | CABLE MARKINGS |
|---|---|---|---|---|
| 814 | CAROLFIRE #6 | GENERAL CABLE | 2006 | GENERAL CABLE® BICC® BRAND (WC) VNTC 12C 18AWG (UL) TYPE TC-ER TFN CDRS SUN RES DIR BUR 600 V 09 MAR 2006 |
| 815 | PURCHASED | GENERAL CABLE | 2011 | GENERAL CABLE® (WC) VNTC 12/C 18AWG (UL) TYPE TC-ER TFN CDRS SUN RES DIR BUR 600 V ROHS 20 JAN 2011 |
| 816 | PURCHASED | ROCKBESTOS | 2011 | 4 SHIELDED PAIRS 16 AWG COPPER ROCKBESTOS-SURPRENANT (G) 600 V 90 DEG C WET OR DRY FIREWALL(R) III SUN RES DIR BUR OIL RES II NEC TYPE TC (UL) FRXLPE SHIELDED CSPE I46-5844 2011 1 D-138 |
| 817 | CAROLFIRE #7 | ROCKBESTOS | 2006 | 2/C 16 AWG COPPER ROCKBESTOS-SURPRENANT (G) 600 V 90 DEG C WET OR DRY FIREWALL(R) III SUN RES DIR BUR OIL RES II NEC TYPE TC (UL) FRXLPE SHIELDED CSPE I46-0021 2006 6C-191 |
| 818 | BROOKHAVEN | ROCKBESTOS | 1981 | ROCKBESTOS® RSS-6-104 1981 |
| 819 | | FIRST CAPITOL | 2003 | NO MARKINGS |
| 822 | BROOKHAVEN | ROCKBESTOS | UNKNOWN | NO MARKINGS |
| 823 | BROOKHAVEN | ROCKBESTOS | UNKNOWN | 12 AWG ROCKBESTOS® FIREWALL® TYPE SIS 600 V (UL) NUCLEAR |
| 824 | | KERITE | 1989 | KERITE 1989 #12 AWG CU 600 V FR3 TEST # A6272 |
| 900 | PURCHASED | LAKE CABLE | 2015 | #2582 FT. TPT127 LAKE CABLE 12AWG 7C PE/PVC2010 CONTROL CABLE 600 V $75^0$ C 2015 “ROHS 11” REACH MADE IN USA 280547 |
| 902 | TVA | CYPRUS WIRE & CABLE | 1975 | 3460 FEET CYPRUS WIRE & CABLE 75K/-8615 U-1 PJJ-600 3/C #14 1975 |

* Certain commercial equipment, instruments, or materials are identified in this report to foster understanding. Such identification does not imply recommendation or endorsement by NIST, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose. In this table “TC” is an abbreviation for tray cable and not thermocouple.

**Table 3-2. Cable properties.**

| Jacket Material | Cable No. | Insulation Material | Class | Conductors | Diameter (mm) | Jacket Thickness (mm) | Insulator Thickness (mm) | Mass per Length (kg/m) | Copper Mass Fraction | Jacket Mass Fraction | Insulation Mass Fraction | Filler Mass Fraction |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PVC | 800 | PVC | TP | 7 | 12.4 | 1.3 | 0.7 | 0.31 | 0.66 | 0.19 | 0.11 | 0.01 |
| PVC | 801 | PVC/Nylon | TP | 7 | 12.5 | 1.3 | 0.6 | 0.31 | 0.66 | 0.19 | 0.11 | 0.01 |
| CSPE | 802 | XLPE | TS | 7 | 15.0 | 2.3 | 1.2 | 0.42 | 0.50 | 0.30 | 0.20 | 0.01 |
| CSPE | 803 | XLPE | TS | 7 | 15.0 | 2.4 | 1.0 | 0.44 | 0.48 | 0.32 | 0.19 | 0.01 |
| PVC | 804 | XLPE | Mix | 7 | 15.1 | 1.6 | 1.0 | 0.41 | 0.52 | 0.23 | 0.22 | 0.01 |
| Tefzel® | 805 | Tefzel® | TP | 7 | 10.2 | 0.8 | 0.5 | 0.29 | 0.74 | 0.08 | 0.15 | 0.02 |
| XLPO | 806 | XLPE | TS | 7 | 12.2 | 1.2 | 0.8 | 0.32 | 0.66 | 0.18 | 0.17 | 0.00 |
| PVC | 807 | PE | TP | 7 | 14.0 | 1.5 | 0.3 | 0.37 | 0.59 | 0.24 | 0.15 | 0.01 |
| VITA-LINK® | 808 | VITA-LINK® | TS | 7 | 19.6 | 2.4 | 1.7 | 0.48 | 0.26 | 0.33 | 0.43 | 0.01 |
| Aramid Braid | 809 | SR | TS | 7 | 14.5 | 1.2 | 1.1 | 0.35 | 0.62 | 0.08 | 0.31 | 0.01 |
| PVC | 810 | PVC/Nylon | TP | 3 | 15.2 | 1.7 | 1.1 | 0.43 | 0.63 | 0.23 | 0.12 | 0.01 |
| CSPE | 811 | XLPE | TS | 3 | 16.3 | 1.9 | 1.72 | 0.43 | 0.55 | 0.29 | 0.16 | 0.03 |
| CSPE | 812 | XLPE | TS | 3 | 16.3 | 2.5 | 1.7 | 0.54 | 0.53 | 0.29 | 0.14 | 0.03 |
| CSPE | 813 | XLPE | TS | 12 | 12.7 | 1.5 | 1.2 | 0.25 | 0.37 | 0.33 | 0.29 | 0.01 |
| PVC | 814 | PVC | TP | 12 | 11.3 | 1.2 | 0.5 | 0.19 | 0.56 | 0.03 | 0.40 | 0.00 |
| PVC | 815 | PVC/Nylon | TP | 12 | 11.3 | 1.2 | 0.5 | 0.19 | 0.59 | 0.02 | 0.29 | 0.06 |
| CSPE | 816 | XLPE | TS | 4 | 16.7 | 2.9 | 1.1 | 0.42 | 0.26 | 0.45 | 0.22 | 0.07 |
| CSPE | 817 | XLPE | TS | 2 | 7.8 | 1.6 | 0.9 | 0.11 | 0.24 | 0.58 | 0.15 | 0.00 |
| PVC | 818 | PE | TP | 1 | 6.3 | 1.4 | 1.4 | 0.06 | 0.38 | 0.40 | 0.07 | 0.15 |

| Jacket Material | Cable No. | Insulation Material | Class | Conductors | Diameter (mm) | Jacket Thickness (mm) | Insulator Thickness (mm) | Mass per Length (kg/m) | Copper Mass Fraction | Jacket Mass Fraction | Insulation Mass Fraction | Filler Mass Fraction |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Glass Braid | 819 | SR | TS | 3 | 16.3 | 1.4 | 20.1 | 0.52 | 0.47 | 0.08 | 0.24 | 0.19 |
| Glass Braid | 822 | SR | TS | 1 | 3.7 | 0.3 | 1.0 | 0.03 | 0.48 | 0.18 | 0.31 | 0.01 |
| XLPE | 823 | TS | | 1 | 3.8 | 1.2 | N/A | 0.04 | 0.70 | 0.30 | 0.00 | 0.00 |
| CSPE | 824 | EPR | TS | 1 | 5.1 | 1.4 | 1.1 | 0.08 | 0.34 | 0.46 | 0.20 | 0.00 |
| PVC | 900 | PE | TP | 7 | 15.9 | 1.9 | 1.1 | 0.38 | 0.55 | 0.27 | 0.10 | 0.08 |
| PVC | 902 | PE | TP | 3 | 10.0 | 1.3 | 1.1 | 0.13 | 0.42 | 0.36 | 0.10 | 0.12 |

## 3.2 Cable Coating Description and Thermal Properties

This section describes the thermal properties of selected fire-retardant coatings that are designed to protect electrical cables from fire. The properties are to be used in the calculation of heat penetration through coated and uncoated cable bundles as measured in experiments conducted at Sandia National Laboratories. The experiments consisted of exposing energized cables within a heated cylindrical chamber. The calculations of the heat transfer in these experiments are performed with techniques like those used in the THIEF model (McGrattan 2008).

### 3.2.1 Carboline Intumastic 285

Carboline Intumastic 285 is a registered product of the Carboline Company (https://www.carboline.com). It is currently marketed under the name Thermo-Lag 270. The coating material is described as a water-based mastic that can be applied to impede fire propagation along the length of coated electrical cables. The wet film thickness is specified at 3.2 mm (1/8 in.), which dries to approximately 1.6 mm (1/16 in.). Common application procedures for this product include troweling and spraying the material onto cables.

### 3.2.2 Flamemastic 77

Flamemastic 77 is a registered product of the Flamemaster Corporation (https://flamemaster.com). According to the manufacturer's literature, the coating material consists of water-based TP resins; flame-retardant chemicals; and inorganic, incombustible fibers. It is further described as a non-intumescent, thixotropic compound with no asbestos. There are two available product variations; one is appropriate for spraying and the other is mastic. The latter was used in the experiments. The wet film thickness is specified at 3.2 mm (1/8 in.), which will dry to approximately 1.6 mm (1/16 in.). Once the coating material is fully cured, it appears off-white with a matte finish.

### 3.2.3 Vimasco 3i

Vimasco 3i, also known as Cable Coating 3i, is a registered trademark product of the Vimasco Corporation (https://vimasco.com). The material is described by the manufacturer as "a heavy-bodied, water-based intumescent coating that is designed to prevent flame spread along the jacketing of electrical (or other) cables and to provide a thermal barrier for protection against heat damage." It is further described as an "acrylic latex emulsion which has excellent resistance to weathering and aging, and which remains flexible indefinitely allowing for cable movement and removal. It is suitable for indoor or outdoor application." As with the other two products, a wet film thickness of 3.2 mm (1/8 in.) is recommended, which dries to approximately 1.6 mm (1/16 in.).

### 3.2.4 FS15

FS15 is a water-based ablative coating manufactured by Fire Security Systems (https://fire-security.com). The primary mode of protection is ablation as opposed to thermal insulation. The recommended dry film thickness is 1 mm (1/25 in.).

### 3.2.5 Density, Heat Capacity, and Thermal Conductivity

The density of the cured coatings was determined in two ways. First, the bulk density was determined by weighing samples that had been prepared for cone calorimeter experiments. The samples were approximately 10 cm by 10 cm by 1.5 cm thick (4 in. by 4 in. by 0.6 in. thick). The uncertainty in the bulk density is mainly due to the uncertainty in the measurement of the sample thickness, which is ±1 mm (0.04 in.) (standard uncertainty).

The "true" density (that is, the density of the solid excluding air gaps within the sample) was determined using a Micromeritics AccuPyc II 1340 gas pycnometer. This technique is based on gas displacement; thus, it measures only the volume of the solid material as opposed to void spaces within the solid. Three samples of each material were measured. Table 3-3 summarizes the results. Note that the true density is substantially greater than the bulk density, indicating that the dried coatings are somewhat porous.

**Table 3-3. Density of coating materials with standard uncertainty.**

| Material | Bulk Density (kg/m$^3$) | True Density (kg/m$^3$) |
|---|---|---|
| Carboline 285 | 804 ± 56 | 1,740 ± 10 |
| Vimasco 3i | 852 ± 60 | 1,480 ± 20 |
| Flamemastic 77 | 1,033 ± 72 | 2,030 ± 10 |
| FS15 | Not measured | 1,660 ± 20 |

### 3.2.6 Heat Capacity

Specific heat capacities at room temperature were measured using differential scanning calorimetry according to ASTM E1269-11, "Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry" (ASTM 2011), but at a heating rate of 10 degrees Celsius (°C)/min (50°F/min). Four replicates of Carboline, FS15, and Vimasco were tested, along with five replicates of Flamemastic. Sapphire and polystyrene were used as verification standards with good reproducibility. Table 3-4 presents the results.

**Table 3-4. Specific heat capacities.**

| Material | $T_g$ (°C)[a] | $c$ (J/g·K)[b] | Temperature Range (°C) |
|---|---|---|---|
| Carboline 285 | 1.5 | 0.00215 $T$ + 0.520 (2σ = ±0.08) | 25–200 |
| Flamemastic 77 | 7.7 | 0.00113 $T$ + 0.944 (2σ = ±0.25) | 25–200 |
| FS15 | 10.6 | 0.00204 $T$ + 0.655 (2σ = ±0.08) | 25–200 |
| Vimasco 3i[c] | 9.1 | 0.00134 $T$ + 0.862 (2σ = ±0.14) | 25–150 |

a error in $T_g$, $2\sigma = \pm$ 2.4°C

b $T$ is in kelvin (K) for calculation of specific heat.

c Vimasco begins to degrade at approximately 160°C (320°F).

### 3.2.7 Thermal Conductivity

Room temperature (20°C (68 °F)) thermal conductivities were measured using a Hot Disk Transient Plant Source (TPS) thermal constants analyzer. For each coating material, two measurements were taken at three different locations for a total of six measurements per material. A nominal 6.4 mm (1/4 in.) Kapton probe was used with typical probing depths of 5 mm to 7 mm (0.2 in. to 0.3 in.). Table 3-5 summarizes the results.

**Table 3-5. Room temperature thermal conductivities.**

| Material | Mean Value (W/(m·K))* | Standard Deviation (W/(m·K)) |
|---|---|---|
| Carboline 285 | 0.332 | 0.004 |
| Vimasco 3i | 0.297 | 0.010 |
| Flamemastic 77 | 0.650 | 0.028 |
| FS15 | 0.642 | 0.022 |

*W/(m·K) , Watt per Meter-Kelvin

### 3.2.8 Thermogravimetric Analysis

The thermal degradation of the three coating samples was studied using TGA (ASTM 2014). In this experiment method, approximately 10 milligrams (mg) of each coating were placed on a small load cell in a heated chamber where the temperature was increased at a rate of 5°C/min (41 °F/min) up to 800°C (1,472 °F). Figure 3-4 shows the relative mass of the sample as a function of temperature. Note that each coating leaves a residue behind, as indicated by the right-hand tail of each plot.

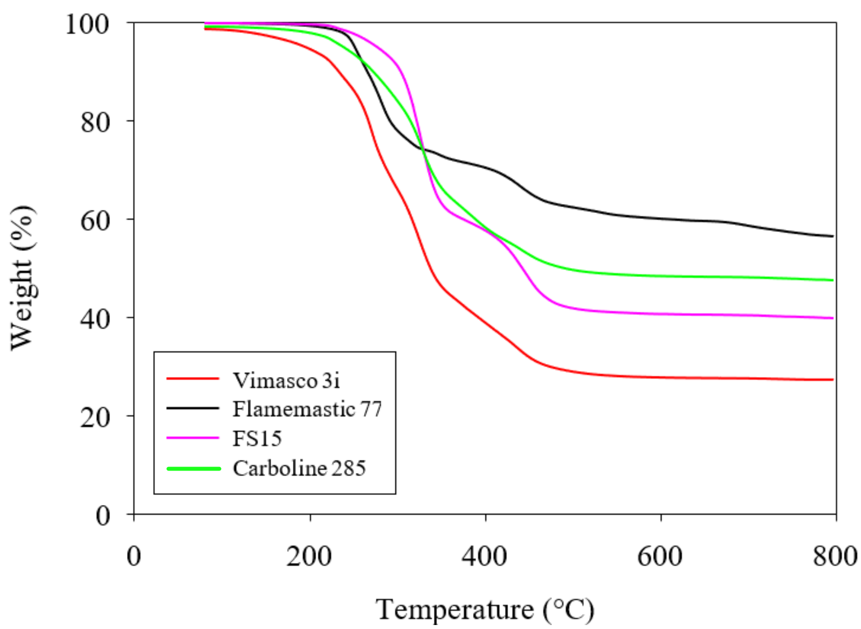



**Figure 3-4. Results of the TGA of the four cable coatings.**

The TGA results indicate that two significant reactions occur: the first at approximately 300°C (572°F) and the second at approximately 450°C (842°F). This is shown more clearly in Figure 3-5, which is basically the slope (first derivative) of the data in Figure 3-4. According to an analysis by Lyon et al. (2012), the relative standard uncertainty of the reaction rate is 3 percent.

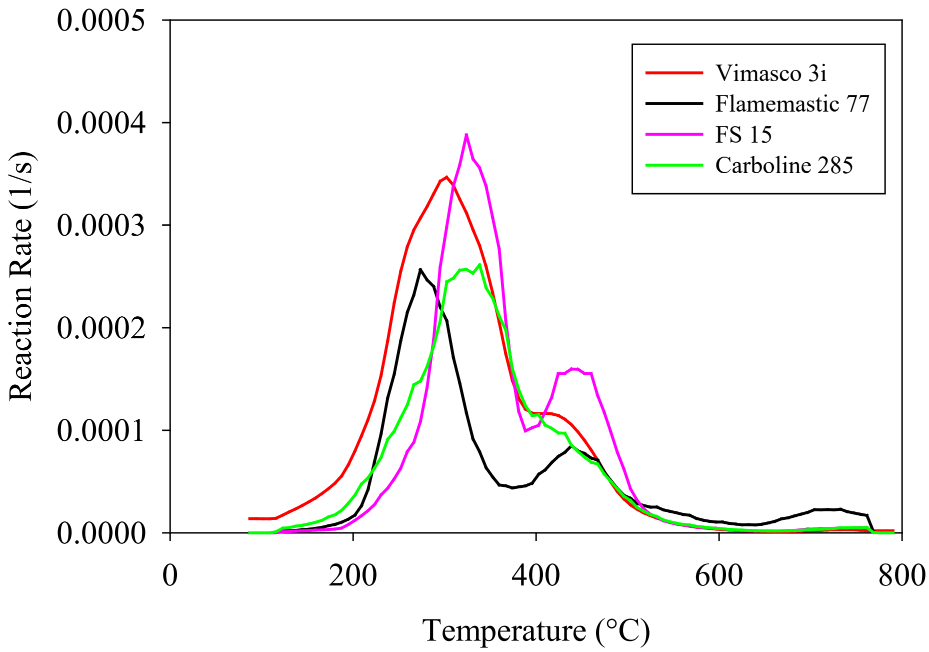



**Figure 3-5. TGA results for the cable coatings, expressed in terms of reaction rate.**

### 3.2.9 Microcombustion Calorimetry

One drawback of TGA is that it indicates only the temperatures at which the sample off-gases. It does not indicate whether these gases are combustible. However, a similar technique, MCC, indicates the relative flammability of the off-gas (ASTM 2013). For each material, three replicate experiments were performed at a nitrogen purge gas flow rate of approximately 80 milliliters/minute (mL/min) and an oxygen flow rate of approximately 20 mL/min. Initial sample masses were approximately 4 mg.

Figure 3-6 presents the results of an MCC analysis of the four coatings. In any event, these experiments indicate that all four coatings do burn, leaving a relatively large amount of residue. According to an analysis by Lyon et al. (Lyon, et al. 2012), the relative standard uncertainty of the HRR is 22 percent.

Table 3-6 lists the heats of combustion (determined from the MCC) and the char yield (determined from the TGA) for the four coatings.

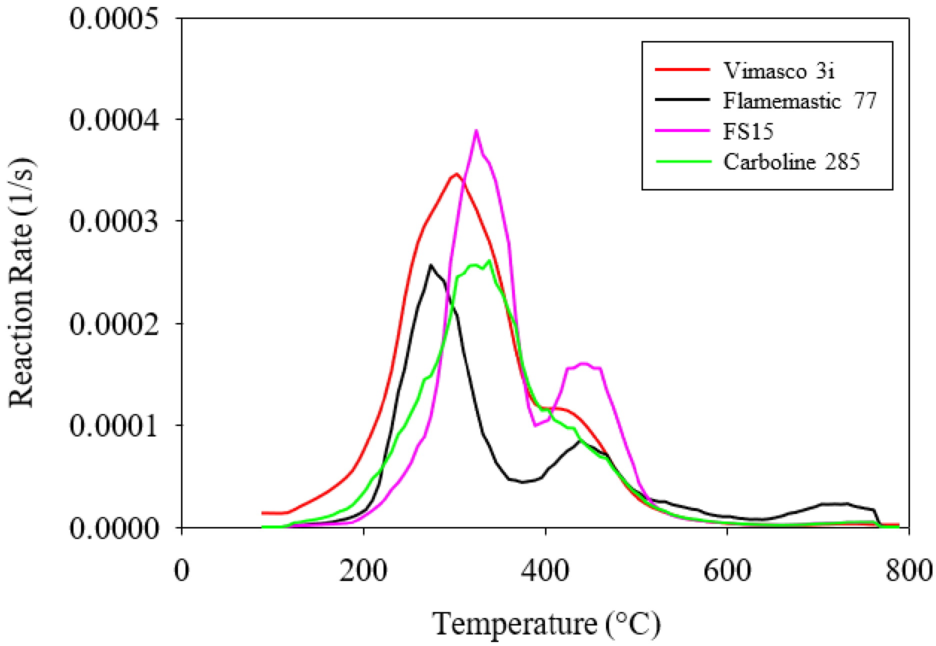



**Figure 3-6. MCC results for the cable coatings.**

**Table 3-6. Heat of combustion and char yield with standard uncertainty.**

| Material | Heat of Combustion (kJ/g) | Char Yield (%) |
|---|---|---|
| Carboline 285 | 16.5 ± 0.1 | 50.5 ± 0.4 |
| Vimasco 3i | 15.4 ± 0.3 | 26.4 ± 0.3 |
| Flamemastic 77 | 12.0 ± 0.2 | 56.9 ± 0.8 |
| FS15 | 17.6 ± 0.4 | 47.4 ± 0.3 |

### 3.2.10 Burning Rate of the Coatings Absent Underlying Cables

Samples similar to those used in the determination of the thermal conductivity were burned in the cone calorimeter at a heat flux of approximately 75 kilowatts (kW)/$m^2$. Section 4 describes the cone calorimeter and its uncertainty. Only one replicate was performed for each sample. Each was approximately 10 cm by 10 cm (4 in. by 4 in.). The sample thickness and mass were as follows:

Flamemastic 77: thickness 14.8 mm ± 1 mm (0.58 in. ± 0.04 in.), mass 153.0 grams (g) ± 0.05 g (standard uncertainty)

Vimasco 3i: thickness 13.4 mm ± 1 mm (0.53 in. ± 0.04 in.), mass 114.2 g ± 0.05 g

Carboline 285: thickness 16.1 mm ± 1 mm (0.63 in. ± 0.04 in.), mass 129.5 g ± 0.05 g

Note that FS15 was not evaluated in this exercise. Figure 3-7 through Figure 3-9 show the HRRs of the samples. The solid line denotes the instantaneous value, and the dashed line represents an average over the course of the experiment. Note that the Vimasco 3i ignites more quickly than the other two, because it undergoes thermal degradation at lower temperatures, according to the TGA and MCC measurements in Figure 3-5 and Figure 3-6.

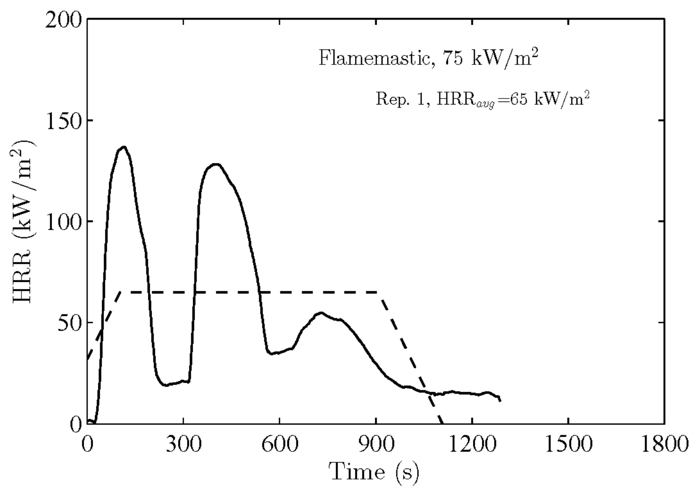



**Figure 3-7. Cone calorimeter results for Flamemastic 77.**

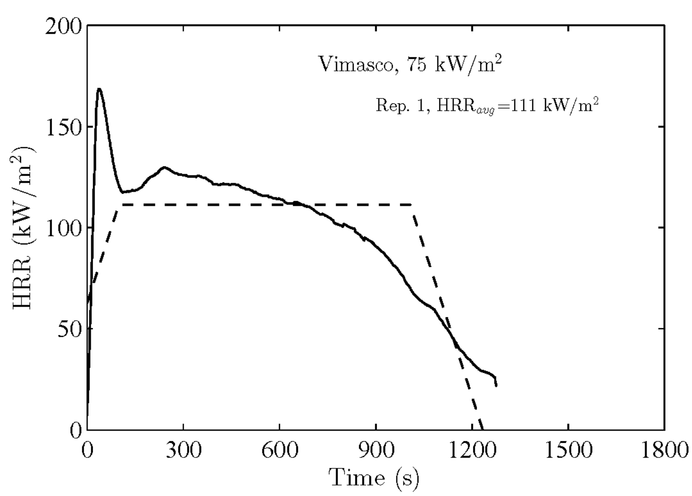



**Figure 3-8. Cone calorimeter results for Vimasco 3i.**

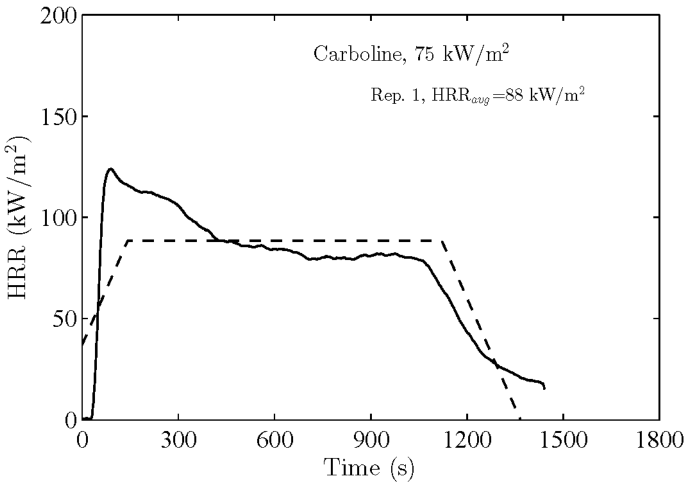



**Figure 3-9. Cone calorimeter results for Carboline 285.**

### 3.2.11 Thermal Penetration Modeling of Coated, Bundled Cables

At Sandia National Laboratories (SNL) in Albuquerque, New Mexico, cables were bundled in groups of 10 and then coated with one of three different coatings (FS15 was not included). After drying, the bundles were subjected to a constant imposed heat flux during which time the internal cable temperatures and electrical response were monitored.[1] Figure 3-10 shows the bundle configuration. The cables lettered A, B, C, D, E, F, and G each had a single thermocouple (TC) positioned just under the jacket at the location closest to the exterior of the bundle. For example, the TC inserted into cable A was at the top. The cables lettered S1, S2, and S3 carried electrical current and were monitored for signs of malfunction.

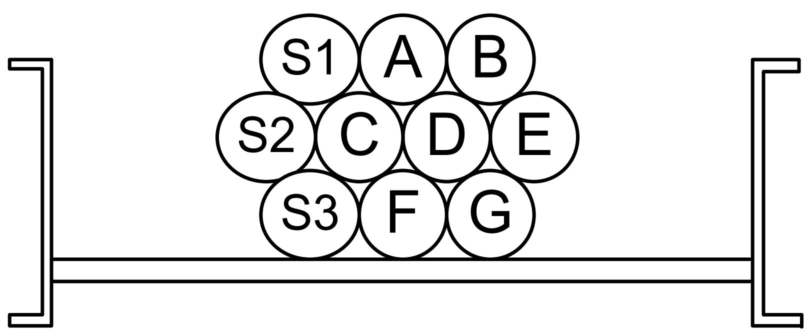



**Figure 3-10. Experiment with 10-cable bundle configuration at SNL.**

The bundles were coated with the manufacturer-recommended thickness, which means that there was at least 1.6 mm (1/16 in.) coverage over all exposed, exterior cable surfaces.

The heat transfer within the bundle can be modeled in several ways. A two- or three-dimensional model could account for the different materials (coating, plastics, copper) and the overall

[1] The measurements reported in this section are not published.

configuration. However, such a calculation requires considerable effort, and it is not always possible to measure the thermal properties of all the materials. Instead, a one-dimensional heat conduction model, called THIEF, was developed in which a single cable is assumed to be homogenous and characterized by a single value of the thermal conductivity and specific heat (McGrattan 2008). In the case of the coated 10-cable bundle, the THIEF model can be applied to the entire bundle. That is, the specific heat and thermal conductivity are assumed constant (1.5 kJ/(kg·K) and 0.2 W/(m·K)), and the density is inferred from the total mass per unit length of the bundle divided by its cross-sectional area.

In the SNL experiments, four configurations were considered. The first consisted simply of the 10 cables tightly bound together with no coating applied. The other three consisted of the same tightly bound bundle with each of the three coatings applied. Figure 3-11 through Figure 3-13 show the measured[2] and predicted temperatures of cables A, B, and C. The THIEF model assumes that the bundle is circular in cross section with a diameter of 4 cm (1.6 in.). Its density, based on the mass of the cables per unit length and its assumed total cross-sectional area, is 2,321 kg/m$^3$. The only parameter in the model that distinguishes the coated and uncoated configuration is the depth of the location of the measured and predicted temperature. In the uncoated case, the depth for cables A and B is simply the thickness of the cable jacket, 1.8 mm (0.7 in.). In the coated case, the depth is 4 mm (0.16 in.). This calculation uses only the relative depths, not the actual measured properties of the coatings. The THIEF model cannot account for the fact that heat more readily penetrates the cable bundle when it is uncoated. However, the THIEF model can explain why the temperature of cable C is significantly lower than cables A and B for the coated bundles.

In the SNL experiments, the uncoated bundles ignited after approximately 24 minutes. The Vimasco and Flamemastic coated bundles ignited after approximately 39 min. and 36 min., respectively. The Carboline bundle ignited after approximately 60 min. Electrical failure occurred after ignition in all cases. The plots in Figure 3-13 are terminated after 30 min. simply because the TC measurements became increasingly erratic as the cables and coatings approached their ignition temperatures, which are in the range of 300°C to 400°C (572°F to 752°F).

2 The measured temperatures are based on the average of three replicate experiments.

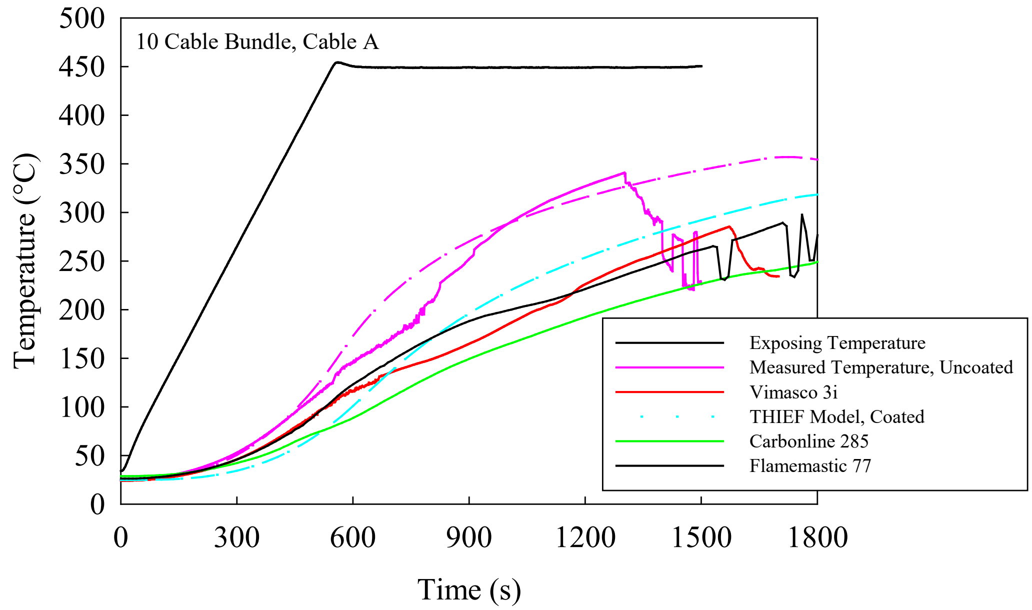



**Figure 3-11. Measured and predicted temperatures inside 10-cable bundle, cable A.**

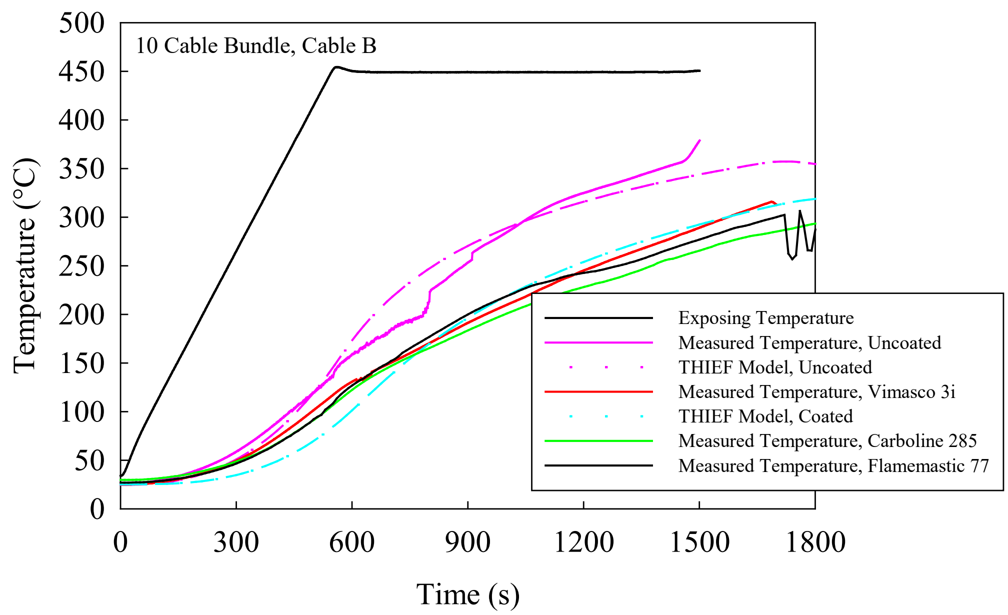



**Figure 3-12. Measured and predicted temperatures inside 10-cable bundle, cable B.**

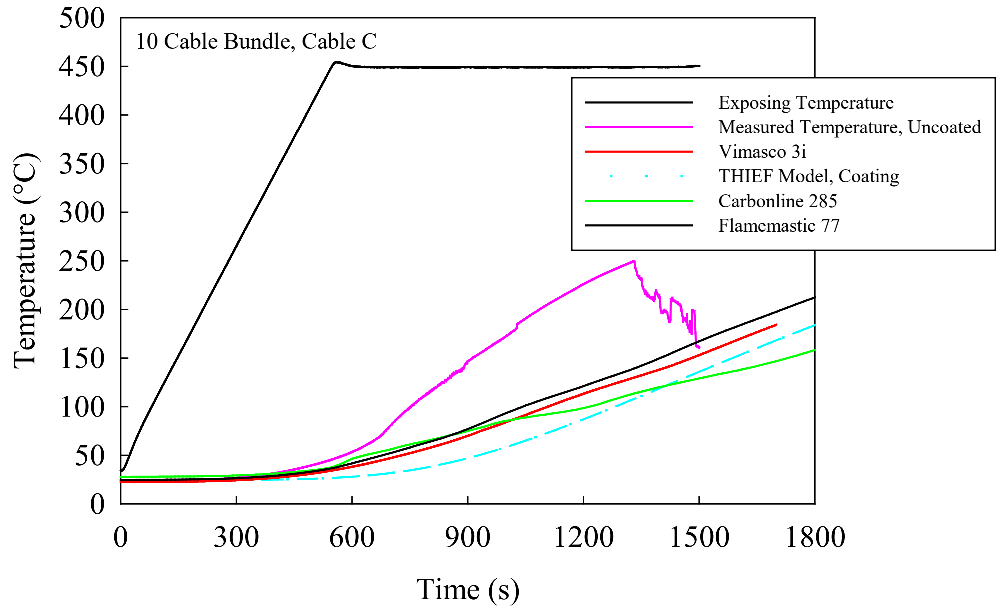



**Figure 3-13. Measured and predicted temperatures inside 10-cable bundle, cable C.**

The results shown in this section demonstrate that a coated cable bundle is difficult to characterize in terms of a homogenous, cylindrical object amenable to a one-dimensional heat conduction calculation. The relative position of the cable within the bundle can have as much of an impact on heating as the presence of an external coating. For example, cable C, buried within the uncoated bundle, heats at approximately the same rate as cable A or B at the exterior of a coated bundle. This observation holds regardless of coating type.

While it is possible to assume “effective” or lumped properties of the bundle and estimate the thermal penetration time, it is problematic to develop a simple model like THIEF that would account for the wide variety of cable/coating configurations. Expert judgment would be required for each scenario, and it would not be practical to codify this judgment into a simple spreadsheet calculation method.

# 4. BENCH-SCALE HEAT RELEASE RATE EXPERIMENTS

This section describes measurements of the burning rate of coated and uncoated cables in a bench-scale apparatus known as the cone calorimeter.

## 4.1 Experimental Description

The cone calorimeter is a widely used device in fire protection engineering for measuring the HRR of a material sample under a constant imposed heat flux. In Phase 1 of the CHRISTIFIRE program (McGrattan, Lock, et al. 2012), 12 cable samples were experimented with at three different heat fluxes (nominally 25 kW/$m^2$, 50 kW/$m^2$, and 75 kW/$m^2$) to determine at which heat flux the burning rate of cables best matched that measured at larger scale. The results indicated that an imposed heat flux of 25 kW/$m^2$ was too low to produce HRRs consistent with larger scale experiments; thus, in subsequent experiments, only heat fluxes of 50 kW/$m^2$ or 75 kW/$m^2$ were used.

The cone calorimeter measurements were made using the standardized procedure for cables, given in 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" (ASTM 2003). Preparation for all cable samples followed the procedure outlined in sections 8.1.2 and 8.1.4 of the standard, with some modifications as described below.

Step 1. The cables were cut into nominal 10 cm (4 in.) segments, arranged in a single row approximately 10 cm wide (4 in.), and coated on all sides uniformly such that the cables were covered by at least 1.6 mm (1/16 in.) (Figure 4-1).

**Figure 4-1. Cable segments coated with Flamemastic F-77.**

Step 2. The sample holder was assembled from its components: frame bottom, several layers of mineral wool to ensure a tight fit, cables, wire grid, and frame top (Figure 4-2). The area of the cover opening was 88.4 $cm^2$ ± 0.9 $cm^2$ (13.7 $in.^2$ ± 0.1 $in.^2$). Two pins were used to hold the frame bottom and top together. The wire grid was designed to prevent the cables from bowing upward when heated. Figure 4-3 shows the entire assembly. Figure 4-4 through Figure 4-6 show the coated samples.

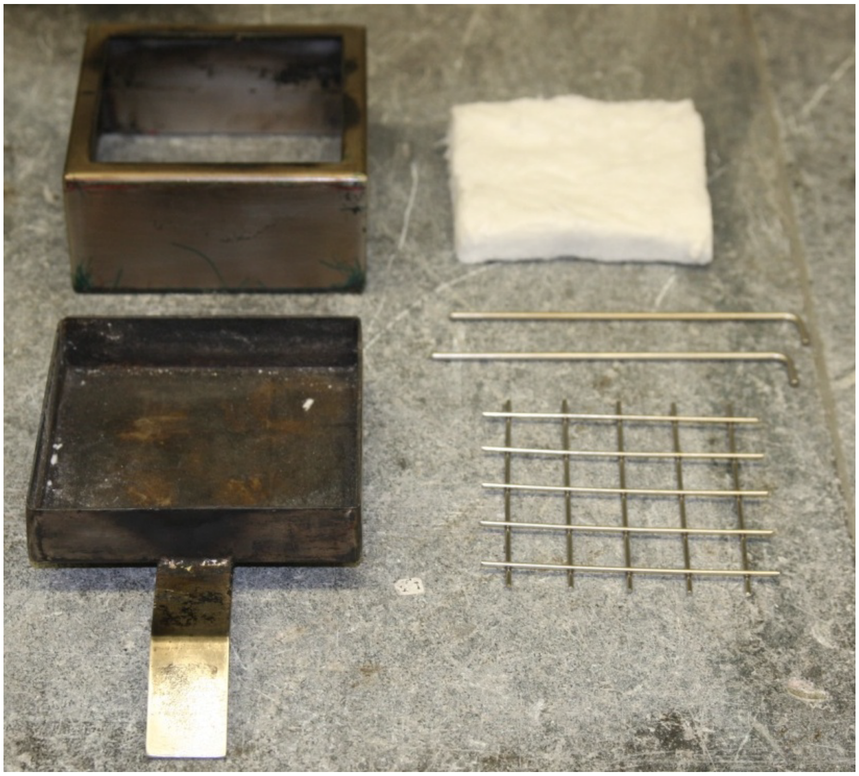


**Figure 4-2. Components of the cone calorimeter sample holder.**

**Figure 4-3. The completed assembly for uncoated cables.**

**Figure 4-4. Cable 802 coated with Flamemastic F-77.**

**Figure 4-5. Cable 802 coated with Carboline Intumastic 285.**

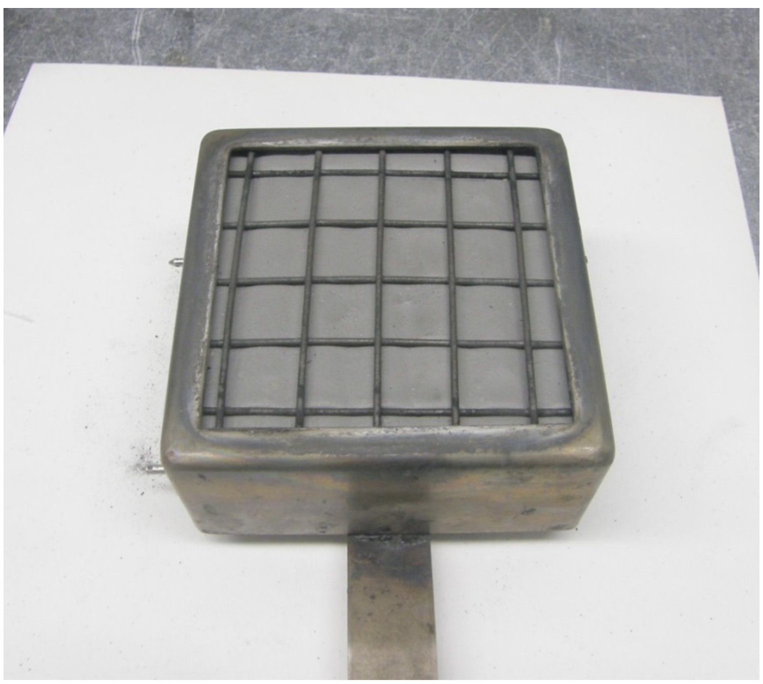


**Figure 4-6. Cable 802 coated with Vimasco 3i.**

## 4.2 Uncertainty

The uncertainty in the HRR measurement is a combination of the systematic uncertainty associated with the various measurements and assumptions underlying the calculation of the

HRR and the random uncertainty associated with the construction of the specimen holder and conduct of the experiment.

Enright and Fleischmann (Enright and Fleischmann 1999) analyzed the calculation method used in most cone calorimeter standards, including the one used here. They report that for a sample whose exact chemical composition is not known, the relative standard uncertainty (Taylor and Kuyatt 1994) is approximately 6 percent during the period in which the bulk of the sample is consumed. The key component of this estimate is the assumption that the heat of combustion based on oxygen consumption is 13,100 kJ/kg of oxygen consumed. This value has an estimated standard relative uncertainty of ±5 percent. The remaining uncertainty is due mainly to the measurement of oxygen consumption and a stoichiometric expansion factor.

To quantify the random uncertainty, three replicate measurements were made for each cable sample at each imposed heat flux value. The relative standard deviation for repeatability of the HRR measurements was 5.6 percent.

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

## 4.3 Results

The following pages briefly describe each set of cone calorimeter measurements, along with the measured HRRs for the cable samples at the two heat flux exposures. As part of the analysis, an effective heat release rate per unit area (HRRPUA) is calculated. Figure 4-7 displays the HRRPUA as a function of time for three replicate experiments. The solid curves indicate the actual experimental data. The dashed lines display a simplified time history of the data that is useful for modeling. The flat part of the simplified function is taken as the average HRR. To compute it, first define the total heat released per unit area, $Q''$, by integrating the HRR per unit area, $\dot{q}''$, over the duration of the experiment:

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

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

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

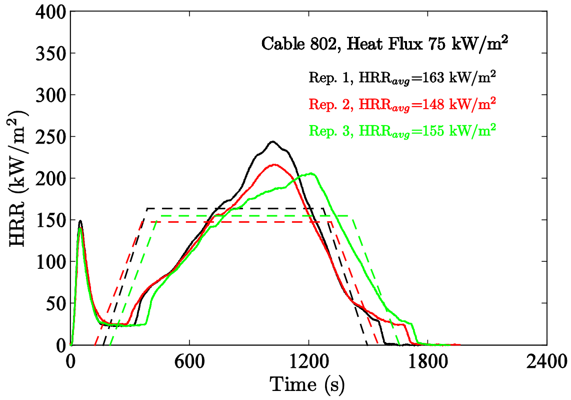



**Figure 4-7. Sample output from cone calorimeter.**

The average HRR per unit area is defined as the HRR during the period between $t_1$ and $t_2$ over which 80 percent of the total energy has been released:

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

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

Data plots of HRR for different cables are presented in Figure 4-8 to Figure 4-19.

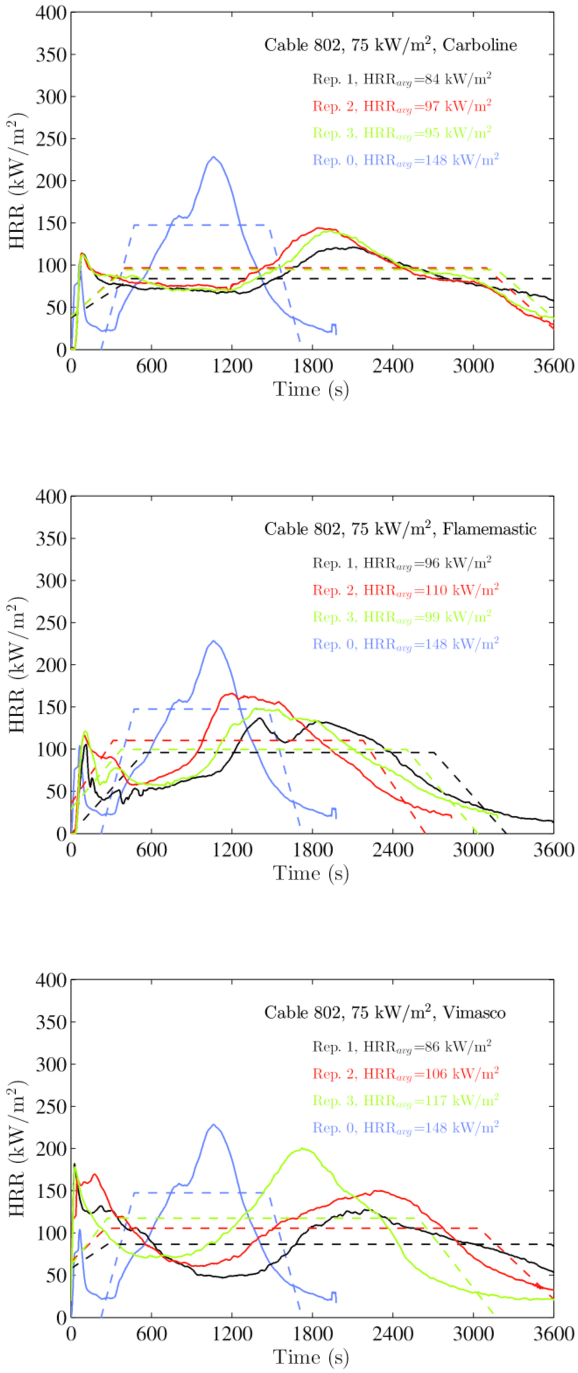



**Figure 4-8. Cone calorimeter results for cable 802. Rep. 0 denotes the uncoated sample.**

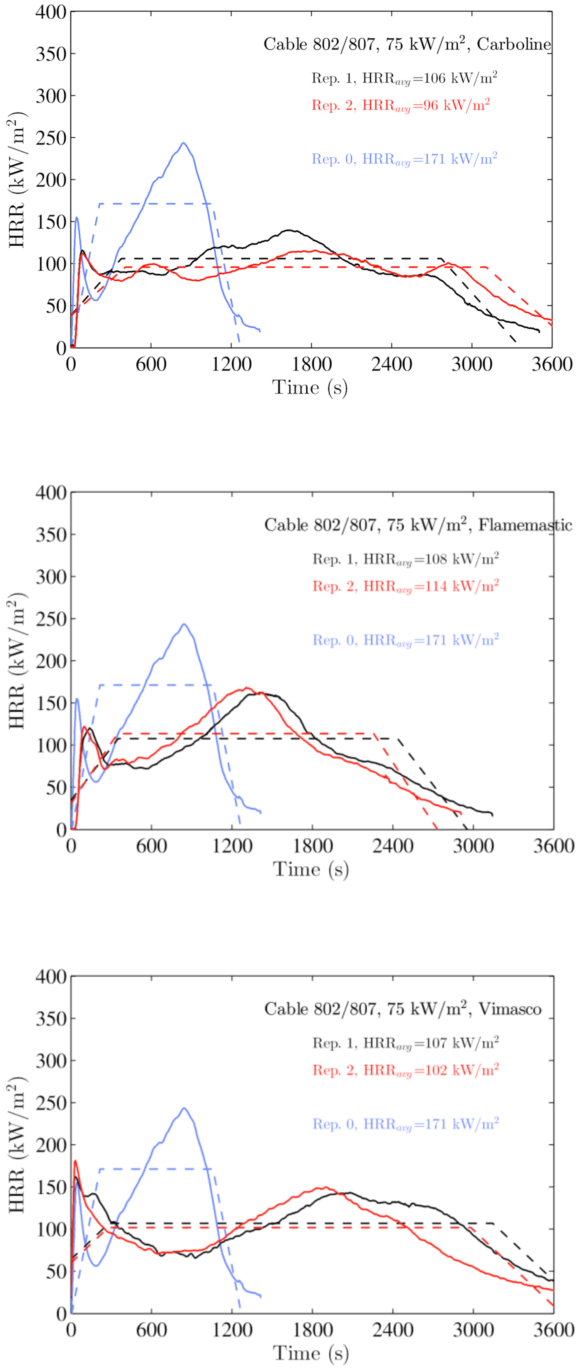



**Figure 4-9. Cone calorimeter results for cables 802 and 807, mixed. Rep. 0 denotes the uncoated sample.**

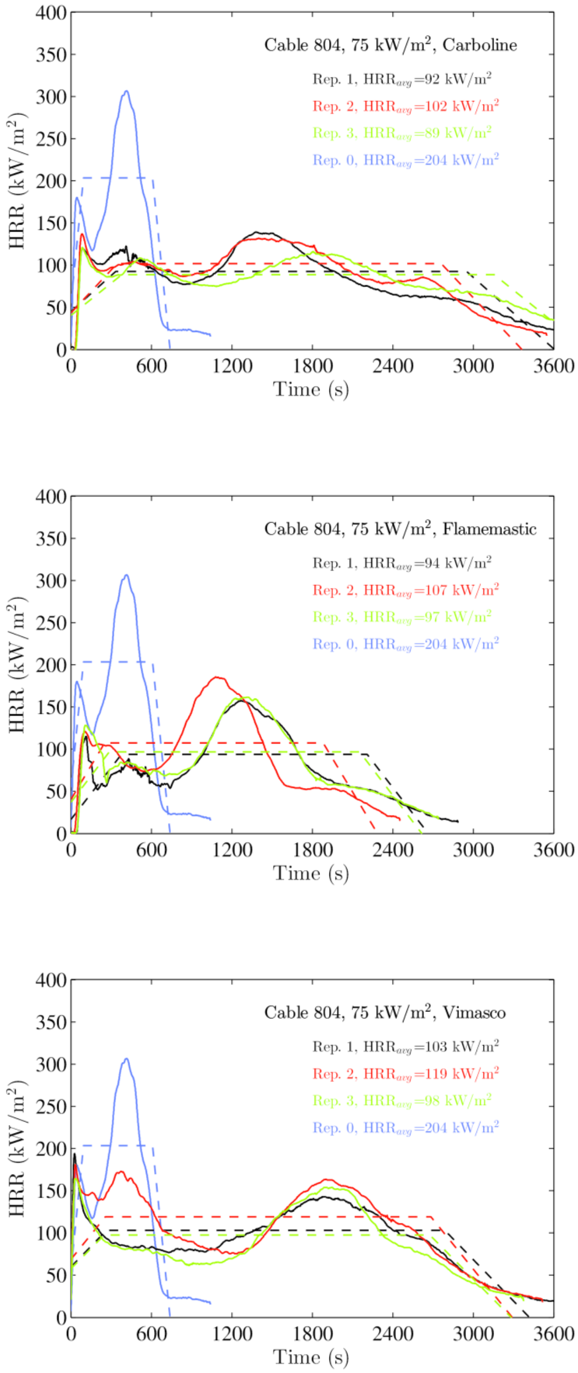



**Figure 4-10. Cone calorimeter results for cable 804. Rep. 0 denotes the uncoated sample.**

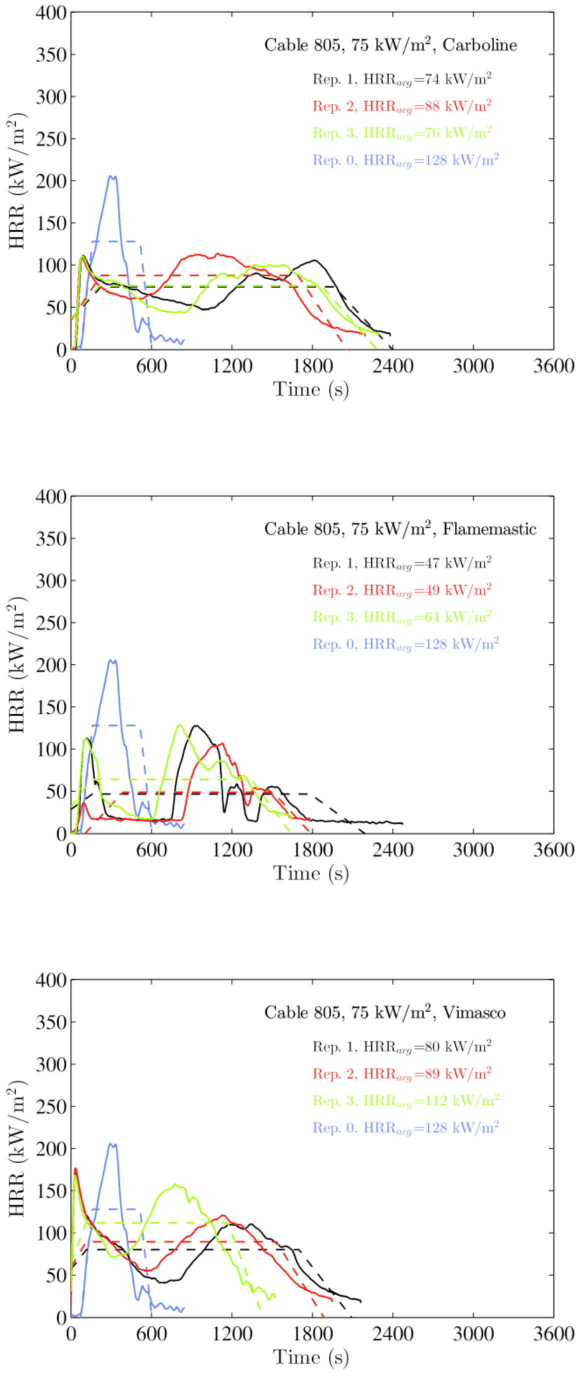



**Figure 4-11. Cone calorimeter results for cable 805. Rep. 0 denotes the uncoated sample.**

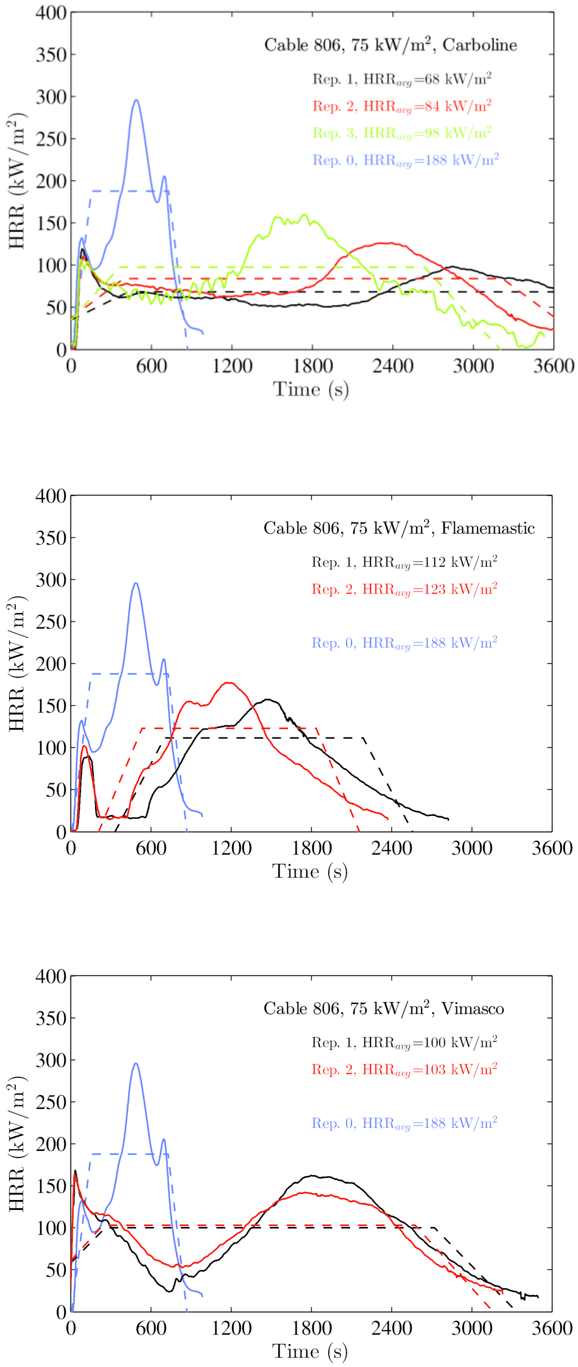



**Figure 4-12. Cone calorimeter results for cable 806. Rep. 0 denotes the uncoated sample.**

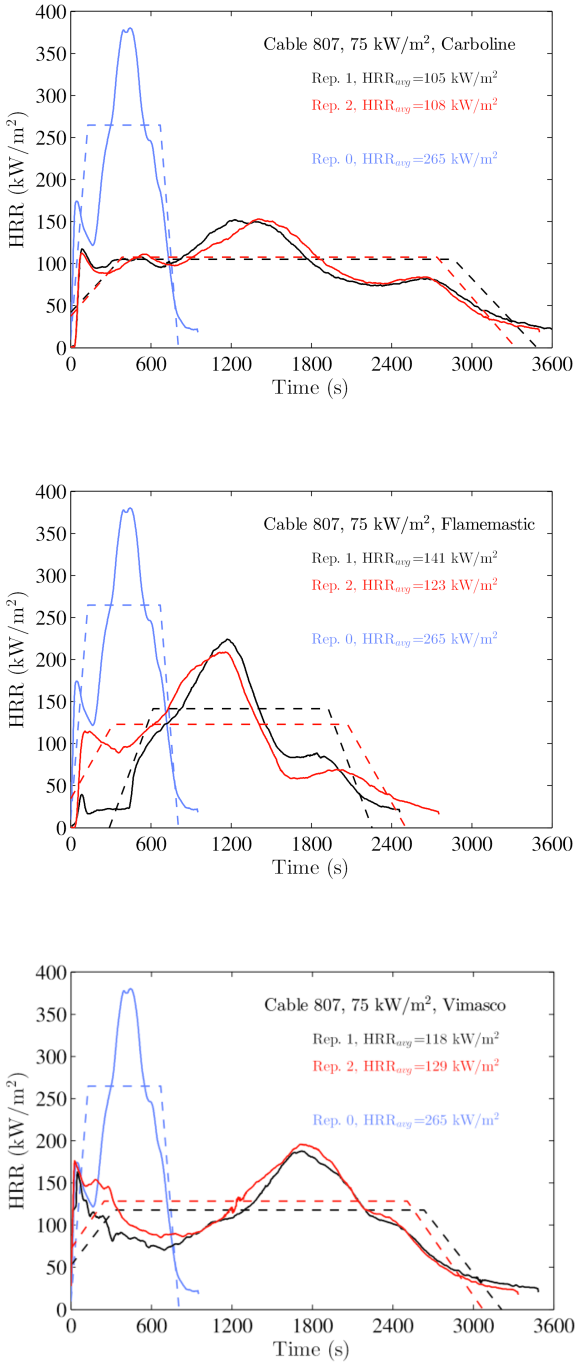



**Figure 4-13. Cone calorimeter results for cable 807. Rep. 0 denotes the uncoated sample.**

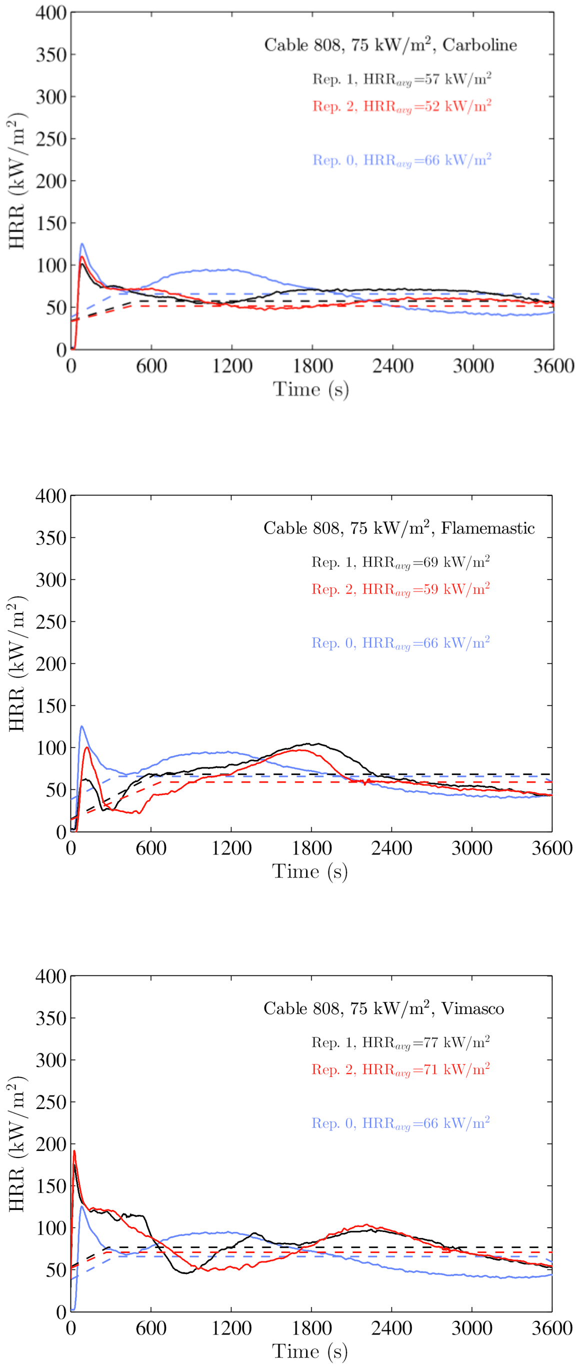



**Figure 4-14. Cone calorimeter results for cable 808. Rep. 0 denotes the uncoated sample.**

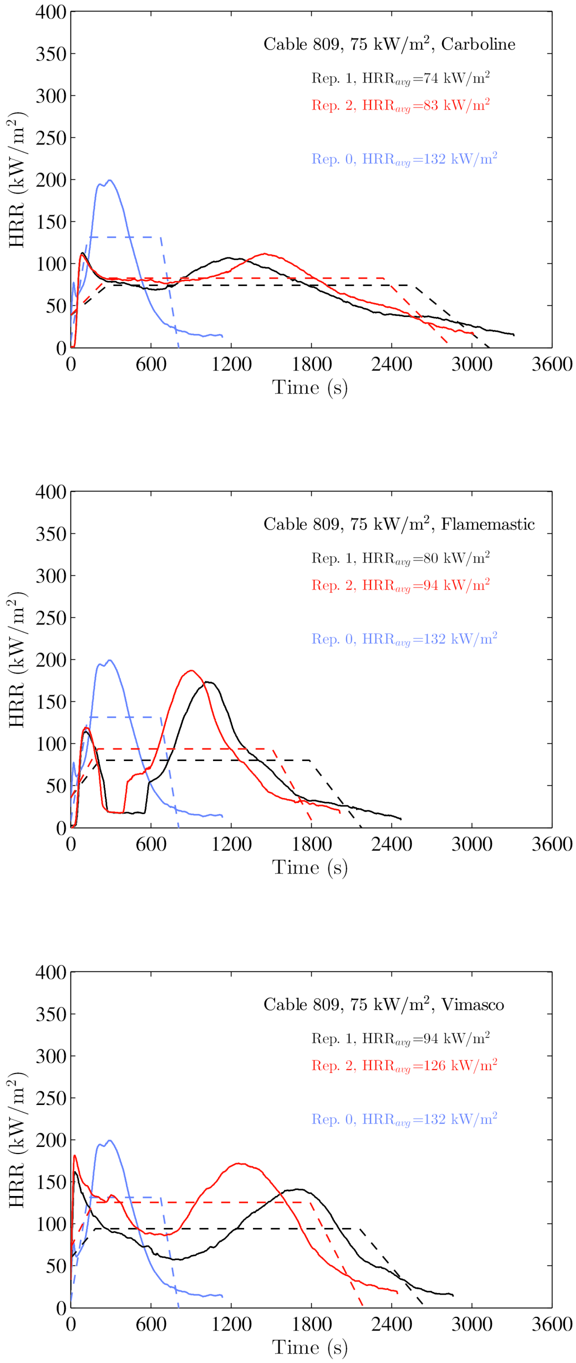



**Figure 4-15. Cone calorimeter results for cable 809. Rep. 0 denotes the uncoated sample.**

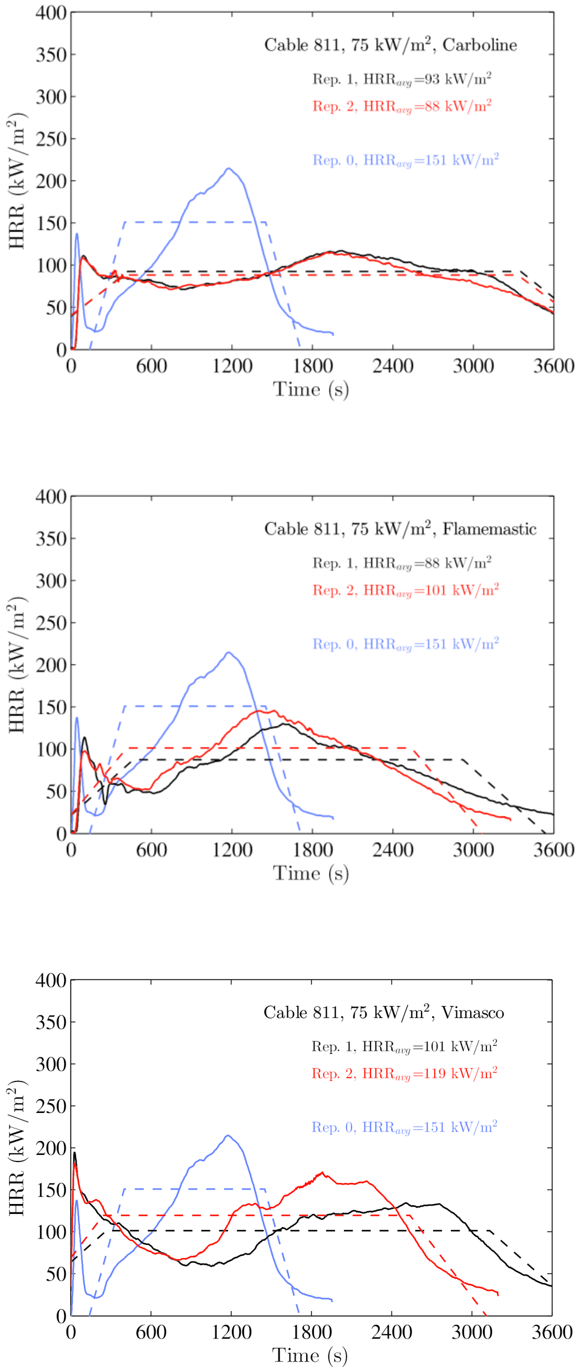



**Figure 4-16. Cone calorimeter results for cable 811. Rep 0. denotes the uncoated sample.**

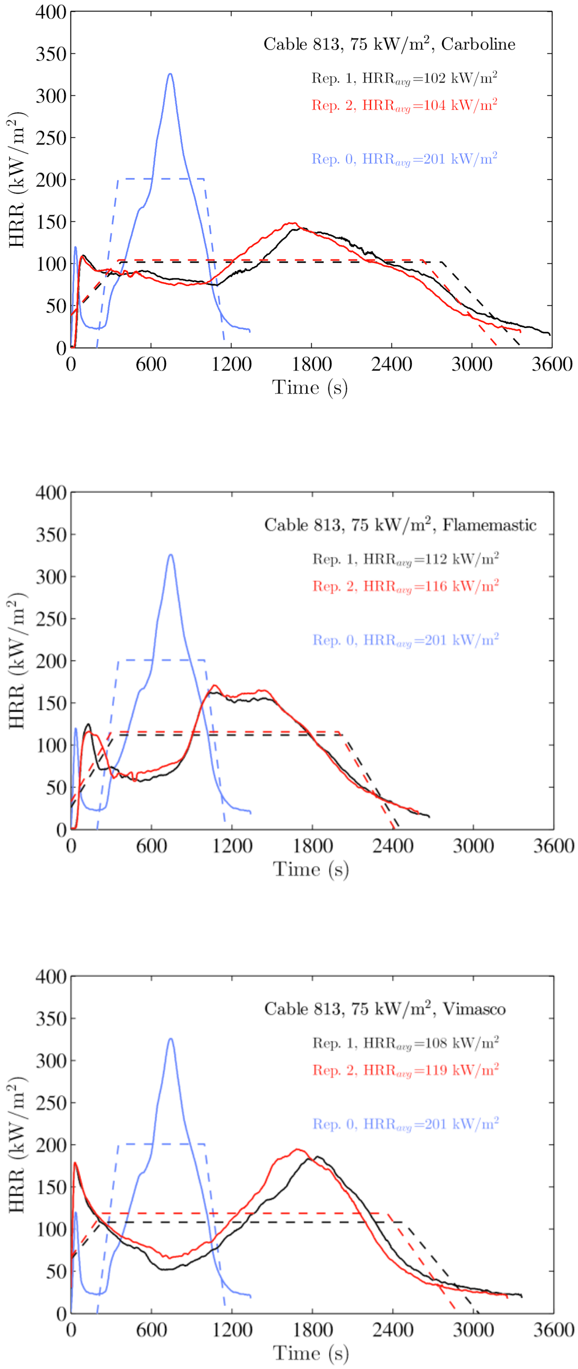



**Figure 4-17. Cone calorimeter results for cable 813. Rep. 0 denotes the uncoated sample.**

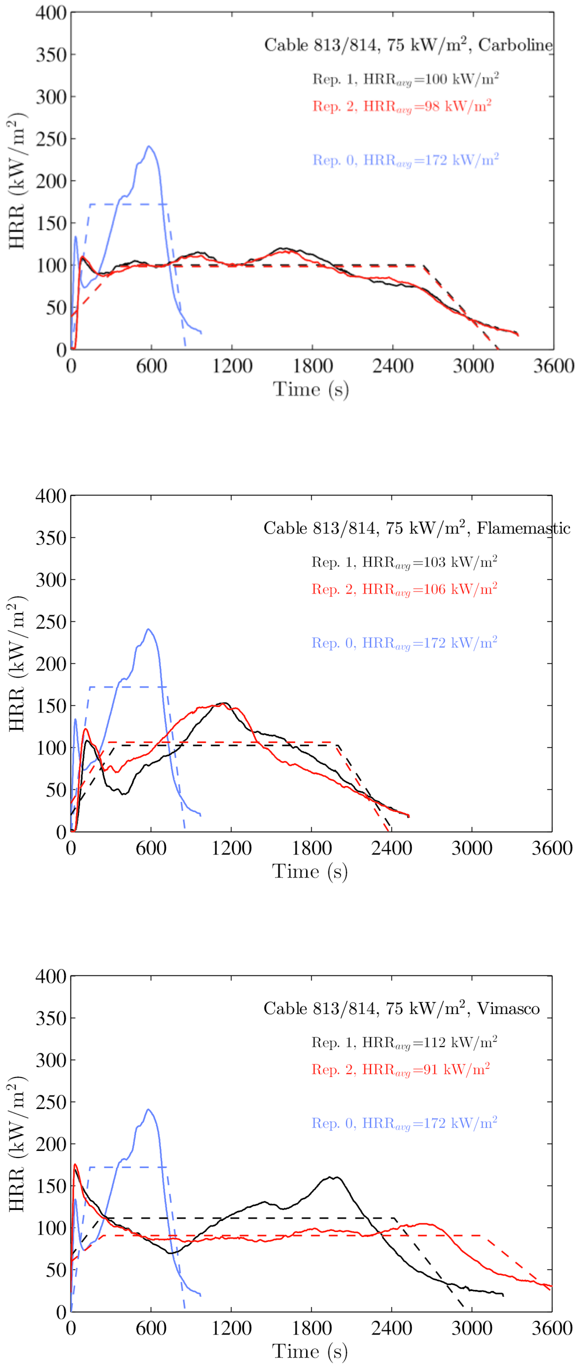



**Figure 4-18. Cone calorimeter results for cables 813 and 814, mixed. Rep. 0 denotes the uncoated sample.**

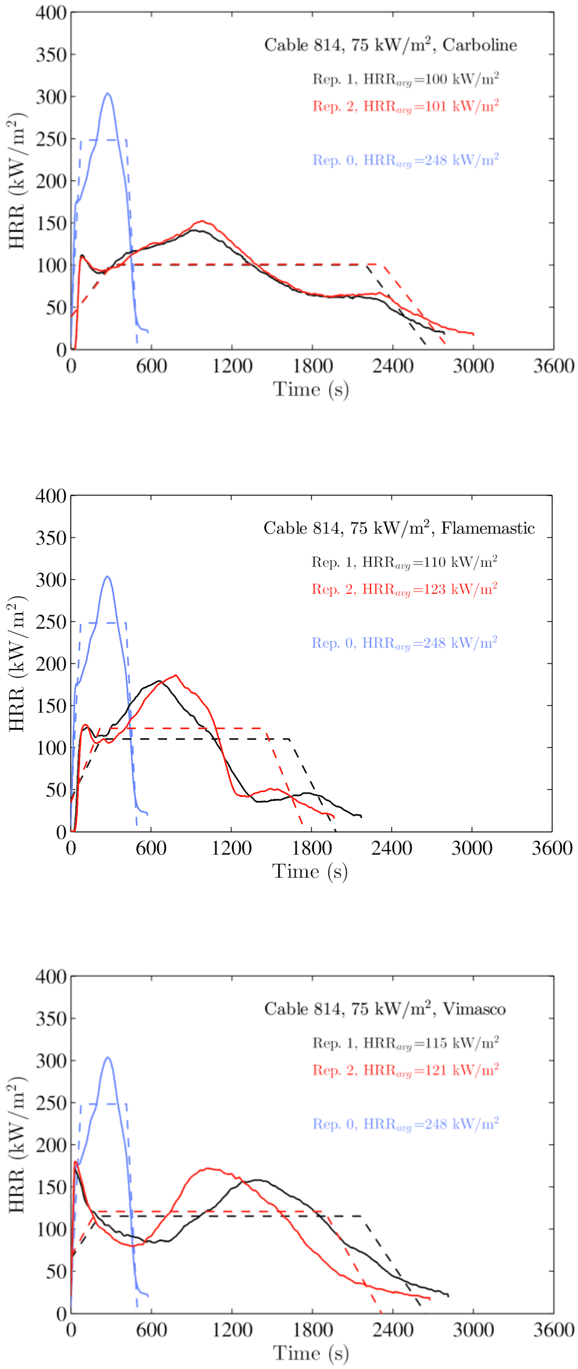



**Figure 4-19. Cone calorimeter results for cable 814. Rep. 0 denotes the uncoated sample.**

## 4.4 Summary

Table 4-1 presents the results of the cone calorimeter measurements of the coated cables. The HRR for each imposed heat flux is an average of the replicate experiments.

As a very rough approximation, for an imposed heat flux of 75 kW/$m^2$, the coatings doubled the ignition time, halved the peak HRR, and doubled the total energy released. Note that this imposed heat flux is relatively high, typical of a fully engulfing fire.

**Table 4-1. Summary of cone calorimeter measurements.**

| Cable No. | Insulation Material | Jacket Material | Diameter (mm) | Class | Average Time to Ignition (s) | | | | Average Heat Release Rate (kW/m²) | | | | Average Energy Released (MJ/m²) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Coating | | | | Coating | | | | Coating | | | |
| | | | | | None | A | B | C | None | A | B | C | None | A | B | C |
| 802 | XLPE | CSPE | 15.0 | TS | 22 | 48 | 49 | 10 | 148 | 92 | 102 | 103 | 184 | 332 | 260 | 355 |
| 804 | XLPE | PVC | 15.1 | Mix | 20 | 51 | 53 | 9 | 204 | 94 | 99 | 107 | 131 | 306 | 220 | 328 |
| 805 | Tefzel® | | 10.2 | TP | 81 | 48 | 65 | 10 | 128 | 79 | 53 | 94 | 56 | 160 | 87 | 155 |
| 806 | XLPE | XLPO | 12.2 | TS | 40 | 40 | 75 | 9 | 188 | 83 | 118 | 102 | 135 | 291 | 204 | 305 |
| 807 | PE | PVC | 15.0 | TP | 20 | 50 | 60 | 9 | 265 | 107 | 132 | 124 | 179 | 323 | 251 | 352 |
| 808 | VITA-LINK | | 19.6 | TS | 46 | 46 | 69 | 9 | 66 | 55 | 64 | 74 | 262 | 333 | 270 | 354 |
| 809 | SR | Aramid Braid | 14.5 | TS | 11 | 45 | 55 | 11 | 132 | 79 | 87 | 110 | 89 | 213 | 156 | 243 |
| 811 | XLPE | CSPE | 16.3 | TS | 21 | 48 | 62 | 10 | 151 | 91 | 95 | 110 | 198 | 332 | 269 | 353 |
| 813 | XLPE | CSPE | 12.7 | TS | 18 | 47 | 57 | 10 | 201 | 103 | 114 | 114 | 161 | 301 | 241 | 310 |
| 814 | PVC | | 11.3 | TP | 15 | 47 | 48 | 9 | 248 | 101 | 117 | 118 | 105 | 246 | 192 | 270 |
| -- | Mixture 802/807 | | -- | Mix | 17 | 46 | 52 | 10 | 171 | 101 | 111 | 105 | 180 | 320 | 276 | 363 |
| -- | Mixture 813/814 | | -- | Mix | 15 | 45 | 57 | 10 | 172 | 99 | 105 | 102 | 122 | 282 | 219 | 315 |

# 5. BENCH-SCALE IGNITION EXPERIMENTS

This section describes the experiments conducted to determine the ignition temperature of coated and uncoated cable samples.

## 5.1 Experimental Description

Cable ignition temperatures were measured in a Carbolite LHT 660 convection oven with a maximum operating temperature of 600°C (1,112°F). The oven door was modified to include an 8 cm (3 in.) diameter window, a pair of 0.6 cm (0.2 in.) gas inlet ports, and eight additional ports for passing instrumentation cables. To simulate an arc resulting from an electrical malfunction or short, the oven door was also outfitted with a pair of movable, ceramic-insulated electrodes which could be slid in and out. The contacts of the electrodes were located 2 cm to 3 cm (1 in.) above the cable specimens. These electrodes were powered by a solid-state induction coil providing direct current at voltages ranging from 15 kilovolts (kV) to 45 kV. The spark energy from this type of ignitor is on the order of 0.1 joule (J).

After the initial experiment with this configuration, it was discovered that the forced convection of the oven was too strong to support flaming combustion on the cable samples. This problem was solved by adding a stainless-steel shroud with a nominal diameter of 15 cm (6 in.) and nominal wall thickness of 2 mm (1/16 in.). Schematics of the final configuration are shown in Figure 5-1 and in the photographs in Figure 5-2 and Figure 5-3.

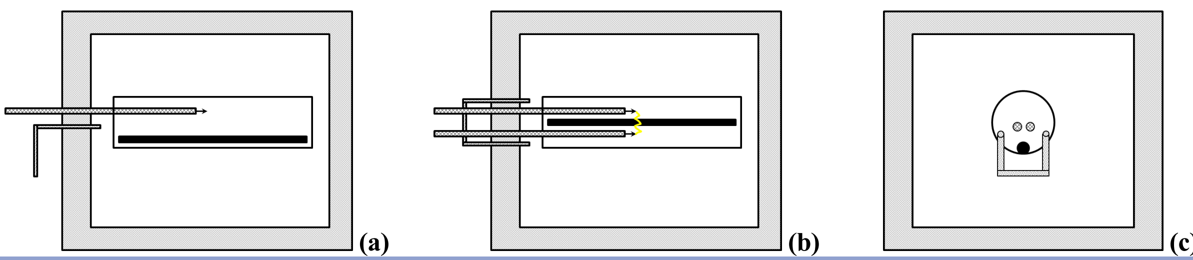



**Figure 5-1. Oven configuration showing electrodes, gas inlets, cylindrical shroud, and cable.**

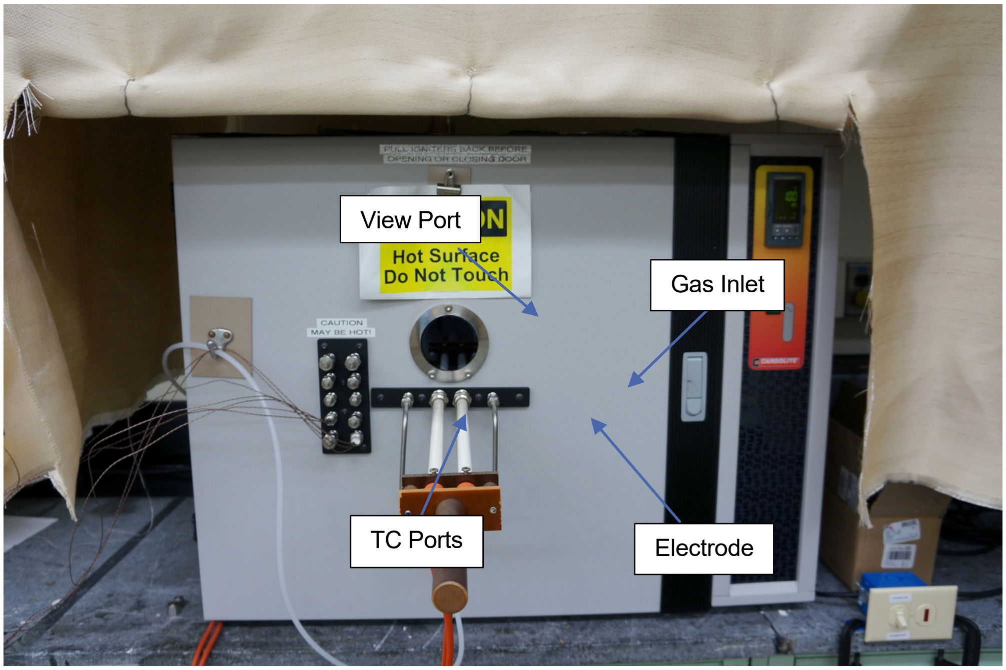



**Figure 5-2. Oven exterior showing electrodes, gas inlets, and thermocouple wire ports.**

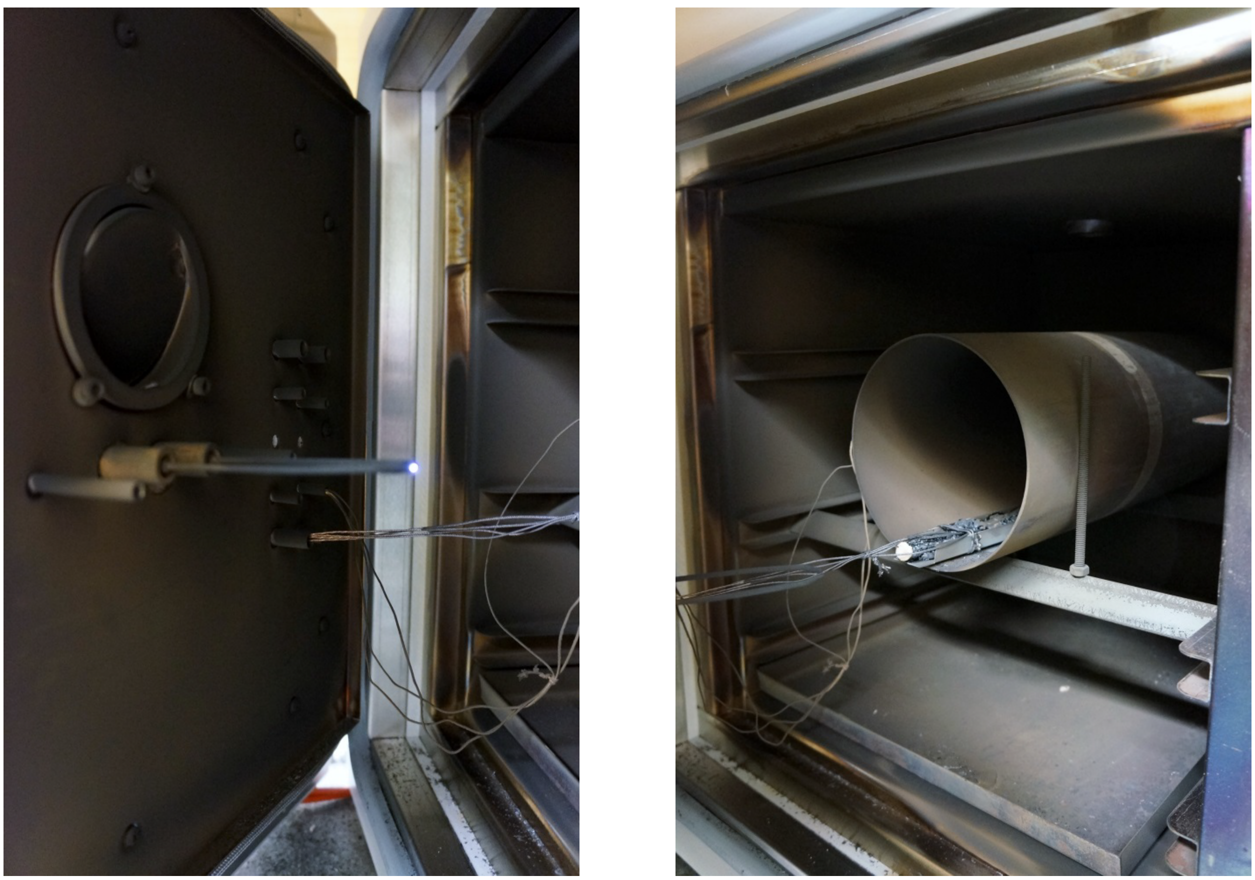


**Figure 5-3. Oven interior showing electrodes, gas inlets, thermocouples, shroud, and cable.**

Cable specimens were prepared in approximately 30 cm (12 in.)lengths. Their ends were capped with a commercial sealant named Omegabond 400. This procedure is consistent with ASTM D6113 (2003). Each specimen was instrumented with several Type K thermocouples (TCs) arranged in one of several configurations:

- One TC at the cable center, 1 cm (0.4 in.) from the cable end; one TC inserted under the cable jacket, 10 cm (4 in.) from the cable end; and one TC inserted into the cable center, 20 cm (8 in.) from the cable end. The cable end is that which is closest to the oven door.

- The previous configuration plus one TC attached to the outer surface, bent downward to provide contact pressure onto the outer surface of the jacket. This TC was 15 cm (6 in.) from the cable end.

- Four TCs inserted under the jacket, at azimuthal locations: 3, 6, 9, and 12 o'clock, distributed evenly along the cable length.

Figure 5-4 shows an example of a cable specimen prepared for an experiment.

**Figure 5-4. Cable prepared for experiment in disposable tray.**

TCs were prepared by welding a junction of approximately 0.5 mm on one end of a 2 m length of TC wire. Once an instrumented cable specimen was placed in the oven for the experiment, the unwelded ends of the TC wires were fed through the ports in the oven doors and then connected to the external data acquisition system. This system consisted of a National Instruments 9213 module connected to a portable computer running Labview data acquisition software. Data were acquired at 1 hertz. In addition to the TC readings from each cable specimen, temperatures were also recorded for the oven operating temperature, the temperature of the gas inside the metal shroud, and the temperature of the surface of the shroud. For reference, the ambient temperature in the lab was also recorded.

For most experiments, cable specimens were heated at the maximum rate available for the oven, approximately 5°C/min (41°F/min).

## 5.2 Ignition Temperature of Uncoated Cables

Cable ignition temperatures fell into four general categories:

(1) those with ignition temperatures around 300°C (572°F)

(2) those with ignition temperatures around 400°C (752°F)

(3) those with an ignition temperature around 400°C (752°F) when experimented individually, but ignited at a much lower temperature (325°C (617°F)) when multiple lengths were experimented

(4) those that exhibited intermittent ignition around 300°C (572°F), but sustained ignition around 350°C (662°F)

Figure 5-5 shows ignition temperatures for cables from the first three categories. For each cable, the temperature was recorded on the surface, under the jacket, near the center of the cable, and 1 cm (0.4 in.) from the end along the centerline. In general, the cables followed expected radial and axial heat transfer behavior; that is, temperatures measured at the external surface exceeded those measured under the jacket, which exceeded those at the cable center, which exceeded those at the cable end. Cables marked “x2” and “x6” were burned as pairs and as a group of six, respectively.

Also shown in Figure 5-5 is an instance of the third category, cable 817. When heated as a single 30 cm (12 in.) length, the cable does not ignite until a relatively high temperature of 430 °C (806 °F). However, if a second cable segment is added (817 x2), the ignition temperature falls to 345°C (653 °F). It is notable that this cable is relatively small in diameter compared to most of the others in the experiment (the other relatively small cable is 818). A similar behavior is observed for cable 809, which has a silicone rubber insulator and a braided fiber jacket, even though its diameter is similar to most of those experimented. When experimented individually, it does not ignite at all; however, when two lengths are experimented together, they ignite at a little over 400°C (752°F). Cable 818, on the other hand, while relatively small compared to the other cables, does not significantly change its ignition temperature when a second length is added (818 x2).

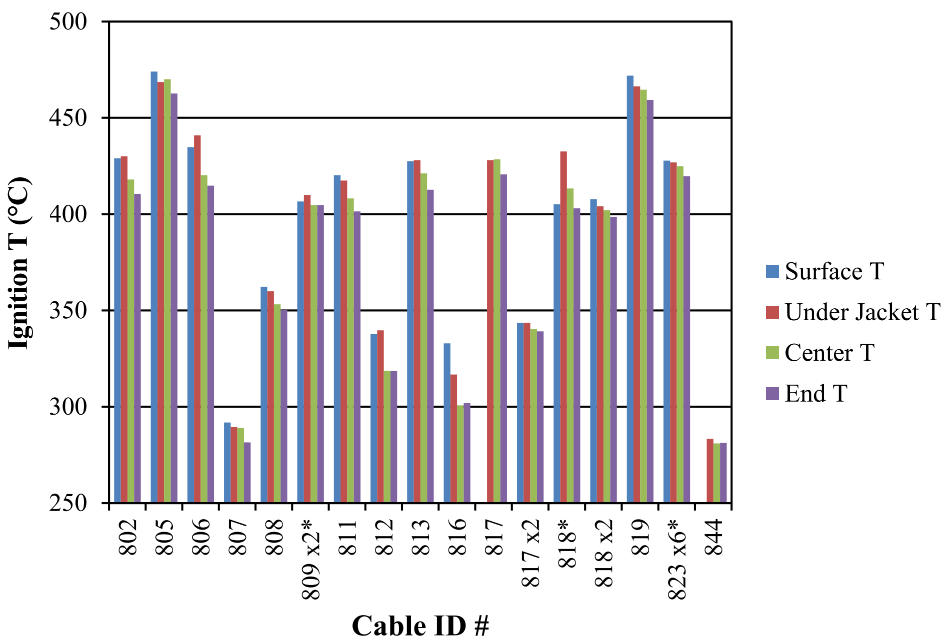



**Figure 5-5. Average measured temperatures at the time of ignition. An asterisk indicates a single cable. Except where noted in the text, uncertainties are 1 to 3 percent.**

Figure 5-6 shows ignition temperatures for cables from the fourth category, intermittent ignition transitioning to sustained ignition. In each case, flames or a significant air temperature rise were observed at a relatively low oven temperature, but they did not sustain. Once the cables in this category had heated to a relatively higher temperature, then flames and a high air temperature were sustained. All these cables contained polyvinyl chloride (PVC) in one or both polymer layers, which presumably helped prevent sustained ignition until higher temperatures were reached. Two other cables (807 and 818) used PVC in the jacket, but both used polyethylene (PE) for the insulation. Of these two, cable 807 ignited near 300°C (572°F) and 818 near 400°C (752°F). However, even though cable 818 was relatively small in diameter, increasing the cable loading had little effect on ignition temperature.

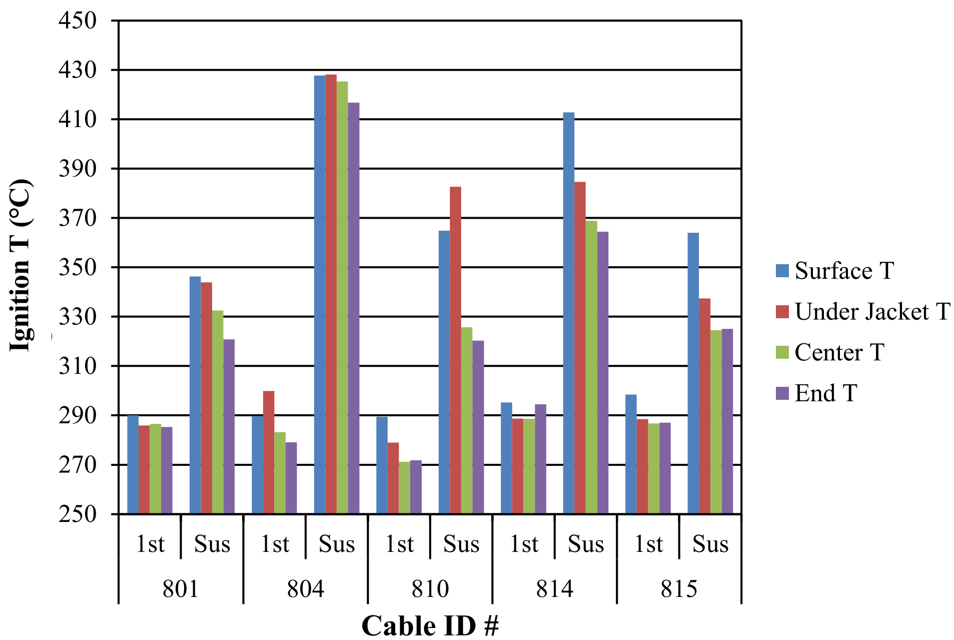



**Figure 5-6. Measured temperatures at the time of ignition—first temperature rise and sustained temperature rise. Except where noted in the text, uncertainties are 1 to 3 percent.**

Two of the cables that ignited at high temperature (806 and 818) and one with intermittent to sustained ignition (810) recorded their highest temperature under the jacket at the time of ignition. This temperature even exceeded the oven temperature, indicating that the cable experienced self-heating by an exothermic reaction (smoldering) of the polymer before flaming combustion. In general, “ignition” was accompanied by a sharp rise in the measured air temperature near the cable. In the cases where the highest temperature was measured under the jacket, there was no corresponding sharp rise in the air temperature.

### 5.2.1 Observations

The surface temperature measurements required that the TC be taped to the outside of the cable and then bent downward to apply light pressure to the jacket surface to ensure good thermal contact. However, during the experiment, it was possible for the jacket to pull away from the TC, rendering these measurements less reliable than the other three locations where the TC was more firmly fixed. Therefore, in some cases it was necessary to infer the surface temperature from the other three cable temperatures.

In cases where the under-jacket temperature exceeded all others at the time of ignition, it may be worthwhile to consider whether this represents a thermal runaway scenario, in which a local exothermic reaction (smoldering) inside the cable provides sufficient thermal feedback to drive the entire cable to full ignition. If this is the case, then it may be more meaningful to define the ignition temperature as the temperature when this under-jacket temperature rise begins, which would be tens of degrees lower than that measured at the actual time of sustained ignition.

There is no strong correlation between the results presented in this section and those from the cone calorimeter experiments (HRR and time to ignition). This is not wholly unexpected, as HRR is more indicative of the consequence of ignition rather than its likelihood. A relation between ignition temperature and time to ignition would be more understandable, but since the heating rate in the cone calorimeter is around 100 times faster than in the oven, the controlling mechanism (heat transfer versus material properties) is different. Within category 1 (ignition temperatures around 300°C (572°F)), there is a weak correlation between higher ignition temperatures and longer times to ignition.

In a single experiment with a reduced heating rate of 2 °C/min (36 °F/min), cable 844 never ignited, but did experience significant self-heating as the oven reached 400°C (752°F).

### 5.2.2 Repeatability/Uncertainty

Apart from cables 809 x2, 818, and 823 x6, all cable experiments were conducted at least twice for each cable (or multiples of the same cable). The relative standard uncertainty of the measured ignition temperature (expressed as the increase above ambient temperature in degrees Celsius) for each location on a given cable was 3 percent, with the exceptions of 808, 812, 817 x2, and 819, which were 6 percent.

Finally, it was observed that it was not always possible to precisely align the cable rotationally so that the surface and under-jacket locations were always at the top. To test the significance of orientation, several experiments were conducted (with an unrated residential cable) in which TCs were installed under the cable jacket at the top, bottom, and lateral locations. In the axial direction, they were spaced evenly along the cable. Figure 5-7 shows the results from these experiments. These results show that the variation in temperature around the cable is no greater than the variation between runs for any given location.

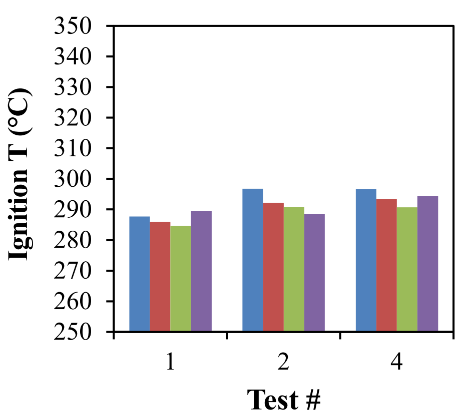



**Figure 5-7. Measured temperature at the time of ignition for the unrated residential cables. Colored bars indicate TC azimuth position at 90° intervals.**

### 5.2.3 Summary of Uncoated Cable Ignition Temperature Measurements

The ignition temperature was measured for 20 electrical cables. The cables fell into four general categories: (1) ignition temperatures around 300°C (572°F), (2) ignition temperatures around 400°C (752°F), (3) an ignition temperature around 400°C (752°F) when tested individually, but with a much lower ignition temperature 325°C (617°F), when multiple lengths were used in the experiment, and (4) intermittent ignition around 300°C (572°F), followed by heating until sustained ignition was achieved around 350°C (662°F). Polymer material was an indicator only of the fourth category, including all cables with PVC and without PE. XLPE/CSPE combinations were found in both the higher and lower ignition temperature categories. The single cable using Tefzel fell into the higher temperature ignition category, but additional cable types using the same material would need to be tested to confirm whether this is truly a material property.

Table 5-1 through Table 5-3 summarize the cable surface temperature at the time of ignition.

**Table 5-1. Summary of cable surface ignition temperatures—high temperature.**

| Cable # | Manufacturer | Insulation | Jacket | $T_{ig}$ (°C) |
|---|---|---|---|---|
| 802 | Rockbestos | XLPE | CSPE | 429 |
| 805 | Cable USA | Tefzel | Tefzel | 474 |
| 806 | Rockbestos | XLPE | XLPO | 435 |
| 809 x2 | First Capitol | SR | Aramid Braid | 410 |
| 811 | Rockbestos | XLPE | CSPE | 420 |
| 813 | Rockbestos | XLPE | CSPE | 428 |
| 817 | Rockbestos | XLPE | CSPE | 428 |
| 818 x2 | Rockbestos | PE | PVC | 408 |
| 819 | First Capitol | SR | Glass Braid | 472 |
| 823 x6 | Rockbestos | XLPE | - | 428 |

**Table 5-2. Summary of cable surface ignition temperatures—low temperature.**

| Cable # | Manufacturer | Insulation | Jacket | $T_{ig}$ (°C) |
|---|---|---|---|---|
| 807 | General Cable | PE | PVC | 292 |
| 808 | Rockbestos | VITA-LINK | VITA-LINK | 362 |
| 812 | Rockbestos | XLPE | CSPE | 338 |
| 816 | Rockbestos | XLPE | CSPE | 333 |
| 817 x2 | Rockbestos | XLPE | CSPE | 344 |
| 844 | General Cable | PVC | PVC | 285 |

**Table 5-3. Summary of cable surface ignition temperatures—transition.**

| Cable # | Manufacturer | Insulation | Jacket | $T_{int}$ (°C) | $T_{sus}$ (°C) |
|---|---|---|---|---|---|
| 801 | General Cable | PVC/Nylon | PVC | 290 | 346 |

| | | | | | |
|---|---|---|---|---|---|
| 804 | General Cable | XLPE | PVC | 290 | 428 |
| 810 | General Cable | PVC/Nylon | PVC | 289 | 365 |
| 814 | General Cable | PVC | PVC | 295 | 413 |
| 815 | General Cable | PVC/Nylon | PVC | 298 | 364 |

## 5.3 Ignition Temperature of Coated Cables

Coated cable ignition temperatures were measured in the same oven that was used to measure the ignition temperature of uncoated cables.

### 5.3.1 Instrumentation and Application of the Coatings

The cables were cut into approximately 20 cm (8 in.) segments and arranged in groups of three. The central segment was instrumented with several Type K TCs with bead diameters of approximately 0.5 mm (0.02 in.). Figure 5-8 shows an example of a cable segment prepared for experimentation without coatings. One TC was placed on the cable surface, just underneath the coating. One was placed just under the cable jacket. One was placed as close to the cable center, or center conductor, as possible. When a coating was applied, one TC was buried inside the coating, roughly halfway between the exterior and the cable jacket.

Once instrumented, the cable, along with two noninstrumented cables, was coated with one of the four coating materials. This configuration represents cables arranged side by side in a single row within a tray. Typically, coatings are applied over the top and bottom of an entire row or rows of cables. The minimum dry thickness was 1.6 mm (1/16 in.). Figure 5-9 shows the coated cable segments.

The cable specimens were heated at the maximum rate of the oven, approximately 5°C/min (41°F/min). Ignition was indicated by a sudden rise in temperature of the various TCs and a visual observation of flames through the oven window.

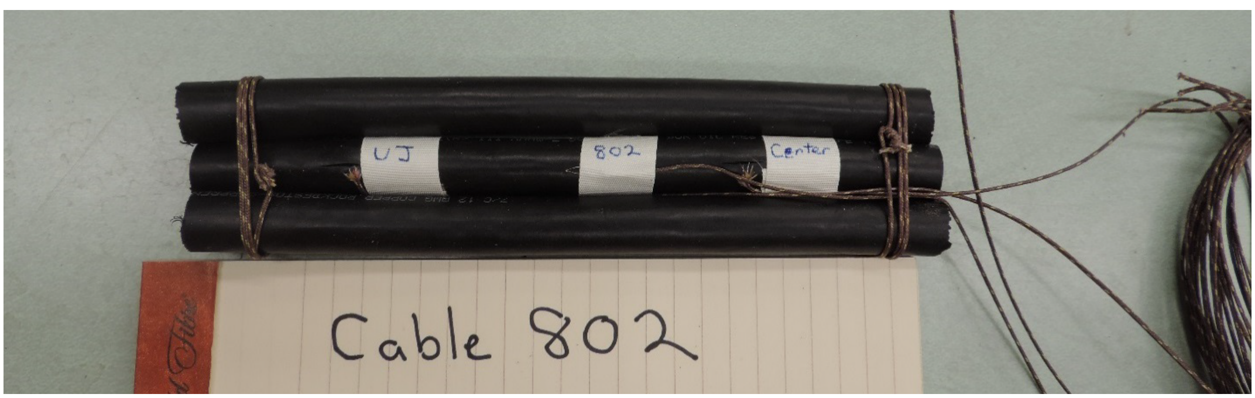



**Figure 5-8. Instrumentation of a cable segment for an uncoated experiment.**

**Figure 5-9. Cables coated with Carboline Intumastic 285.**

### 5.3.2 Results

The four different cables and four different cable coatings listed in Table 5-4 were tested. Cable 802 is a thermoset cable with a relatively high ignition temperature. Cables 805 and 807 are TP cables with a significant difference in ignition temperature when uncoated. Cable 814 is a TP cable with a relatively low ignition temperature. Table 5-4 summarizes the results of the ignition experiment.

**Table 5-4. Results of oven ignition experiments.**

| Cable | Coating | Temperature at Ignition (°C) | | |
|---|---|---|---|---|
| | | Jacket | Under Jacket | Cable Center |
| 802 | None | 416 | 416 | 416 |
| 802 | Carboline | 444 | 436 | 430 |
| 802 | Flamemastic | 409 | 400 | 400 |
| 802 | FS15 | 292 | 290 | 288 |
| 802 | Vimasco | 427 | 413 | 413 |
| 805 | None | 483 | 483 | 483 |
| 805 | Carboline | 326 | 318 | 318 |
| 805 | Flamemastic | 433 | 433 | 433 |
| 805 | FS15 | 318 | 314 | 311 |
| 805 | Vimasco | 481 | 480 | 479 |
| 807 | None | 292 | 292 | 292 |
| 807 | Carboline | 439 | 454 | 454 |
| 807 | Flamemastic | 363 | 368 | 360 |
| 807 | FS15 | 391 | 377 | 355 |
| 807 | Vimasco | 307 | 311 | 307 |
| 814 | None | 335 | 335 | 300 |
| 814 | Carboline | 492 | 492 | 493 |
| 814 | Flamemastic | 351 | 350 | 360 |

| Cable | Coating | Temperature at Ignition (°C) | | |
| --- | --- | --- | --- | --- |
| | | Jacket | Under Jacket | Cable Center |
| 814 | FS15 | 309 | 320 | 314 |
| 814 | Vimasco | 288 | 288 | 288 |

# 6. FULL-SCALE VERTICAL FLAME SPREAD EXPERIMENTS

This section includes the results of a modified version of IEEE Standard 1202.

## 6.1 Experimental Description

Figure 6-1 shows the vertical flame spread apparatus. An approximately 0.3 m (12 in.) wide, 2.4 m (8 feet (ft)) long tray was positioned vertically above a 1.2 m by 1.2 m (4 ft by 4 ft) base made of plywood topped with gypsum board. Three 2.4 m (8 ft) by 1.2 m (4 ft) panels of gypsum board formed an enclosure to minimize drafts and spurious air currents. In the IEEE standard test, this is accomplished using a four-sided brick enclosure.

The cables were tied to the cable rungs using wire and separated by half the cable diameter (Figure 6-2). IEEE Standard 1202 dictated the number of cable segments. The vertical tray was locked in place at both top and bottom by angle iron (Figure 6-3).

A ribbon burner (Figure 6-4) was purchased from the American Gas Furnace Company, Inc., of Elizabeth, New Jersey. It is nominally 30 cm (12 in.) wide with a 25 cm (10 in.) wide orifice. A mixture of air and propane was supplied to the burner. The flow rate of propane was 220 $cm^3/s$ ± 8 $cm^3/s$ (28 $ft^3/h$ ± 1 $ft^3/h$), and the flow rate of air was 1,280 $cm^3/s$ ± 80 $cm^3/s$ (163 $ft^3/h$ ± 10 $ft^3/h$). The temperature in the laboratory during the experiments was approximately 25°C (77°F). This air/fuel mixture produced a flame with an HRR of 20 kW ± 1 kW.

The burner was positioned approximately 0.3 m (1 ft.) above the base of the cable tray as defined in IEEE Standard 1202. As shown in Figure 6-4, the burner was angled upward approximately 20° from the horizontal and abutted the rails of the cable tray so that there was approximately 8 cm (3 in.) separating the burner orifice from the cable surface. The HRR of the ensuing fire was measured using oxygen consumption calorimetry.

The coatings were either painted (Figure 6-5), sprayed (Figure 6-6), or troweled (Figure 6-7) onto the cables depending on the thickness of the coating. The coating FS15 was either painted or sprayed on, Flamemastic 77 and Vimasco 3i were painted on, and Carboline Intumastic 285 was troweled on. As a consequence of troweling, the Carboline coating was much thicker than the other three coatings. At its manufactured consistency, it could not be applied in a thinner coat and was considerably thicker than the manufacturer's recommended dry thickness of 1.6 mm (1/16 in.).

The experiments were divided into series I and series II, and the cables were exposed to flames for 20 minutes. Table 6-1 shows the experiment matrix.

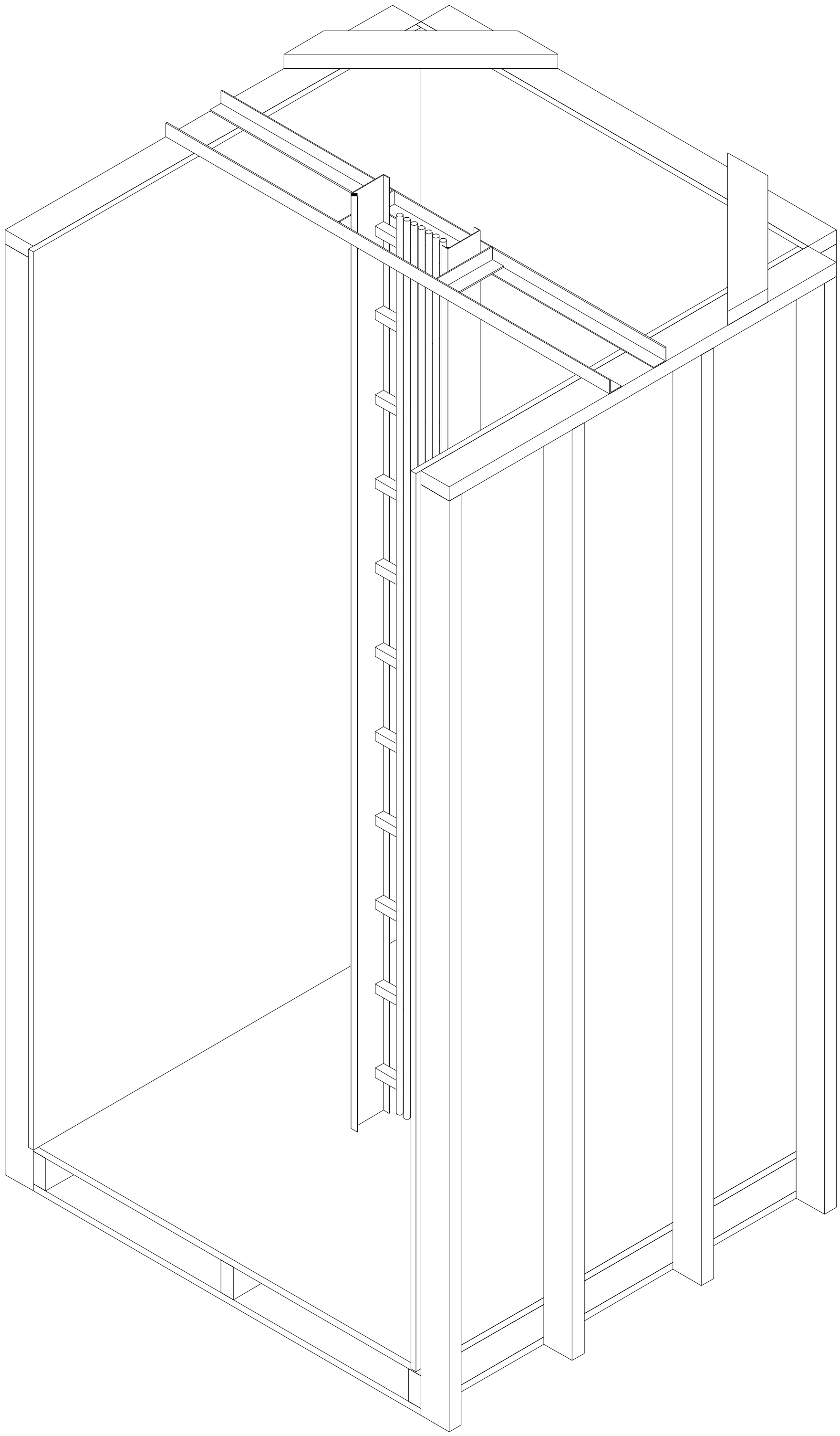


**Figure 6-1. Drawing of the vertical flame experiment apparatus.**

**Figure 6-2. Typical configuration of uncoated cables attached to a tray.**

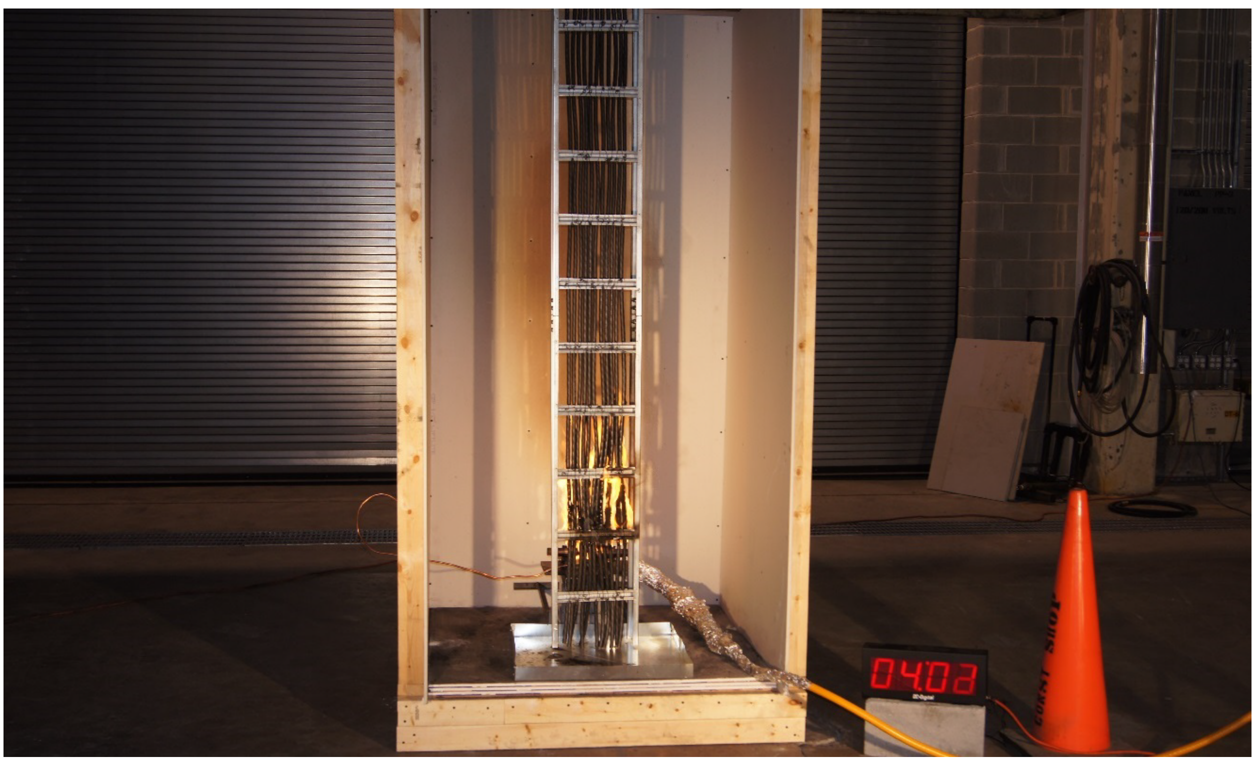


**Figure 6-3. Photograph of vertical flame spread experiment apparatus.**

**Figure 6-4. Photograph of propane line burner.**

**Figure 6-5. Application of FS15 cable coating by paintbrush.**

Figure 6-6. Applying the cable coating FS15 via a sprayer.

Figure 6-7. Cross-sectional view of the three different cables coated with Carboline.

**Table 6-1. Vertical flame spread results.**

| Experiment Number | Cable Number | Coating | Spread Distance |
|---|---|---|---|
| I-3 | 900 | None | Top of tray |
| I-4 | 900 | None | Top of tray |
| I-5 | 900 | None | Top of tray |
| I-6 | 900 | Flamemastic | Approx. 1 m |
| I-7 | 900 | Carboline | 0 |
| I-8 | 900 | FS15 | 0 |
| I-9 | 900 | Vimasco | Approx. 2 m |
| I-10 | 900 | None | Top of tray |
| I-11 | 900 | Vimasco | 0 |
| I-12 | 902 | None | Top of tray |
| I-13 | 813 | None | 0 |
| I-14 | 900 | Flamemastic | 0 |
| I-15 | 902 | None | Top of tray |
| I-16 | 900 | Vimasco | 0 |
| I-17 | 900 | FS15 | 0 |
| I-18 | 900 | Carboline | 0 |
| I-19 | 900 | Flamemastic | 0 |
| I-20 | 813 | None | 0 |
| I-21 | 900 | FS15 | 0 |
| II-1 | 900 | None | Top of tray |
| II-2 | 900 | FS15 | 0 |
| II-3 | 900 | Flamemastic | 0 |
| II-4 | 900 | Vimasco | 0 |
| II-5 | 900 | Carboline | 0 |
| II-6 | 813 | None | 0 |
| II-7 | 902 | None | Top of tray |
| II-8 | 902 | FS15 | 0 |
| II-9 | 902 | Flamemastic | 0 |
| II-10 | 902 | Vimasco | 0 |
| II-11 | 902 | Carboline | 0 |
| II-12 | 900 | None | Top of tray |
| II-13 | 900 | Vimasco | 0 |
| II-14 | 900 | Flamemastic | 0 |
| II-15 | 900 | Vimasco | 0 |
| II-16 | 813 | FS15 | 0 |
| II-17 | 813 | Vimasco 3i | 0 |
| II-18 | 813 | None | 0 |
| II-19 | 813 | Carboline | 0 |
| II-20 | 813 | Flamemastic | 0 |

## 6.2 Heat Release Rate Measurements

The following pages show the measured HRRs of the vertical flame spread testing. The cables selected for the experiments were as follows:

- **Cable 900**, a PE-insulated, PVC-jacketed, seven-conductor control cable. It is not qualified under IEEE Standard 383, "Standard for Qualifying Electric Cables and Splices for Nuclear Facilities," and it was selected specifically because it fails the modified IEEE Standard 1202 flame spread test.

- **Cable 902**, a PE-insulated, PVC-jacketed, three-conductor instrument cable. It was manufactured in 1975 and is not qualified under IEEE Standard 383 qualified. Like cable 900, it was seen as a good candidate to test the performance of the coatings.

- **Cable 813**, an XLPE-insulated, CSPE-jacketed, 12-conductor instrument cable. It is qualified under IEEE Standard 383. Normally, a cable such as this would not require a coating because it passes the vertical flame spread test. However, it was used in the testing simply as a means of evaluating the performance of a range of cables.

### 6.2.1 Cable 900 Uncoated

Figure 6-8 displays the HRR of cable 900 with no coating applied. In experiment I-3, the burner was positioned on the side of the tray where the rungs are attached (see Figure 6-9). For all other tests, the burner was positioned opposite to the rung side, as called for in IEEE Standard 1202 (see Figure 6-10). In experiment I-10, a slight draft in the laboratory caused the fire to spread up one side of the tray and then gradually spread to the other.

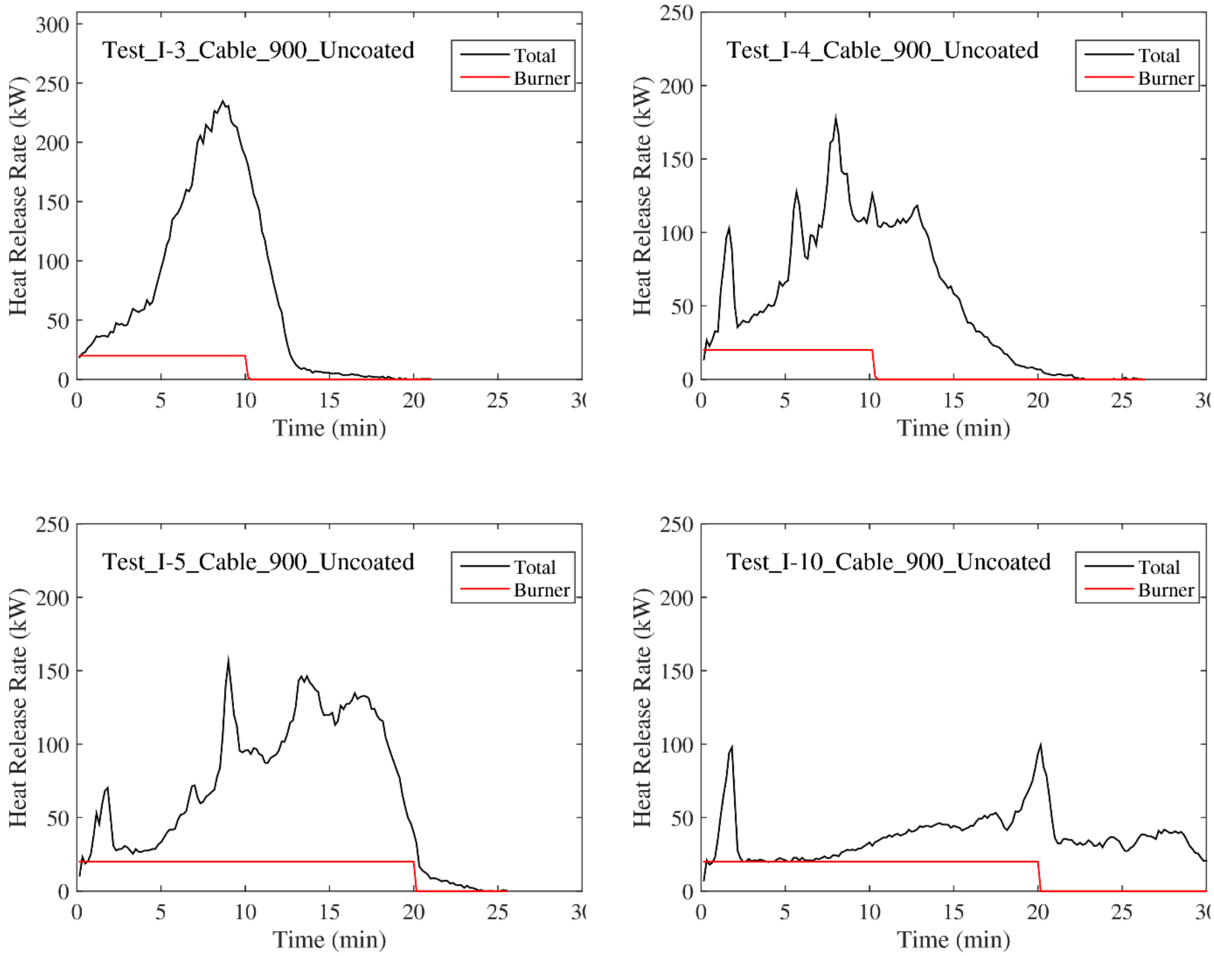



**Figure 6-8. HRR of vertical flame spread experiments for cable 900 with no coating applied.**

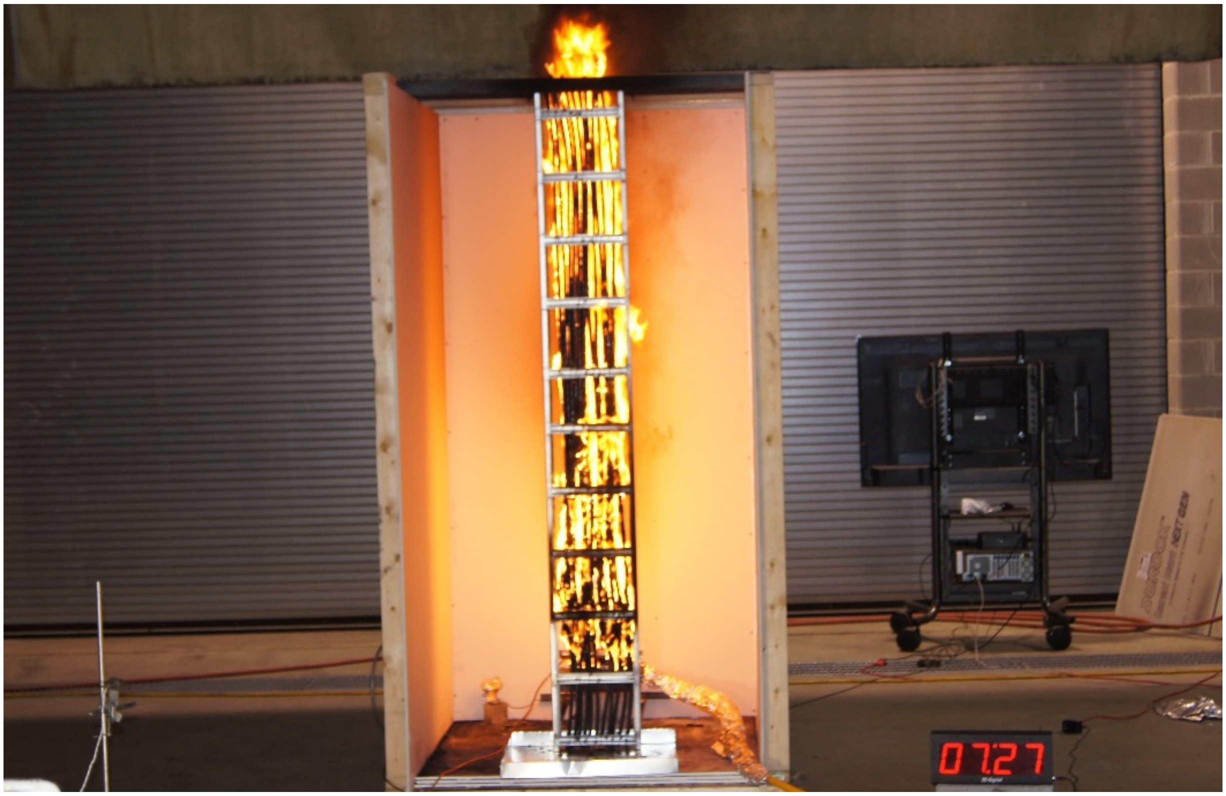


**Figure 6-9. Photograph of experiment I-4, cable 900, uncoated.**

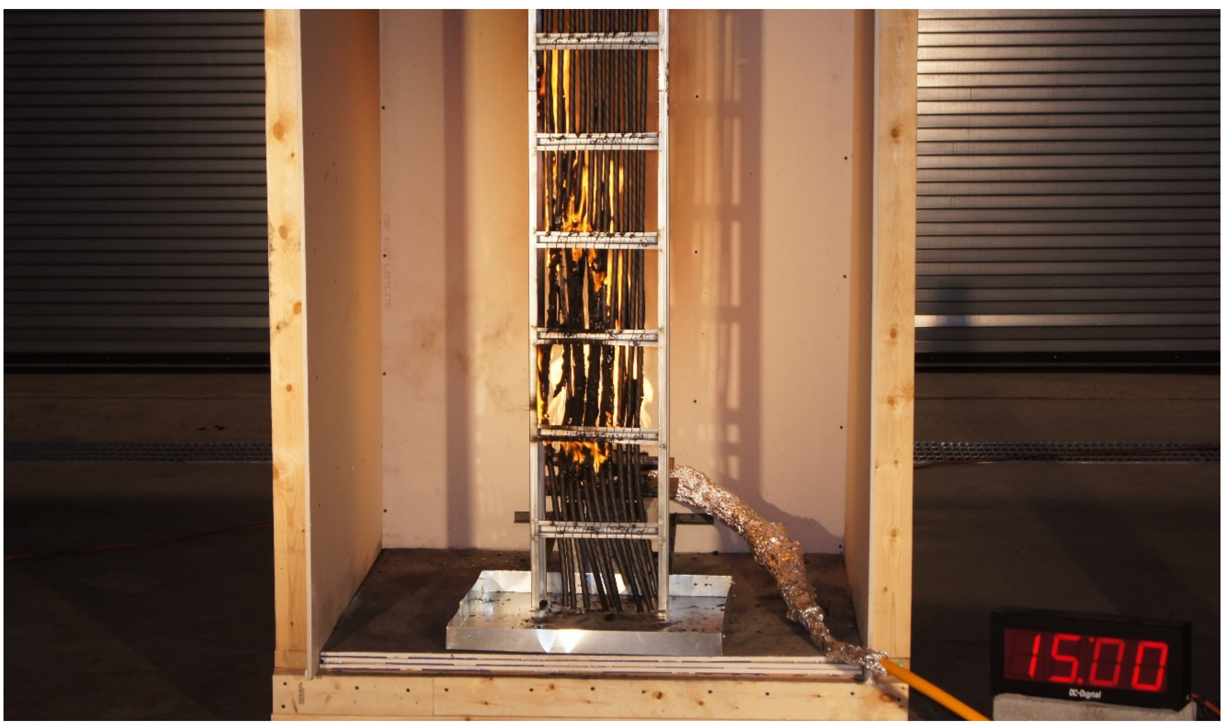


**Figure 6-10. Photograph of experiment I-10, showing the shift of fire spread to the left of the tray.**

### 6.2.2 Cable 900 Coated with FS15

Figure 6-11 displays the HRRs for cable 900 coated with FS15. In only one case, experiment I-17, there was a very slight increase in heat release over that of the propane burner. Figure 6-12 and Figure 6-13 display photographs of experiment I-8, both during and after the exposure to the burner. There was a noticeable swelling (intumescence) of the coating.

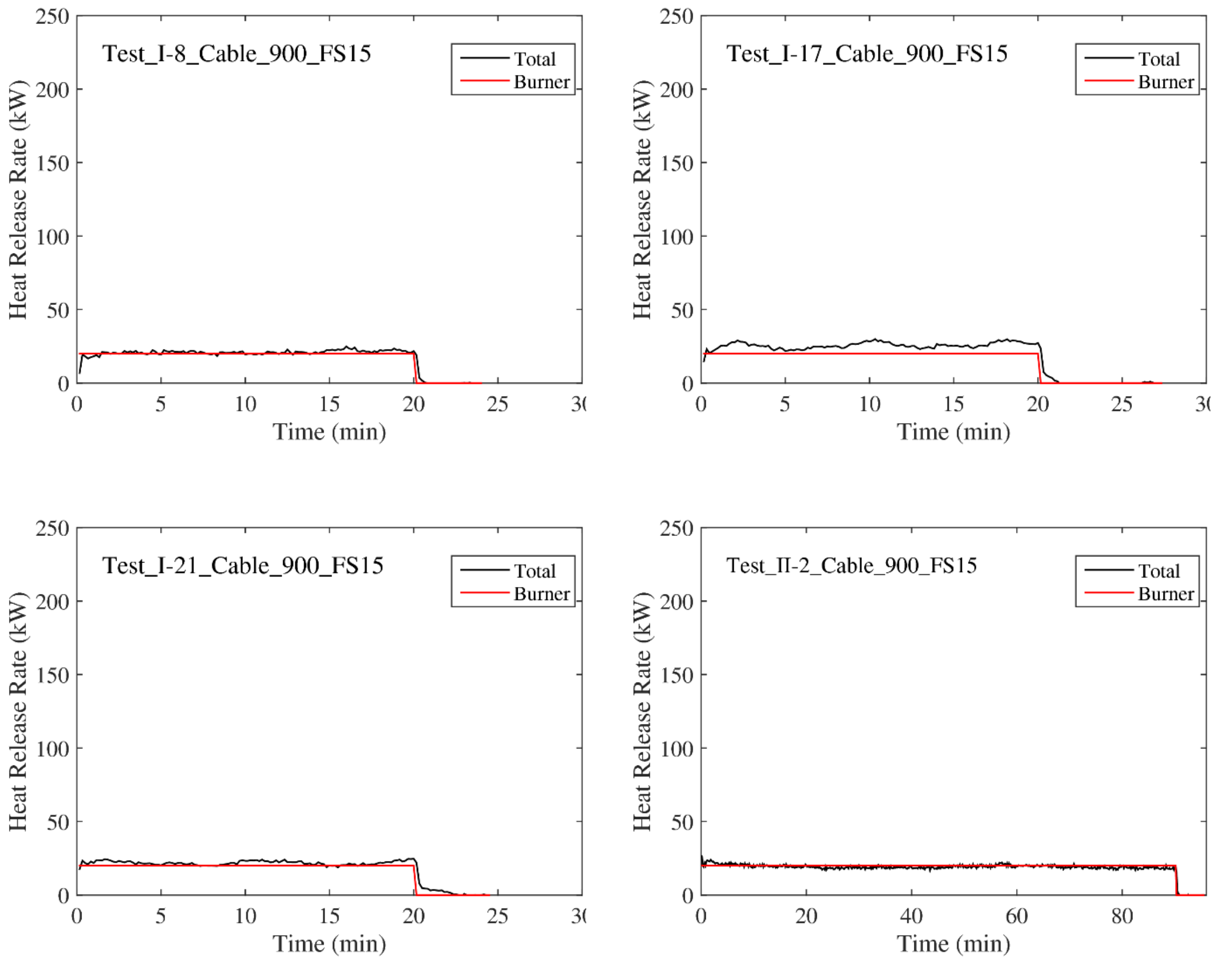



**Figure 6-11. HRR of vertical flame spread experiments for cable 900 coated with FS15.**

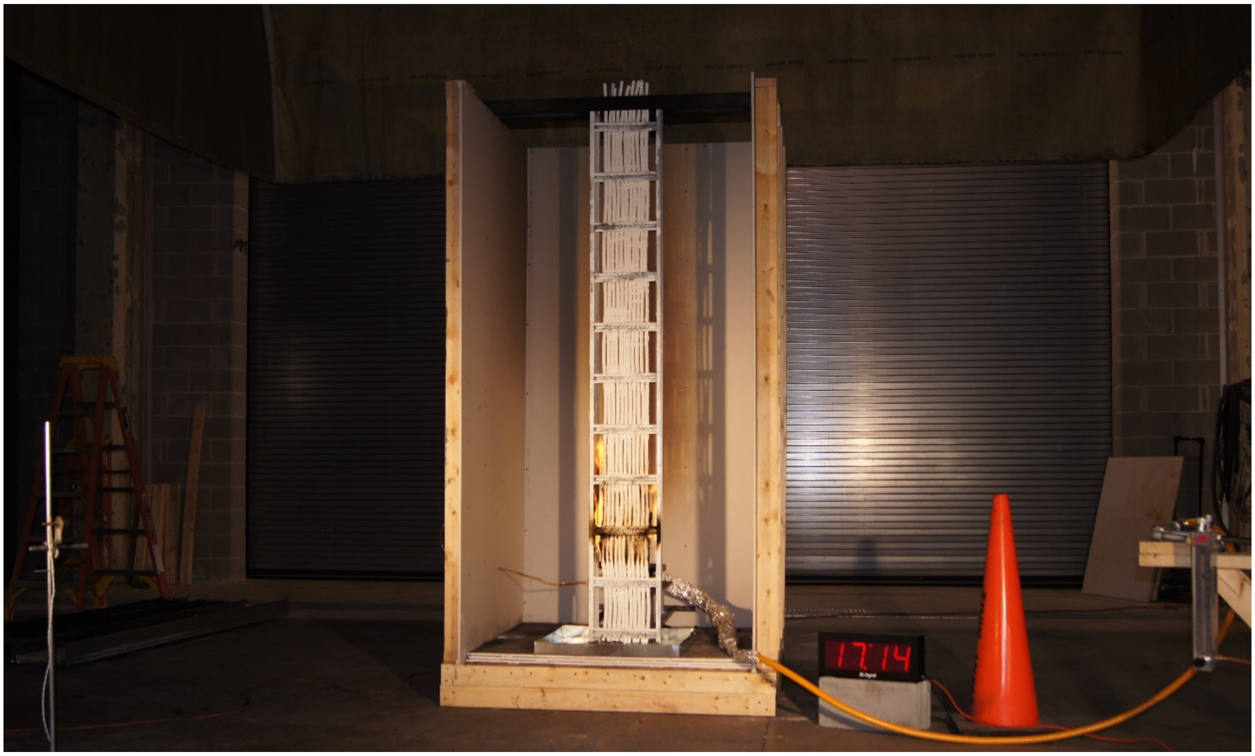



**Figure 6-12. Photograph of experiment I-8, cable 900 coated with FS15.**

**Figure 6-13. Photograph of cable 900 coated with FS15 after experiment I-8.**

### 6.2.3 Cable 900 Coated with Flamemastic 77

A photo of Flamemastic 77 applied to cable 900 prior to experiment is shown Figure 6-14. Figure 6-15 shows the flaming conditions during experiment I-6. Figure 6-16 displays the HRR of cable 900 coated with Flamemastic 77. In one of the three experiments, I-6, the fire did spread approximately 1 m (3 ft) above the burner and generated at its peak an additional 60 kW of energy. The other two experiments had only slight increases in heat release and no upward spread.

**Figure 6-14. Photograph of cable 900 coated with Flamemastic 77.**

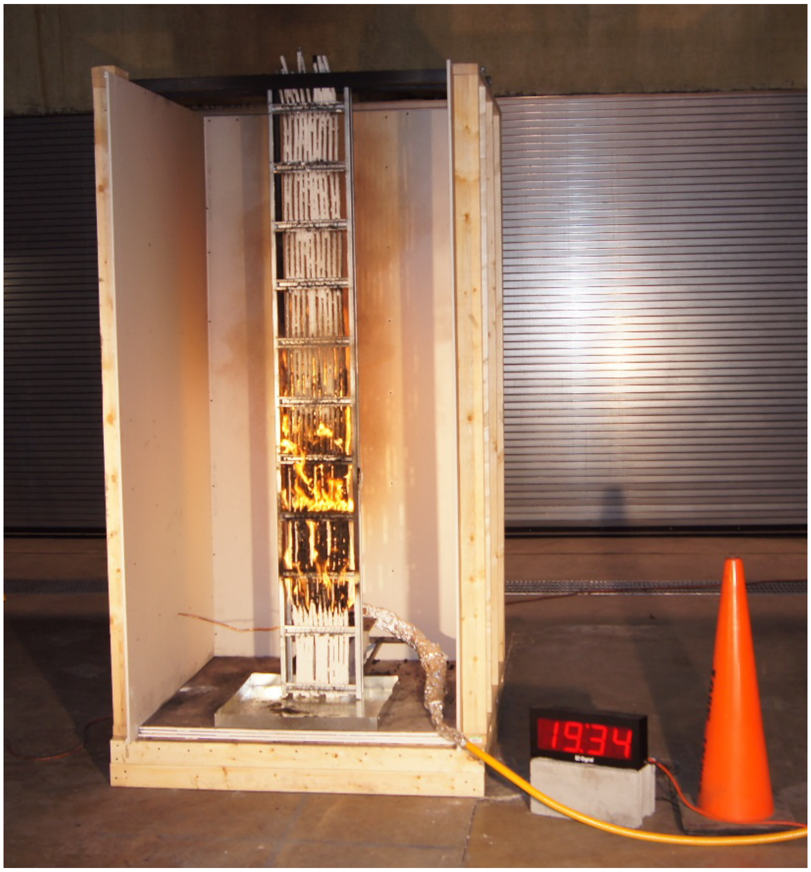
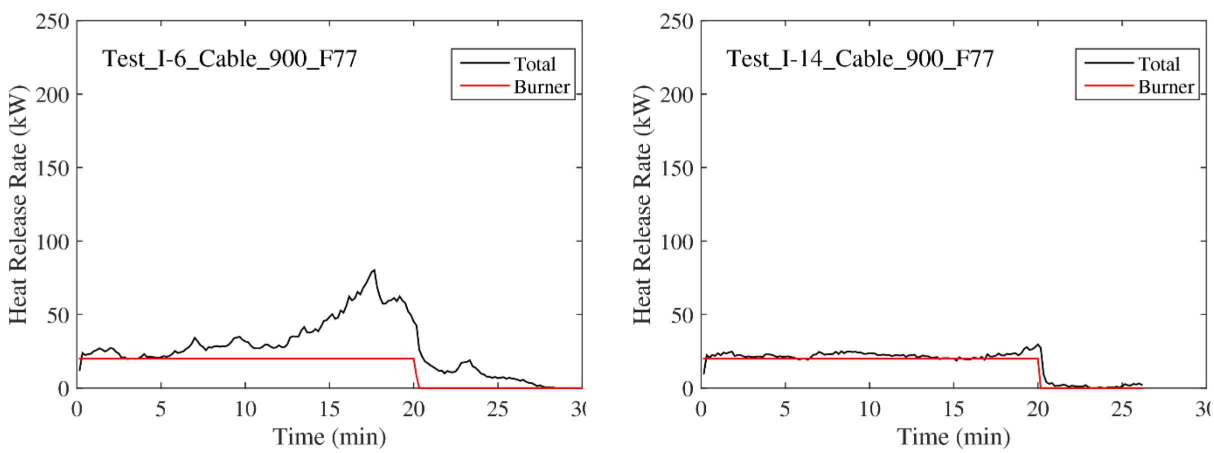



**Figure 6-15. Photograph of experiment 6, cable 900 coated with Flamemastic 77.**



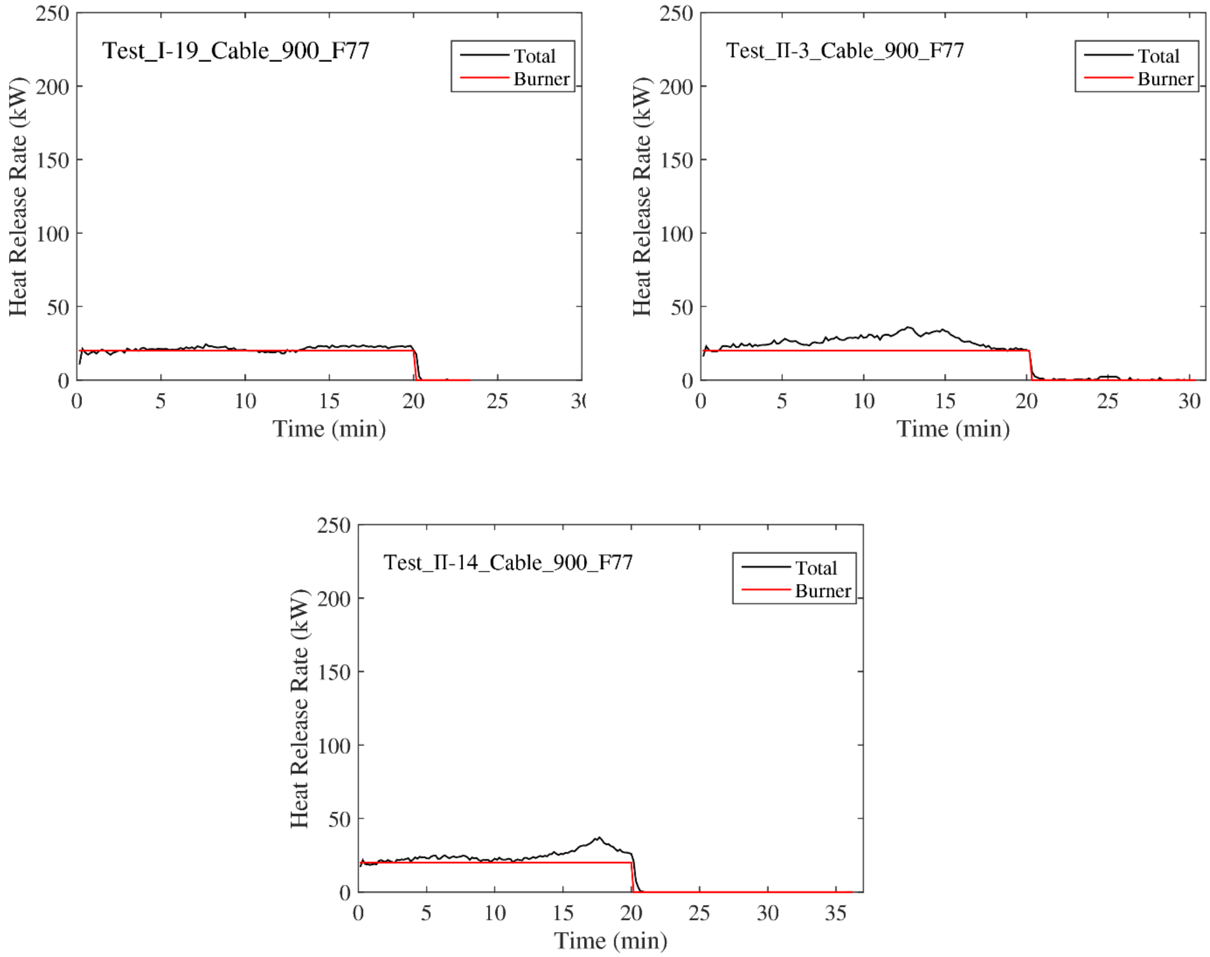



**Figure 6-16. HRR of vertical flame spread experiments for cable 900 coated with Flamemastic 77.**

### 6.2.4 Cable 900 Coated with Vimasco 3i

A photo of Vimasco 3i applied to cable 900 prior to experiment is shown in Figure 6-17. During experiment I-9, the fire spread nearly to the top of the tray, as seen in Figure 6-18. This did not occur during the other experiments of series I (I-11 and I-16). However, an examination of the cables following the experiments indicated that the coating thickness may have been slightly less than the manufacturer-suggested dry thickness of 1.6 mm (1/16 in.). Figure 6-19 displays the HRR for experiments with cable 900 coated with Vimasco 3i. In preparation for series II, the coating was applied in a slightly thicker layer, and none of the three series II experiments exhibited any significant heat release or spread.

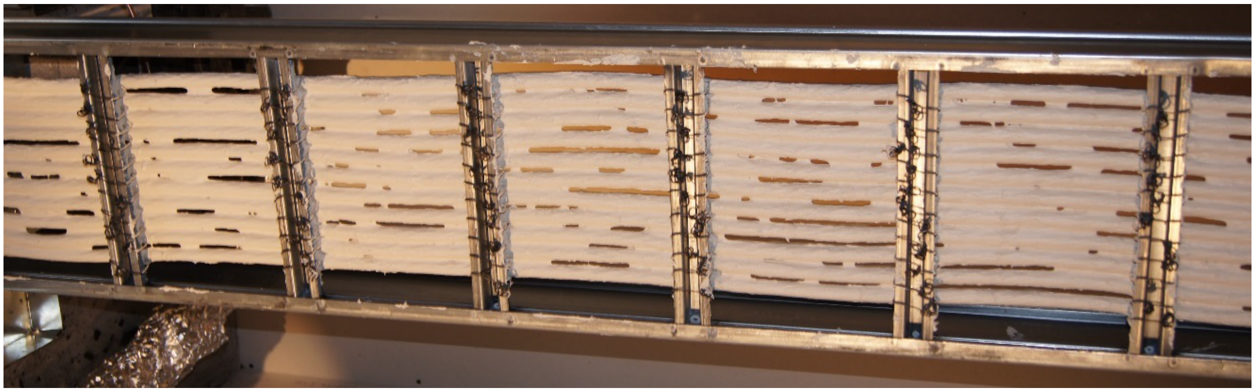


**Figure 6-17. Photograph of cable 900 coated with Vimasco 3i.**

**Figure 6-18. Photograph of experiment I-9, cable 900 coated with Vimasco 3i.**

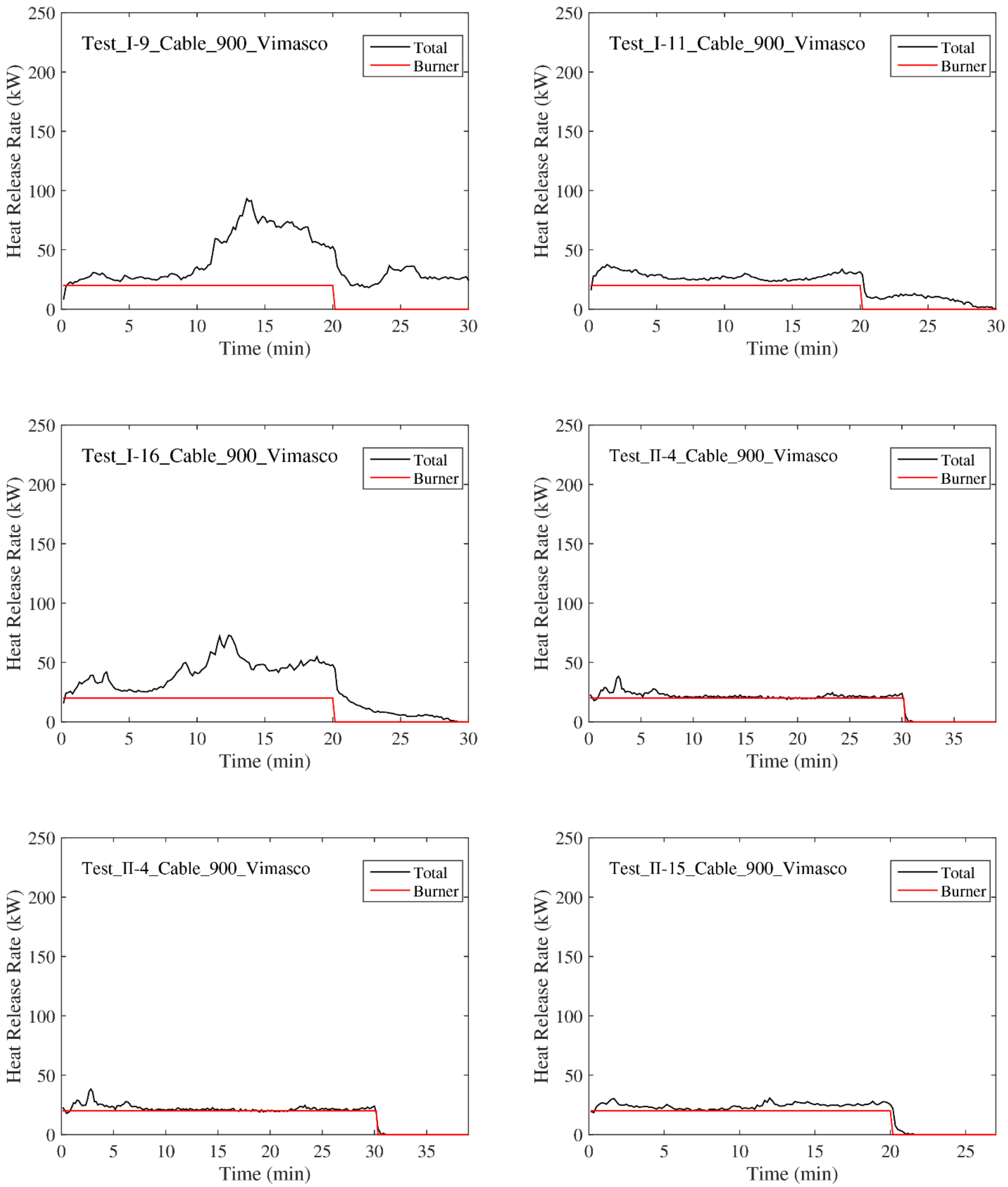



**Figure 6-19. HRR of vertical flame spread experiments for cable 900 coated with Vimasco 3i.**

### 6.2.5 Cable 900 Coated with Carboline 285

Figure 6-20 displays the HRR for the experiments with cable 900 coated with Carboline 285. None yielded any additional heat release or flame spread beyond the propane burner. Unlike the other coatings, Carboline 285 was thick and formed a solid block around the cables. It was not possible to manually coat the cables individually; thus, the overall coating thickness was greater than for the other coatings. Figure 6-21 is a photograph of experiment I-7. The burner flame is barely perceptible behind the block of coated cables.

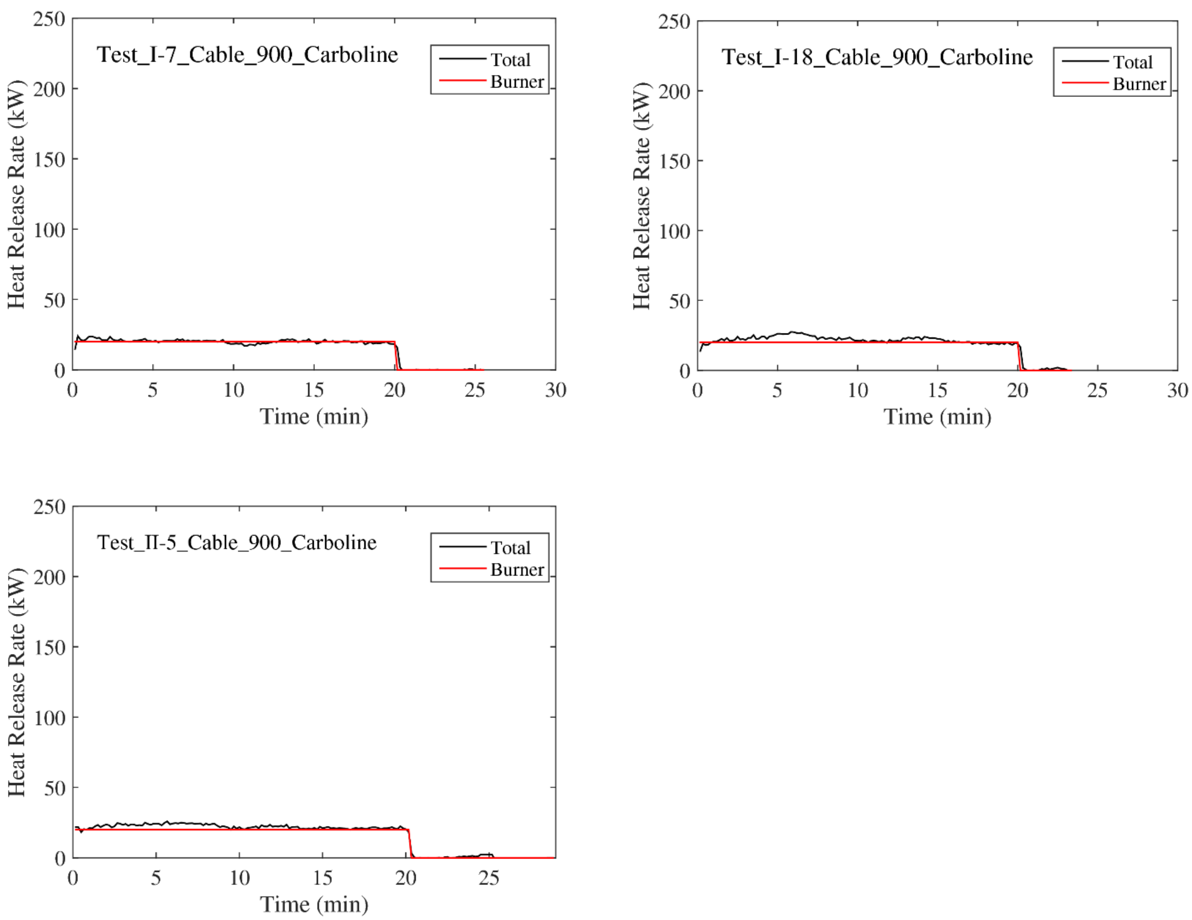



**Figure 6-20. HRR of vertical flame spread experiments for cable 900 coated with Carboline 285.**

**Figure 6-21. Photograph of cable 900 coated with Carboline 285.**

### 6.2.6 Cable 902 Uncoated

Figure 6-22 displays the HRR from three replicate experiments involving Cable 902 with no coatings applied. Figure 6-23 is a photograph of one of the experiments.

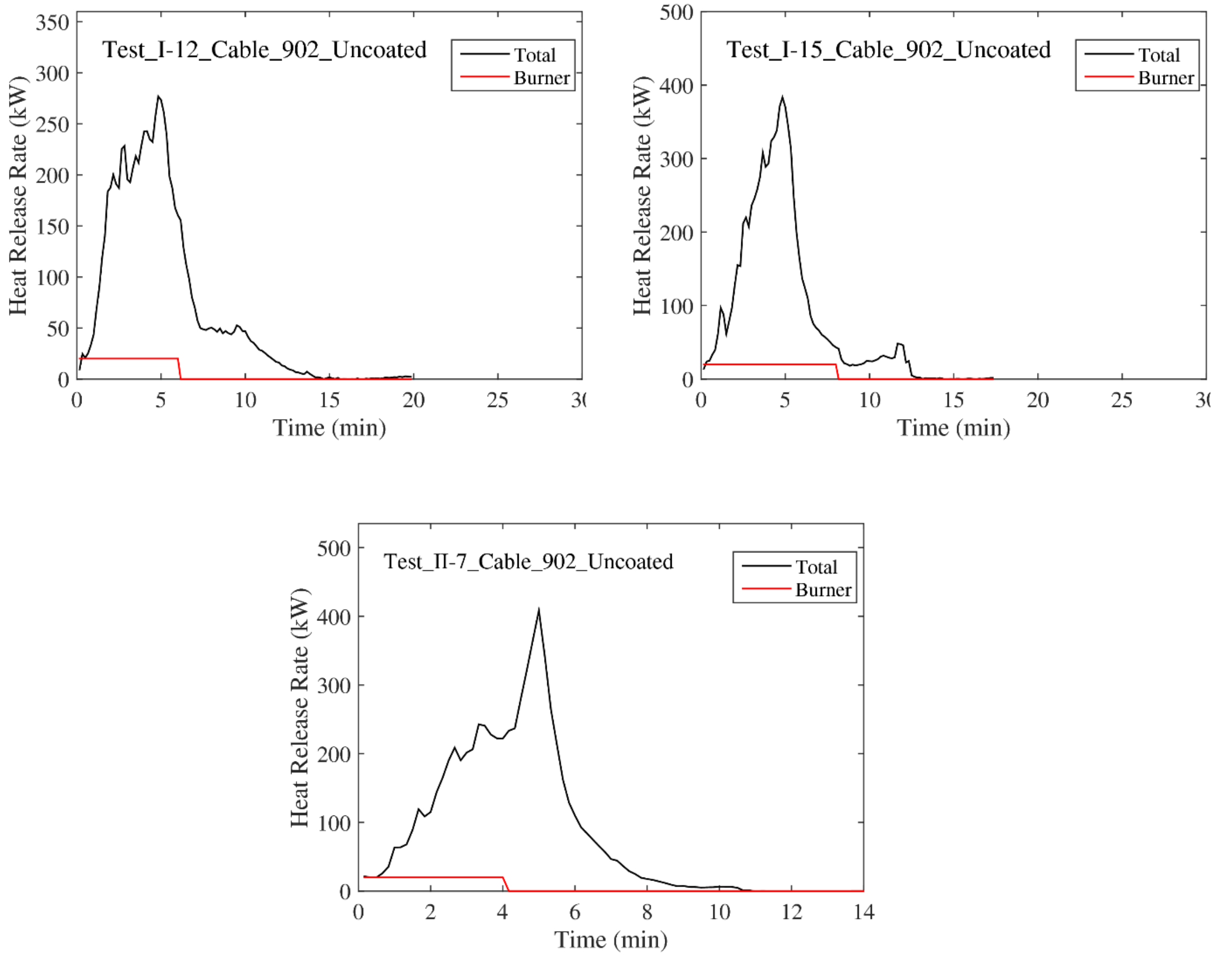



Figure 6-22. HRR of vertical flame spread experiments for cable 902.


**Figure 6-23. Photograph of experiment II-7, cable 902 uncoated.**

### 6.2.7 Cable 902 Coated

There was no appreciable heat release for cable 902 when coated.

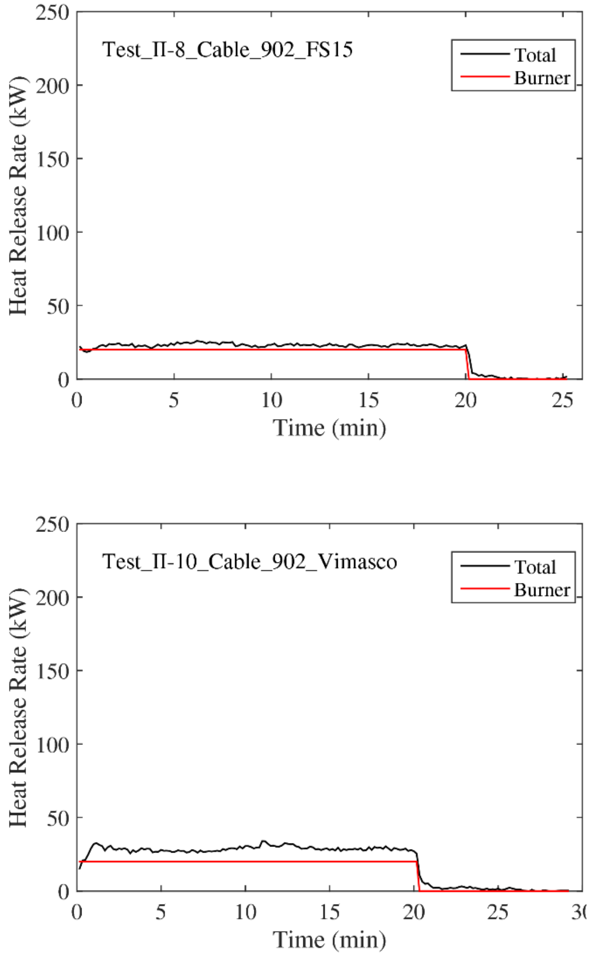



**Figure 6-24. HRR of vertical flame spread experiments for cable 902.**

## 6.3 Cable Temperatures and Electrical Failure Times

During the series II experiments, the cables were instrumented with thermocouples (TCs) (at the cable center) to measure their inner temperature during the vertical flame spread experiments. Figure 6-25, Figure 6-26, and Figure 6-27 display the inner temperatures of cables 900, 902, and 813, respectively. The plots also show the time at which the four energized cables short-circuited due to heating by the fire. The exact nature of the short was not investigated. While the data could not be used to correlate electrical failure time and inner cable temperature, it does show that the FS15 and Carboline coatings restricted the inner temperatures to approximately 400°C (752°F), while the Vimasco and Flamemastic coatings did not. The FS15 coating acted very much like an intumescent paint, which expands upon heating and forms a thermal barrier between coating and cable. The Carboline coating, on the other hand, is simply applied in a relatively thick coat (see Figure 6-7); because of its consistency, it is difficult to apply this product in a thin coat like the Vimasco and Flamemastic coatings. Thus, the Carboline, Vimasco, and Flamemastic coatings cover the cable like a thermal blanket, whereas the FS15 coating appears to have the additional feature of intumescence (at least to the naked eye, intumescence is far more apparent than for the other three coatings).

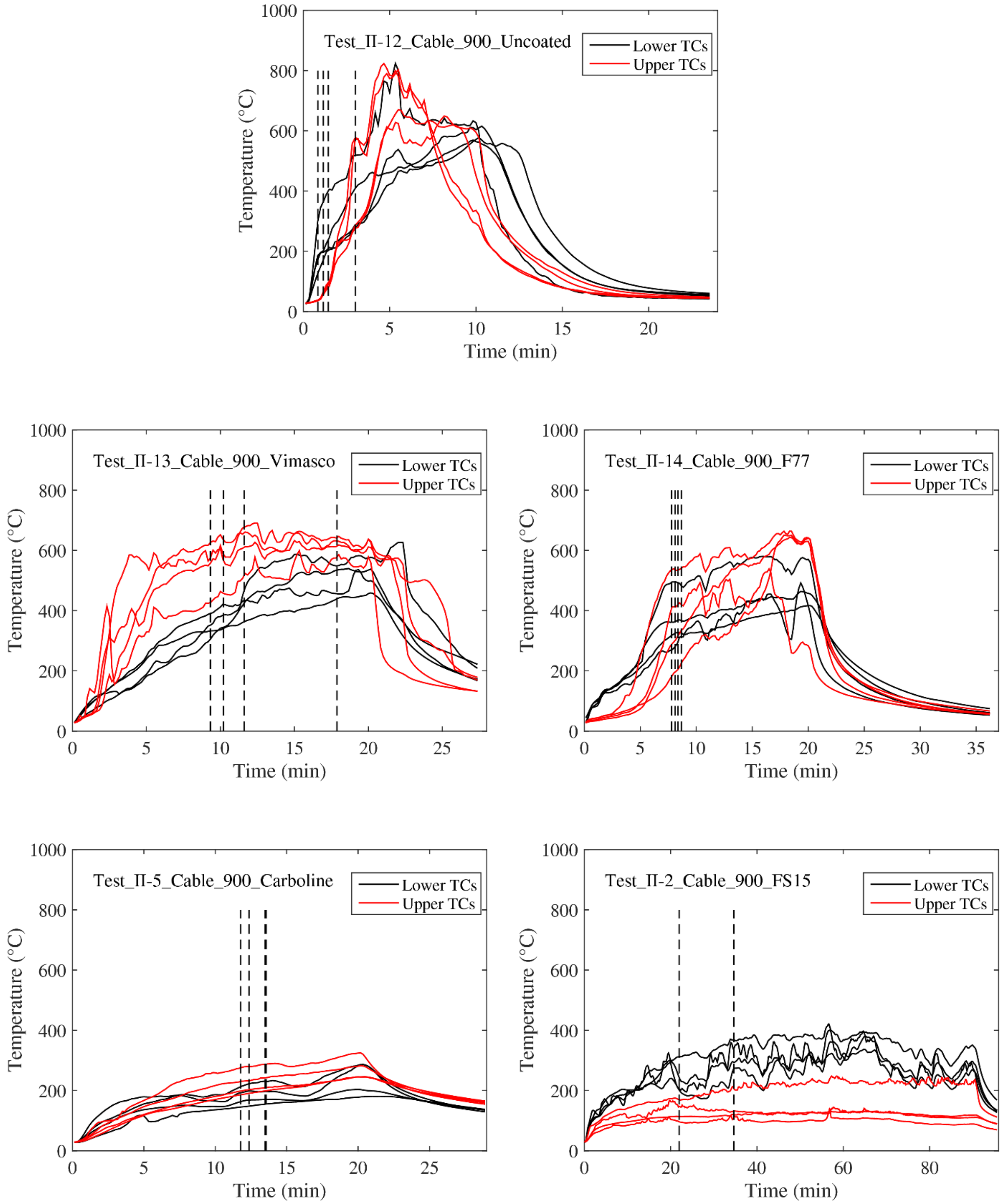



**Figure 6-25. Inner cable temperatures, cable 900.**

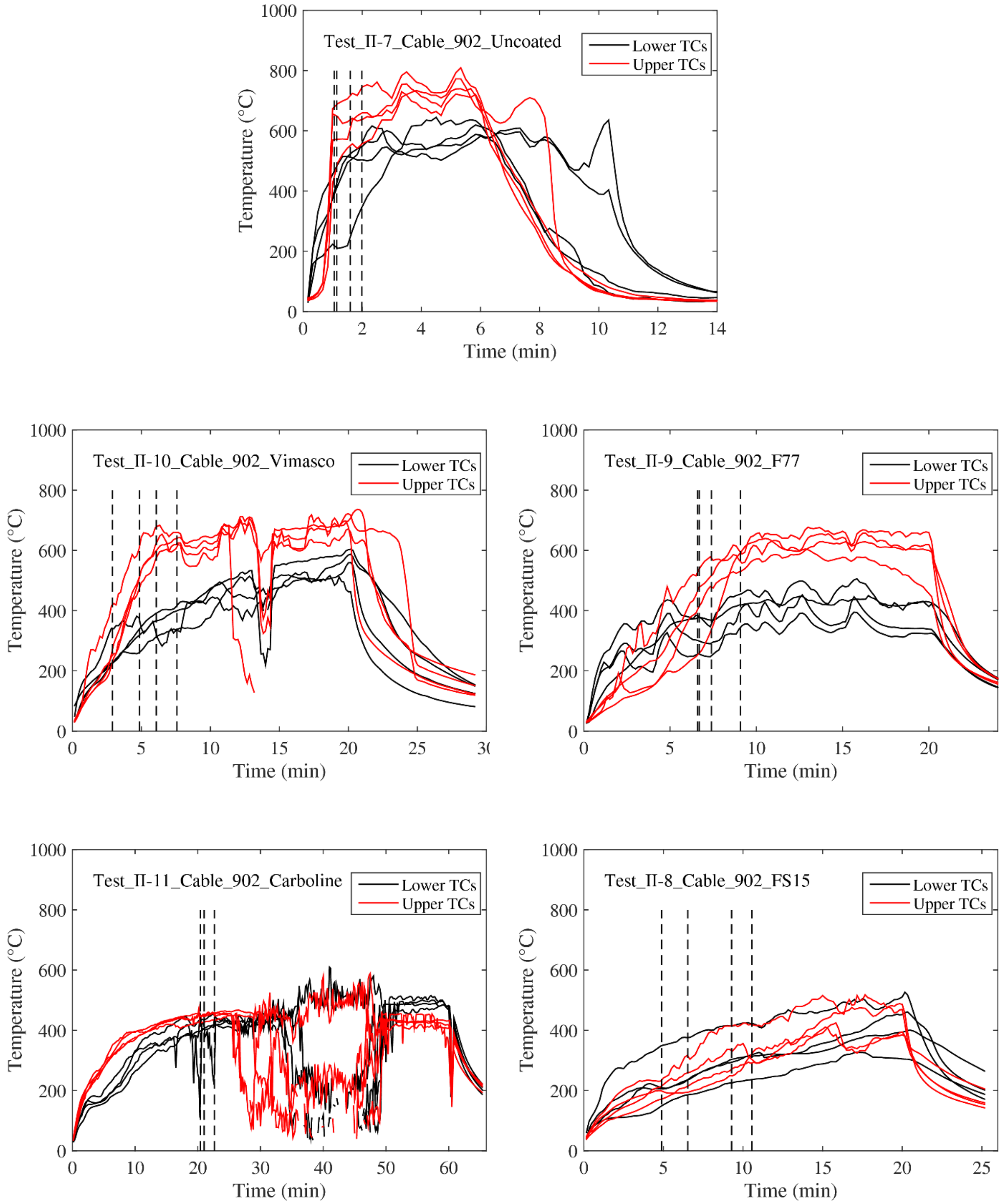



**Figure 6-26. Inner cable temperatures, cable 902.**

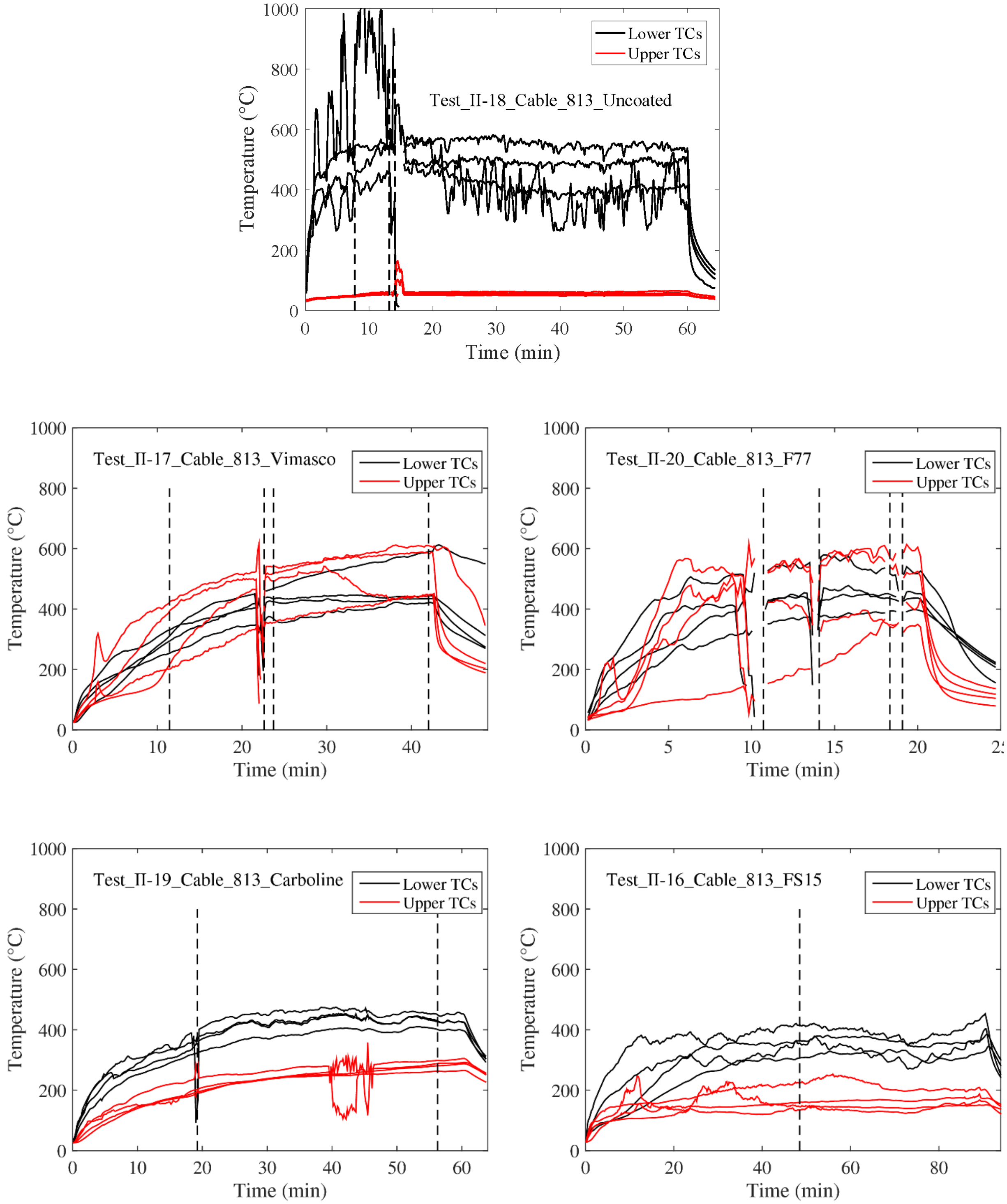



**Figure 6-27. Inner cable temperatures, cable 813.**

## 6.4 Summary

The four cable coatings tested in the vertical flame spread apparatus prevented the upward spread of fire from the 20 kW burner when applied according to the manufacturers' recommendations. In several experiments in which the coatings were applied at a thickness just less than the recommended value, the fire did spread upward to various extents, but this behavior was not repeated when the coatings were applied as directed.

In the experiments in which the inner cable temperatures were measured with TCs, it was not possible to discern a definitive temperature at which the cables failed electrically. There are several reasons for this:

- The TCs were not necessarily placed at the location of peak heat flux from the fire.
- The coating thickness varied from point to point and cable to cable.
- The TCs were installed in separate cables from those that were energized to avoid damaging the energized cables.

For these reasons, it is not possible to use the temperature data collected in these experiments to develop or validate a model or empirical correlation that can be applied to predict the duration of time that a given coating would protect a given cable from electrical failure.

# 7. BENCH-SCALE CIRCUIT INTEGRITY EXPERIMENTS

This section describes experiments in which uncoated and coated electrical cables were exposed directly to a premixed air-propane flame with a nominal temperature of 750°C (1,382°F) at the point of impingement.

## 7.1 Experimental Description

The experiments are like those described in the International Electrotechnical Commission (IEC) Standard 60331-11, "Tests for electric cables under fire conditions—Circuit integrity—Part 11: Apparatus—Fire alone at a flame temperature of at least 750°C" (IEC 2009). Figure 7-1 shows a typical experiment.

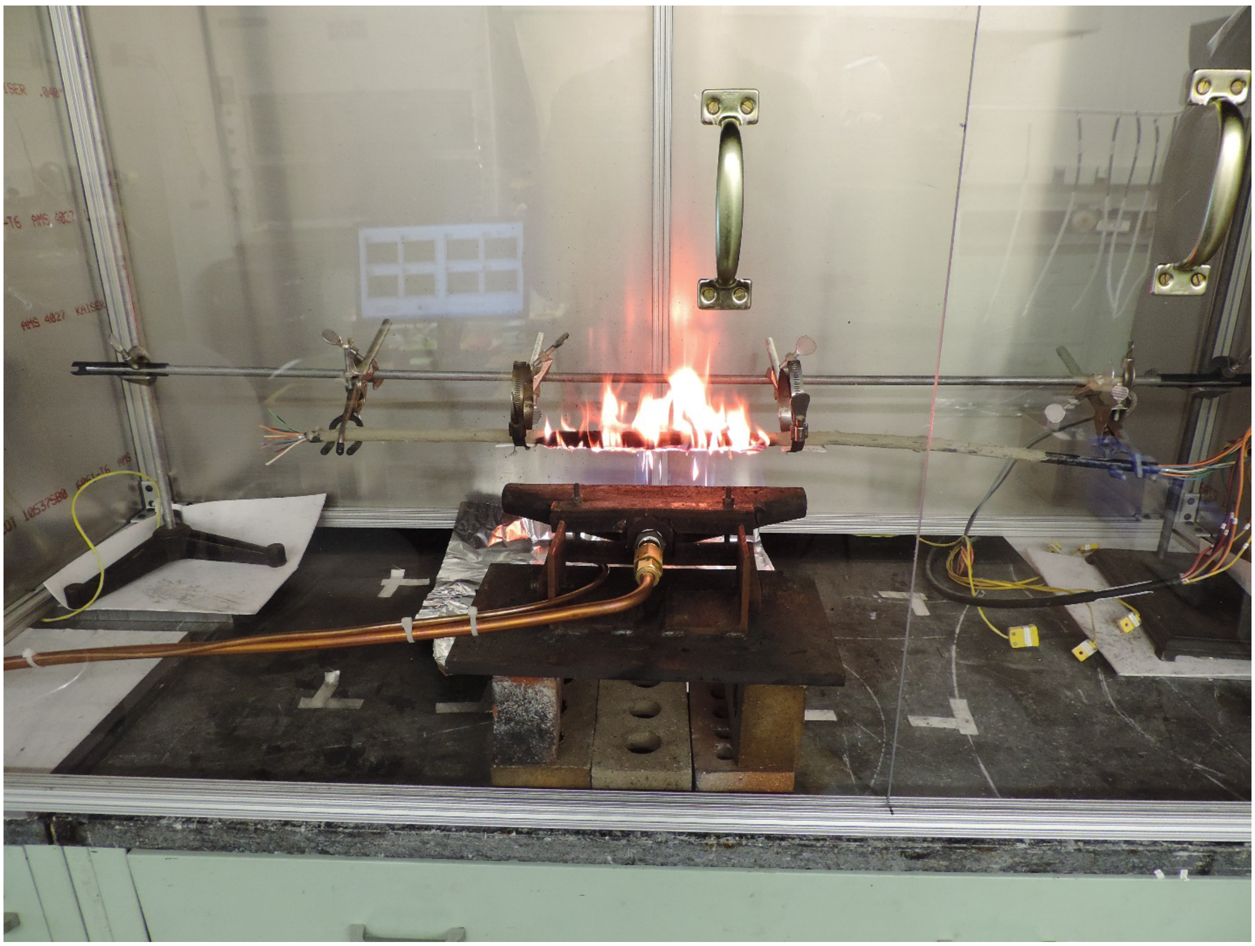


**Figure 7-1. Photograph of a typical circuit integrity experiment.**

In this experiment, a single cable, either coated or uncoated, was immersed in a premixed propane-air flame generated by a line burner. The main deviation from the test standard was that the burner had a nominal face length of 25 cm (10 in.) rather than 50 cm (20 in.) as specified in the standard. The width of the burner was nominally 1 cm (0.4 in.). The propane and air flow rates entering the premixed burner were half of what is called for in the standard—2.5 liters (L)/min propane and 40 L/min air at 1 bar and 20°C (68 °F), producing a 3.6 kW flame. The burner was manufactured by AGF Burner, Inc., of Lakewood, New Jersey.

The center of the cable was laterally displaced 45 mm (1.8 in.) from the burner face and vertically displaced 60 mm (2.4 in.) from the centerline of the burner orifice. Two shielded TCs were positioned at the location of the cable centerline to ensure that the average flame temperature over 10 minutes was between 700°C (1,292°F) and 800°C (1,472°F).

The apparatus was confined within a chamber with a plexiglass front face with sliding doors. The chamber was approximately 1.6 m (64 in.) wide, 0.66 m (26 in.) deep, and 1.1 m (42 in.) high. The top was open to an exhaust hood, and a 2 cm (0.75 in.) gap was maintained along the bottom periphery.

Two cables were used in these experiments. Cable 900 is a 7-conductor TP cable, and cable 813 is a 12-conductor TS cable.

Each cable was coated with one of the four coatings to a nominal dry thickness of 1.6 mm (1/16 in.) or 3.2 mm (1/8 in.). The coatings were applied by drawing the cable through a funnel holding the wet coating material. The dry coating thickness was approximately half the wet thickness. The funnel openings were cut accordingly. Figure 7-2 displays some coated cables in preparation for the experiments. Table 7-1 lists the average coating thicknesses for the two cables and the four different coatings.

The experiment apparatus could accommodate only one cable segment at a time, and temperature and electrical integrity measurements could not be done within the same cable. Thus, for each experiment sample, separate experiments were conducted—one for circuit integrity and one for temperature measurement. Experiments involving coated cables were repeated three times. For example, three circuit integrity experiments were performed, and three temperature measurements were performed. For uncoated cables, this procedure was repeated six times.

For the circuit integrity experiments, three circuit pairs were energized with 120 volts (V), and the cable was heated until a 3 ampere circuit breaker tripped.

For the temperature measurements, two TCs were inserted in the center of the cable, as near as possible to the central conductor. The TCs were placed 5 cm (2 in.) to the left and right of the midpoint of the burner.

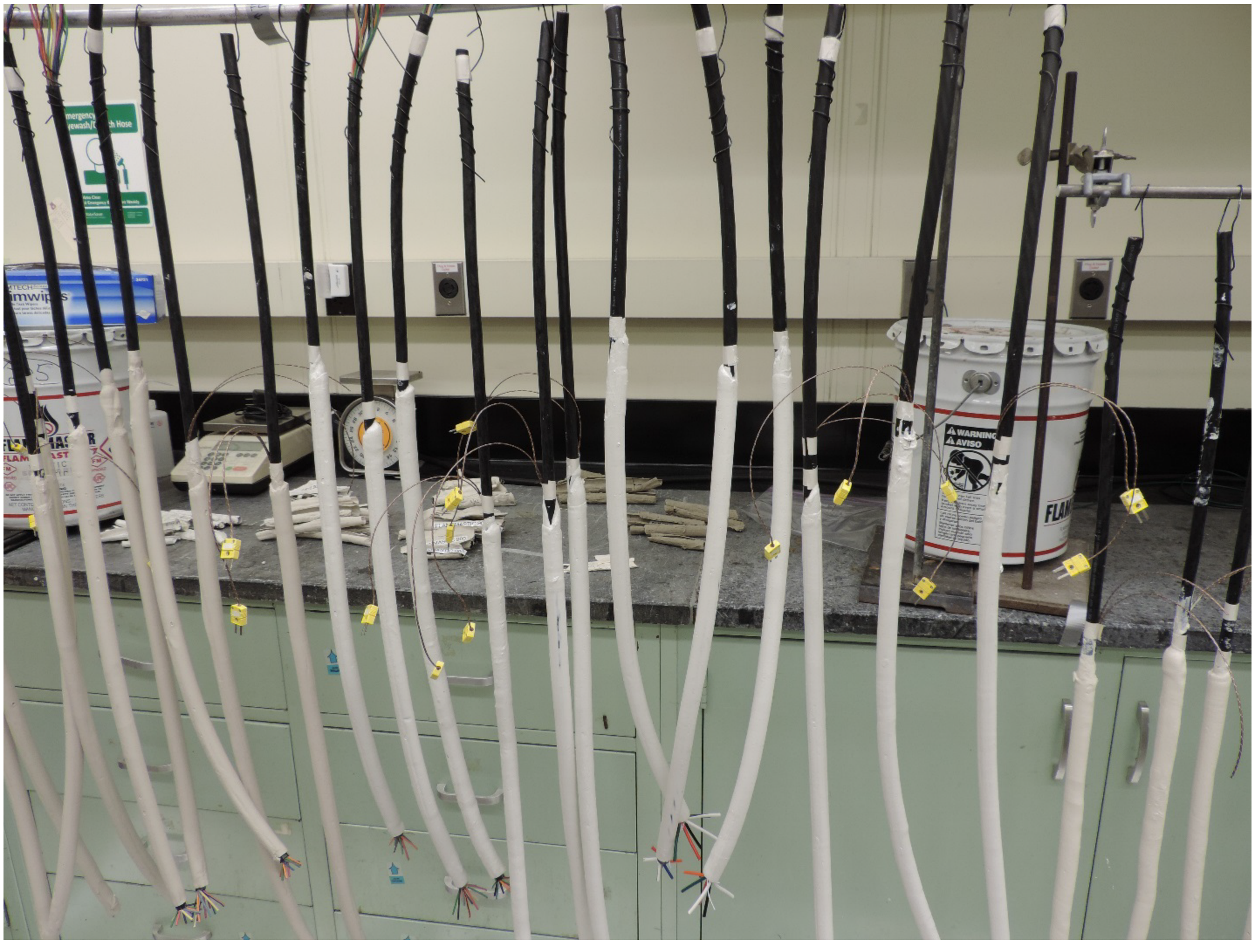



**Figure 7-2. Coated cables in preparation for experiments.**

## 7.2 <u>Results</u>

Table 7-1 summarizes the results of the experiments. The table lists the average time to circuit failure of three replicate experiments, and the corresponding cable interior temperature at the time of failure. The results vary significantly with both cable type and coating type.

The range in performance of the four different coatings is significant, and it is difficult to draw firm conclusions as to the effectiveness of coatings overall.

APPENDIX A contains the complete results of the experiments.

**Table 7-1. Summary of the in-flame circuit integrity experiments.**

| Cable No. | Coating | Thickness | | Avg. Failure Time (min) | | Avg. Failure Temp. | |
|---|---|---|---|---|---|---|---|
| | | (mm) | (mil) | $t_{\mathrm{fail}}$ | $\Delta t_{\mathrm{fail}}$ | (°C) | (°F) |
| 813 | None | 0.0 | 0.0 | 4.1 | -- | 370 | 698 |
| | Carboline | 1.0 | 39 | 6.5 | 2.4 | 380 | 716 |
| | | 3.3 | 130 | 8.0 | 3.9 | 330 | 626 |
| | Flamemastic | 1.6 | 63 | 8.8 | 4.7 | 375 | 707 |
| | | 3.7 | 146 | 10.5 | 6.4 | 340 | 644 |
| | FS15 | 1.4 | 56 | 7.4 | 3.3 | 375 | 707 |
| | | 3.8 | 151 | 27.5 | 23.4 | 550 | 1022 |
| | Vimasco | 0.9 | 37 | 7.3 | 3.2 | 360 | 680 |
| | | 3.7 | 147 | 21.5 | 17.4 | 460 | 860 |
| 900 | None | 0.0 | 0.0 | 6.3 | -- | 490 | 914 |
| | Carboline | 1.2 | 49 | 9.0 | 2.7 | 490 | 914 |
| | | 2.9 | 113 | 11.7 | 5.4 | 480 | 896 |
| | Flamemastic | 1.4 | 54 | 11.4 | 5.1 | 480 | 896 |
| | | 3.1 | 124 | 12.6 | 6.3 | 450 | 842 |
| | FS15 | 1.4 | 55 | 11.2 | 4.9 | 410 | 770 |
| | | 3.3 | 129 | 18.4 | 12.1 | 420 | 788 |
| | Vimasco | 1.3 | 52 | 33.8 | 27.5 | 490 | 914 |
| | | 3.1 | 124 | 75.8* | 69.5 | 500 | 932 |

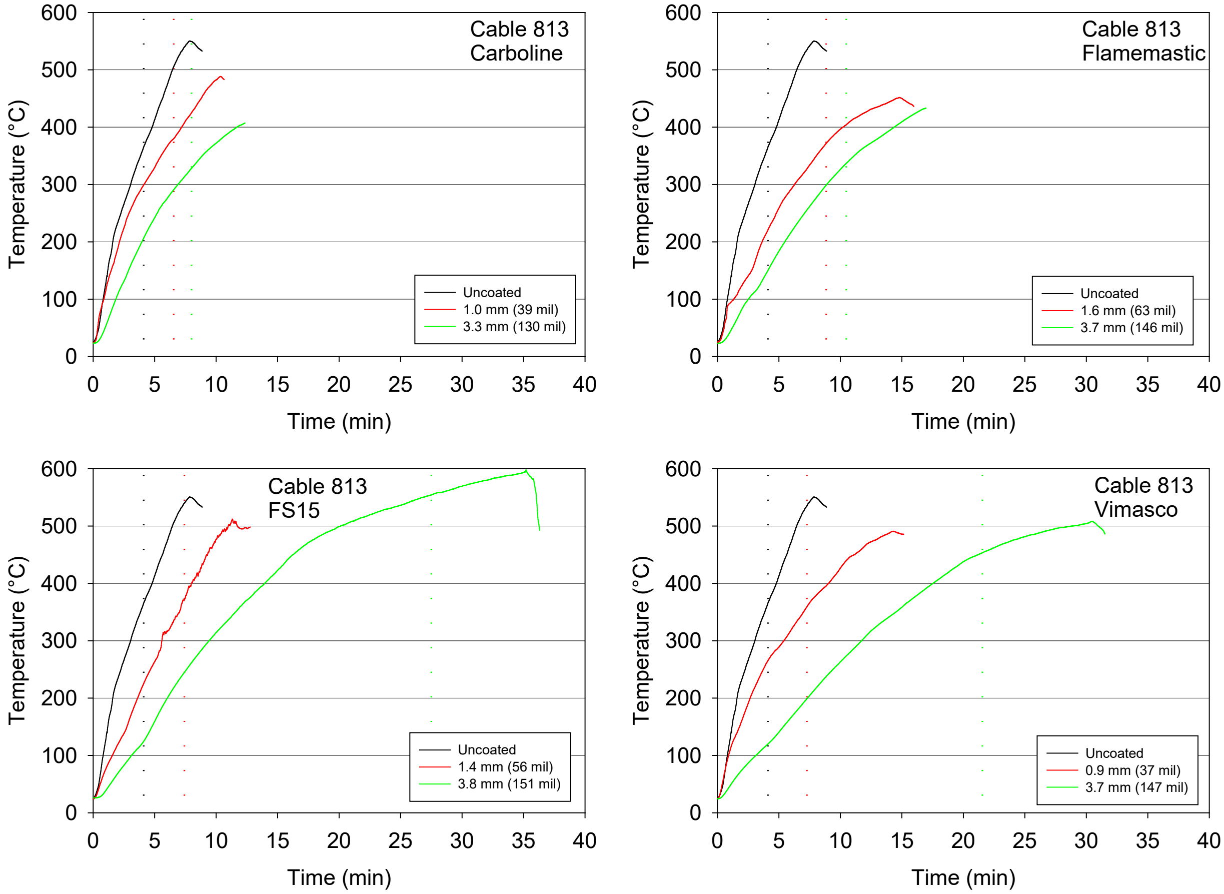



**Figure 7-3. Inner temperature and circuit failure time for cable 813.**

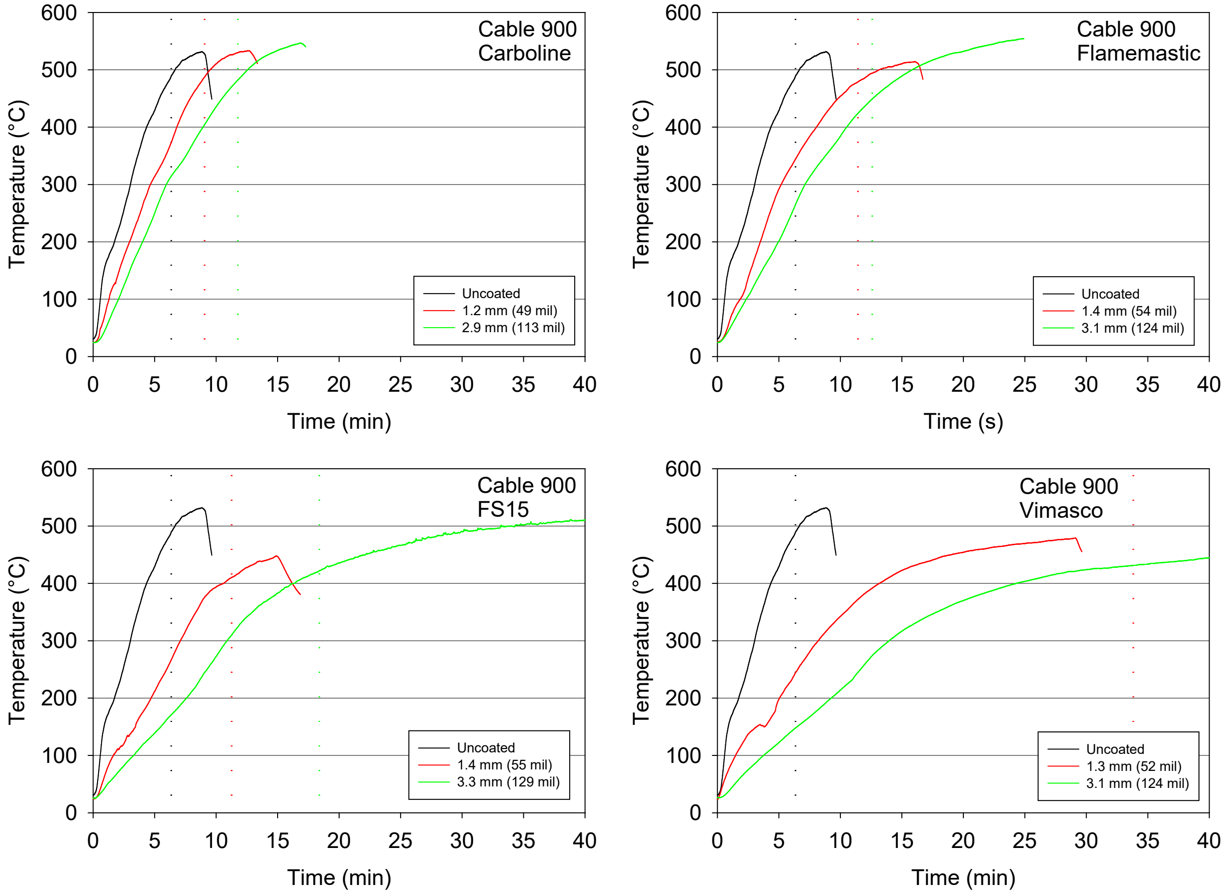



**Figure 7-4. Inner temperature and circuit failure time for cable 900.**

# 8. FULL-SCALE HORIZONTAL FLAME SPREAD EXPERIMENTS

This section describes experiments conducted in May 2017, in which bare and coated cables within horizontal trays were positioned at various locations within a compartment heated by a natural gas burner. The tray locations were intended to provide heating rates characteristic of direct flame impingement, immersion in the smoke plume above the fire, and immersion in the hot gas layer beneath the ceiling.

## 8.1 Experimental Description

Figure 8-1 shows the experiment compartment. The compartment is approximately 2.4 m (8 ft) long, 1.2 m (4 ft) wide, and 2.4 m (8 ft) tall, and it is open all around the lower half. The upper half was lined with a layer of 1.6 cm (5/8 in.) thick Type X gypsum board covered with 0.6 cm (1/4 in.) thick Durock[3] concrete board. The frame was made of steel studs. The compartment was positioned under an oxygen consumption calorimeter with a capacity of approximately 5 megawatts.

Four horizontal trays 30 cm (12 in.) wide and 1.8 m (6 ft) long were positioned as shown in the figure. The trays contained equal numbers of uncoated and coated cables. This arrangement allowed for direct flame impingement on the lowest tray, exposure to plume temperatures on the middle tray, and a gradual heating for the upper trays (see Figure 8-2). All eight experiments used cable 900, a seven-conductor TP with a diameter of approximately 1.5 cm (0.6 in.). The cables were arranged in the trays in two different ways (see Figure 8-3). For a given experiment, one coating and one cable arrangement were applied in all trays. The cables in the uppermost two trays dropped down from one tray to the other. In each tray, four cables were energized (yellow) and four cables were instrumented with TCs (red), as shown in the figure. Given that there were two cable configurations and four coatings, eight experiments were conducted.

Cable 900 has a mass of 0.38 kg/m (257 pounds (lb) per 1,000 ft). For configuration A (see Figure 8-3), the six uncoated cables have a mass of 2.3 kg/m (1,540 lb per 1,000 ft), and the six coated cables have a mass of approximately 2.6 kg/m (1,740 lb per 1,000 ft). For configuration B, the 15 uncoated cables have a mass of 5.7 kg/m (3,860 lb per 1,000 ft), and the 15 coated cables have a mass of 6.1 kg/m (4,090 lb per 1,000 ft). The dry thickness of the coatings was at least 1.6 mm (1/16 in.), as specified in the manufacturer instructions. Measured samples fell between 1.6 mm (1/16 in.) and 3.2 mm (1/8 in).

A 53 cm (21 in.) square natural gas diffusion burner was positioned under the lowest tray (Figure 8-2). The HRR of the burner was initially 50 kW. After 15 minutes, it was increased to 100 kW; after 30 minutes, 200 kW; and after 45 minutes, 400 kW.

Sheathed TCs were positioned just below the two lower trays to measure the gas temperature of the fire plume. Two were positioned directly under each tray, approximately 15 cm (6 in.) apart along the tray centerline. Five TCs were positioned in a vertical line near the double tray under the ceiling. The first TC was 7.5 cm (3 in.) below the ceiling, and the remaining four were spaced 15 cm (6 in.) apart.

[3] Durock is a product of U.S. Gypsum, which also manufactured the Type X gypsum board.

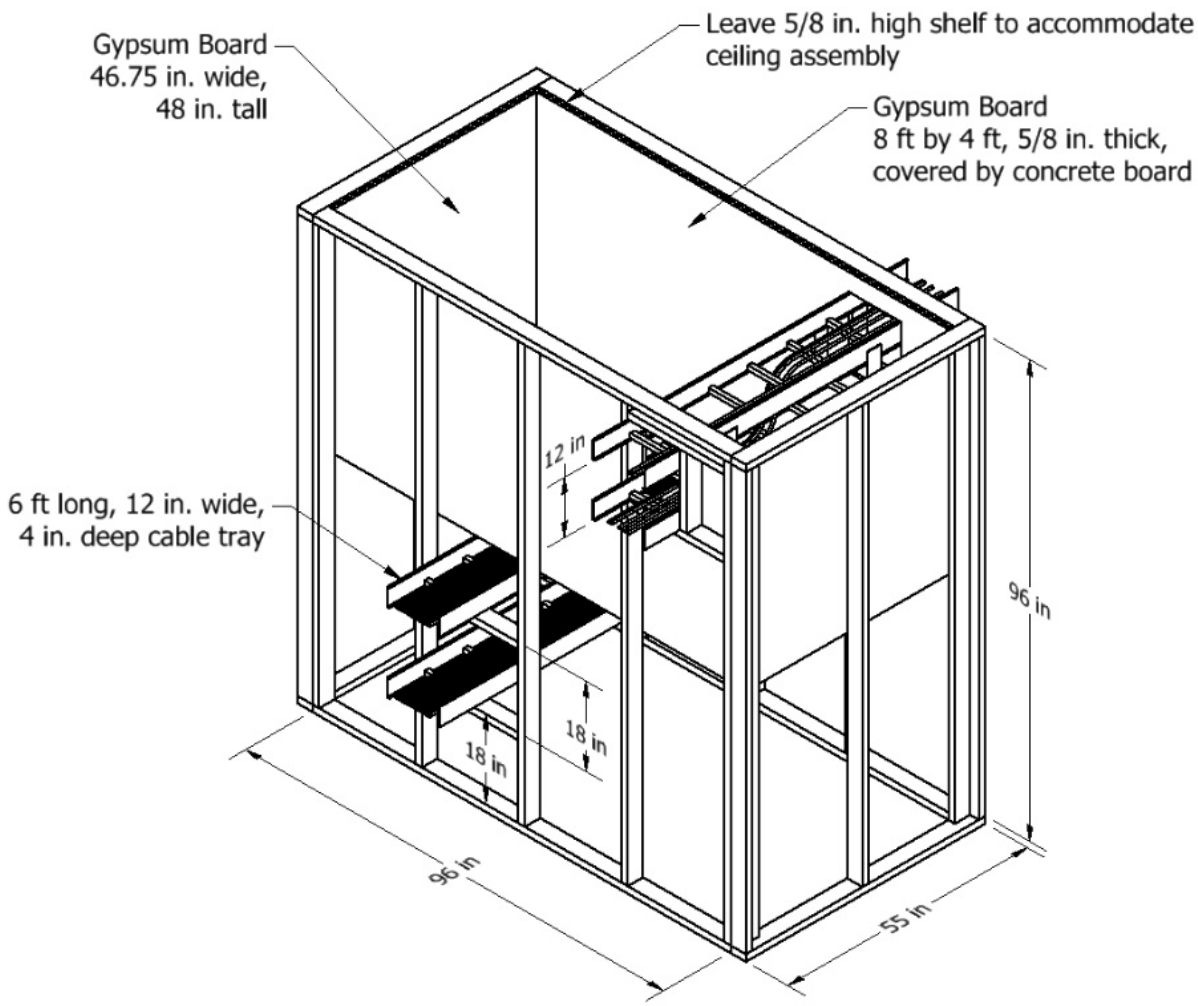



**Figure 8-1. Compartment to be used for the horizontal cable experiments.**

**Figure 8-2. End view of the experiment compartment, showing the burner at 50 kW.**

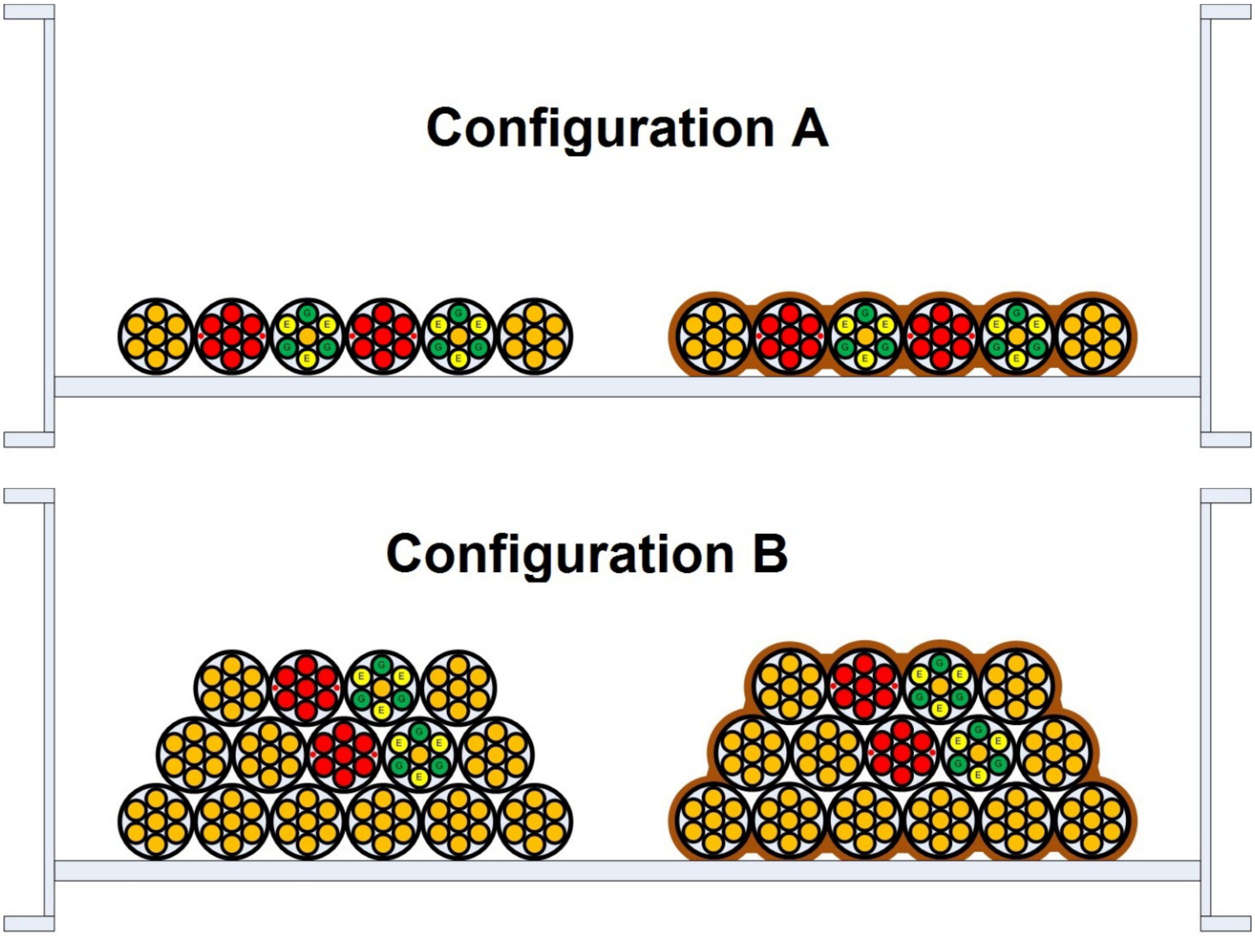



**Figure 8-3. Schematic diagram of cable layouts: A "single row," B "bundle."**

## 8.2 Results

Eight experiments were conducted. Table 8-1 and Figure 8-4 through Figure 8-7 summarize the results. Tray 1 was just above the burner and was initially exposed to direct flame impingement. Tray 2 was just above tray 1 and was initially immersed in the plume. Tray 3 was the uppermost tray and was immersed in the hot gas layer. Each tray contained identical sets of coated and uncoated cables. Each set contained two energized cables and two cables with TCs inserted near their center. These cables are referred to as "Uncoated 1," "Uncoated 2," "Coated 1," and "Coated 2." In the experiments involving a single row of six cables (experiments 1–4), the "Uncoated 1" and "Uncoated 2" cables, as well as the coated cables, were essentially exposed to the same conditions. However, in the experiments involving the bundles of 15 cables (experiments 5–8), "Uncoated 1" and "Coated 1" cables were positioned at the top of their respective bundles, and the "Uncoated 2" and "Coated 2" cables were buried within the bundle and were fully surrounded by other cables.

Table 8-1 lists the electrical failure time of the four energized cables within each tray, and the temperature of the corresponding instrumented cable at the time of electrical failure. The energized cables could not be simultaneously instrumented with TCs because the TCs would interfere with the electrical current and vice versa. Figure 8-4 through Figure 8-7 graphically show the correspondence between electrical failure time and cable temperature, where the electrical failure times are depicted using solid and dashed vertical lines and the temperature histories are depicted using solid and dashed curves. The solid lines indicate the “Uncoated 1” and “Coated 1” cables; the dashed lines indicate the “Uncoated 2” and “Coated 2” cables. Red indicates uncoated cable; green indicates coated cable.

**Table 8-1. Summary of compartment experiments.**

| Experiment Number Coating Configuration | Tray No. | Uncoated 1 | | Uncoated 2 | | Coated 1 | | Coated 2 | |
|---|---|---|---|---|---|---|---|---|---|
| | | Time (min) | Temp. (°C) | Time (min) | Temp. (°C) | Time (min) | Temp. (°C) | Time (min) | Temp. (°C) |
| Experiment H-1 Carboline Single row, 6 cables | 1 | 5.7 | 200 | 14.6 | 290 | 24.2 | 330 | 21.4 | 190 |
| | 2 | 15.5 | 235 | 14.4 | 210 | 24.7 | 270 | 23.3 | 190 |
| | 3 | 34.4 | 225 | 34.4 | 215 | 48.4 | 260 | 44.9 | 190 |
| Experiment H-2 Flamemastic Single row, 6 cables | 1 | 10.0 | 560 | 6.6 | 250 | 17.3 | 270 | 19.8 | 240 |
| | 2 | 13.6 | 220 | 9.9 | 180 | 26.9 | 290 | 27.9 | 260 |
| | 3 | 33.0 | 210 | 34.5 | 210 | 46.6 | 255 | 39.8 | 195 |
| Experiment H-3 FS15 Single row, 6 cables | 1 | 3.9 | 140 | 7.8 | 280 | 24.4 | 370 | 29.0 | 315 |
| | 2 | 12.7 | 315 | 9.0 | 170 | 43.0 | 560 | 24.7 | 205 |
| | 3 | 33.3 | 220 | 34.6 | 235 | 40.2 | 205 | 39.5 | 200 |
| Experiment H-4 Vimasco Single row, 6 cables | 1 | 9.0 | 305 | 4.7 | 170 | 19.0 | 400 | 18.1 | 200 |
| | 2 | 5.9 | 110 | 6.0 | 110 | 23.5 | 275 | 21.7 | 175 |
| | 3 | 28.5 | 210 | 30.5 | 220 | 39.6 | 190 | 36.8 | 170 |
| Experiment H-5 Carboline Bundle, 15 cables | 1 | 14.8 | 520 | 17.9 | 390 | 29.1 | 355 | 45.8 | 360 |
| | 2 | 17.9 | 385 | 25.2 | 280 | 36.8 | 240 | 41.6 | 210 |
| | 3 | 37.3 | 245 | 44.6 | 210 | 60.3 | 330 | 55.5 | 170 |
| Experiment H-6 Flamemastic Bundle, 15 cables | 1 | 16.5 | 590 | 22.0 | 355 | 24.6 | 400 | 33.6 | 590 |
| | 2 | 24.6 | 625 | 25.1 | 200 | 27.3 | 330 | 39.1 | 250 |
| | 3 | 42.5 | 300 | 45.7 | 215 | 54.4 | 440 | 51.0 | 170 |
| Experiment H-7 FS15 Bundle, 15 cables | 1 | 12.9 | 490 | 18.6 | 205 | 19.8 | 245 | 34.9 | 620 |
| | 2 | 21.9 | 540 | 24.0 | 225 | 43.9 | 630 | 41.6 | 305 |
| | 3 | 34.0 | 235 | 41.9 | 195 | 50.7 | 270 | 53.8 | 160 |
| Experiment H-8 Vimasco Bundle, 15 cables | 1 | 10.1 | 550 | 14.8 | 280 | 19.0 | 410 | 28.1 | 165 |
| | 2 | 20.2 | 625 | 23.4 | 275 | 25.6 | 170 | 39.7 | 340 |
| | 3 | 33.4 | 280 | 41.6 | 200 | 44.3 | 235 | 51.2 | 180 |

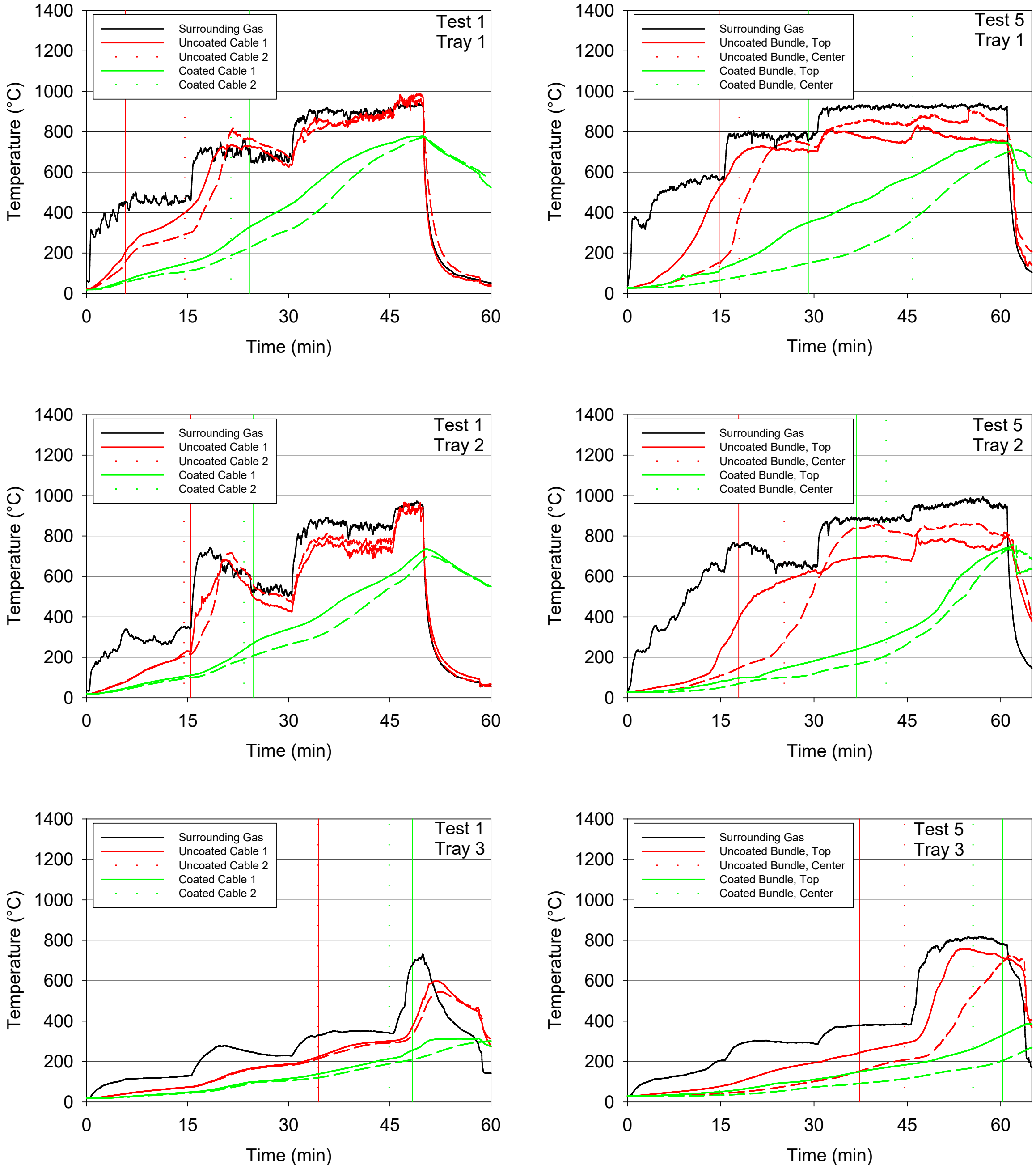



**Figure 8-4. Full-scale compartment temperatures, Carboline.**

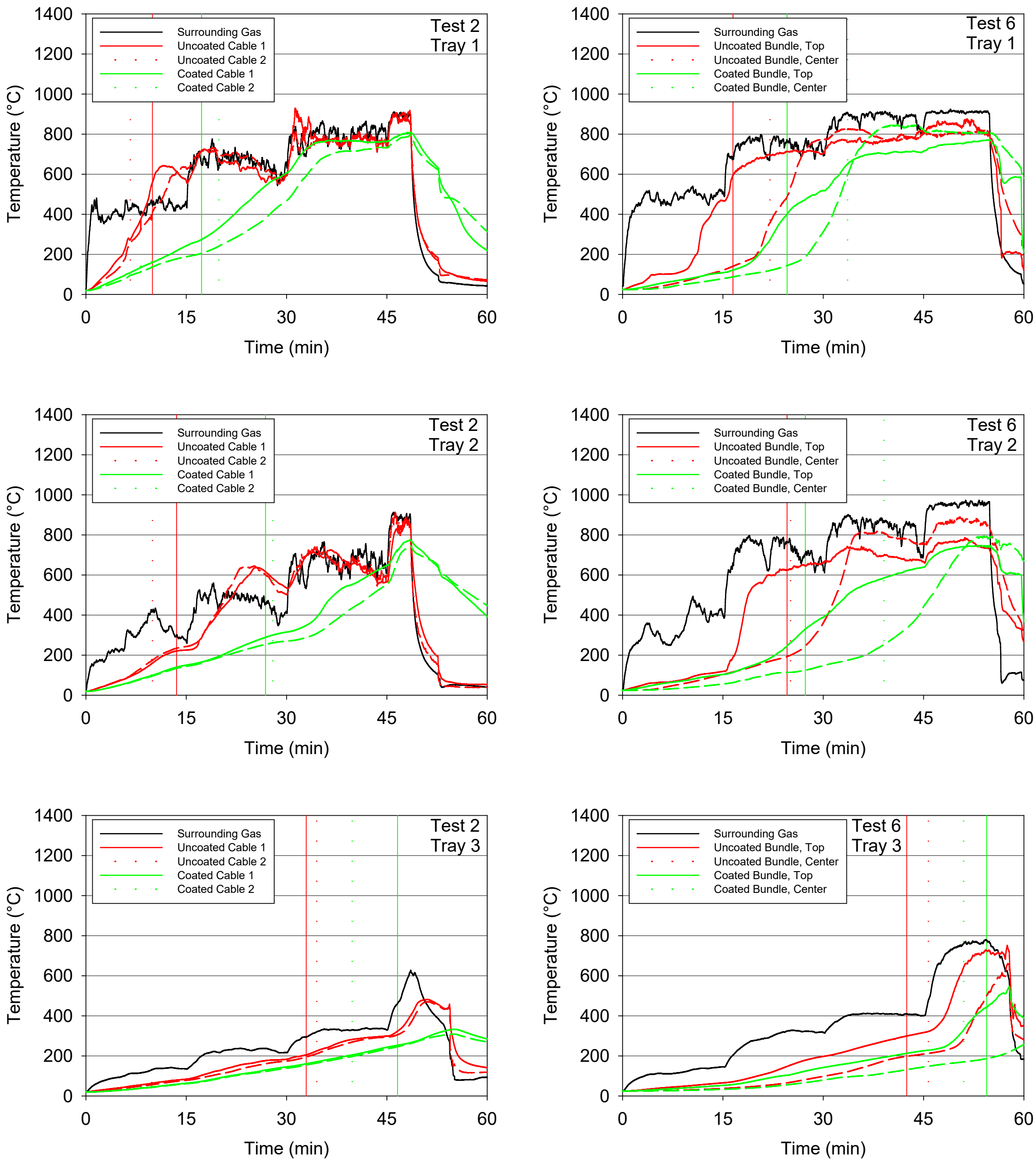



**Figure 8-5. Full-scale compartment temperatures, Flamemastic.**

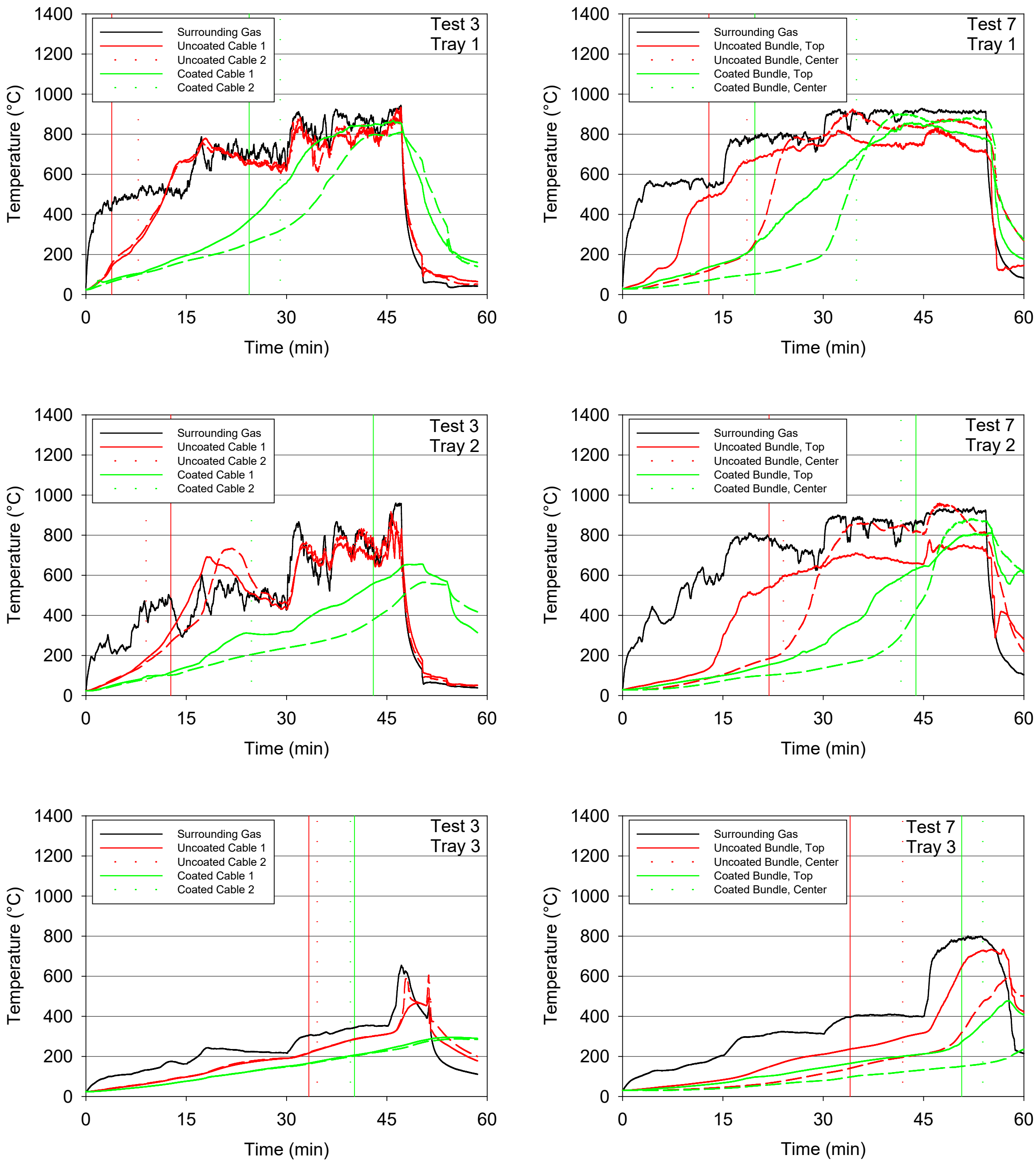



**Figure 8-6. Full-scale compartment temperatures, FS15.**

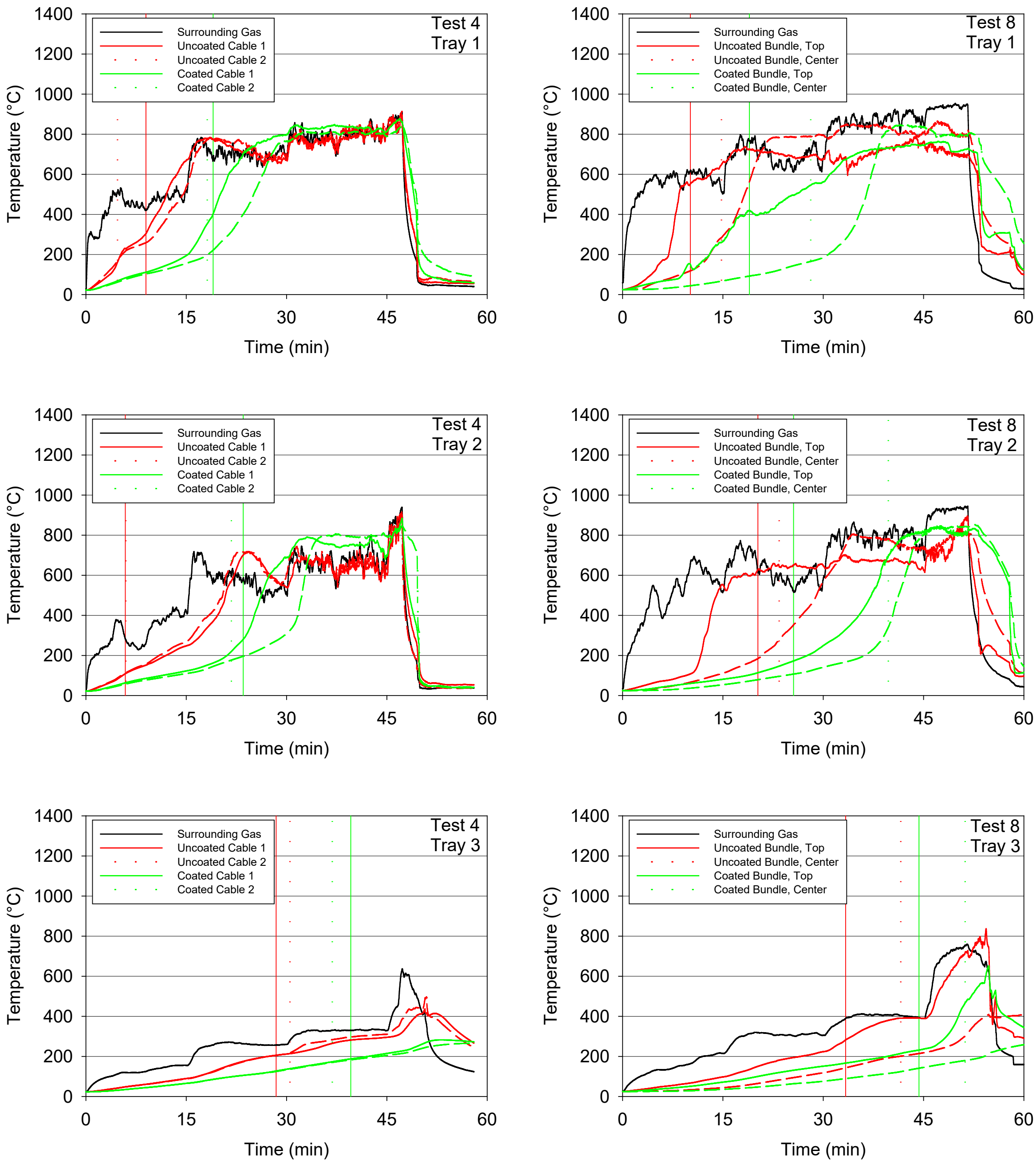



**Figure 8-7. Full-scale compartment temperatures, Vimasco.**

## 8.3 Discussion

The data in Table 8-1 can be analyzed in several different ways. One way to simplify the analysis is to average results of the four different coatings to better understand the effect of cable location and configuration on the failure times and temperatures. Table 8-2 shows these results. For example, the average time to failure for all uncoated cables in the single row configuration in tray 1 was 7.8 minutes.

The average interior cable temperature at the time of failure was approximately 300°C (572°F). The range of failure temperatures was considerable—from less than 200°C to over 500°C (392 °F to over 932 °F). The only clear trend for the failure temperature is that the cables in tray 3, immersed in the hot gas layer, tended to fail at lower temperatures than the cables in tray 1 and tray 2.

**Table 8-2. Average cable failure times and corresponding temperatures.**

| Tray No. | Cable Position | Uncoated Cables | | Coated Cables | |
|---|---|---|---|---|---|
| | | Time (min) | Temp. (°C) | Time (min) | Temp. (°C) |
| 1 | Single row of 6 | 7.8 | 274 | 21.7 | 289 |
| 2 | Single row of 6 | 10.9 | 194 | 27.0 | 278 |
| 3 | Single row of 6 | 32.9 | 218 | 42.0 | 208 |
| 1 | Bundle of 15, exterior | 13.6 | 538 | 23.1 | 353 |
| 2 | Bundle of 15, exterior | 21.2 | 544 | 33.4 | 343 |
| 3 | Bundle of 15, exterior | 36.8 | 265 | 52.4 | 319 |
| 1 | Bundle of 15, interior | 18.3 | 308 | 35.6 | 434 |
| 2 | Bundle of 15, interior | 24.4 | 245 | 40.5 | 276 |
| 3 | Bundle of 15, interior | 43.4 | 205 | 52.9 | 170 |

In these experiments, the difference in performance among the four different coatings was not nearly as pronounced as in the bench-scale circuit integrity experiments discussed in section 7.

# 9. OBSERVATIONS

This second volume describing the research program focuses on the burning behavior of protective cable coatings. The sections below summarize the observations of the measurements. Phases 2 and 3 of this research will evaluate the effects of aging and use the collected data to develop updated guidance to NUREG/CR-6850 Appendix Q, “Appendix for Chapter 11, Passive Fire Protection Features”. Users should be cautious in applying the observations of this research before the subsequent phases are completed.

## 9.1 Burning Rate

The burning rate of coated cables was measured at bench scale in the cone calorimeter. In general, the coatings decrease the peak burning rate and increase the total energy released.

## 9.2 Ignition Temperature

Coated and uncoated cable segments were placed in a convection oven and heated gradually until ignition was observed, and the temperature was measured with TCs at various depths within the cable. The objective of the experiments was to determine if the coatings increased the “effective” ignition temperature of the cable. The quotation marks are added to emphasize that ignition temperature is not a well-defined quantity in fire science. The temperature at which a solid object ignites is a function not only of the material properties, but also of the geometrical configuration of the solid. For example, bundled cables might ignite at a lower effective temperature than a single cable simply because the bundle produces fuel vapors at a high enough concentration to sustain flames whereas the single cable does not.

In general, uncoated thermoplastic cables ignited at temperatures about 300°C (572°F), whereas TS cable ignited at about 400°C (752°F). However, some cables would exhibit periodic “flashing” at relatively low temperatures but would not sustain flames until higher temperatures were reached.

The coatings did not systematically increase the effective ignition temperature of the cables. In fact, the bench-scale TGA and MCC and the cone calorimeter measurements indicate that the coatings pyrolyze at about 350°C (662°F).

Vertical flame spread experiments based on IEEE Standard 1202 were performed for three different cables and four different coatings. The coatings prevented the upward spread of fire from the 20 kW burner when applied according to the manufacturers’ recommendations. In several experiments in which the coatings were applied at a thickness just less than the recommended value, the fire did spread upward to various extents, but this behavior was not repeated when the coatings were applied as directed.

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# APPENDIX A
# Flaming Cable Coating Experiments

The plots on the following pages present all the data from the bench-scale circuit integrity experiments described in section 7. In these experiments, a single horizontal cable segment was immersed in a 25-centimeter (cm) (10-inch (in.)) long flame whose temperature at the point of impingement was approximately 750 degrees Celsius (°C) (1,382 degrees Fahrenheit (°F)). For each cable type (either 813 or 900), and two coating thicknesses (nominally 1.6 mm or 3.2 mm (1/16 in. or 1/8 in.)), and four coatings (Carboline, Flamemastic, FS15, and Vimasco), six experiments were conducted. For three, the internal temperature of the cable was monitored to the left and right of the flame center. For the other three, the voltage and amperage of an imposed current was monitored until a 3 ampere fuse tripped.

On the following pages, each set of six plots pertains to one type of coating. The top two plots show the results of uncoated cables on the same time scale as the plots below. The time of circuit failure for the three replicate experiments is indicated by vertical dashed lines. The word “Rep” in the plot legends indicates “Replicate.” Note that there is no correspondence between replicate thermal and electrical measurements because these measurements were made on separate cables.

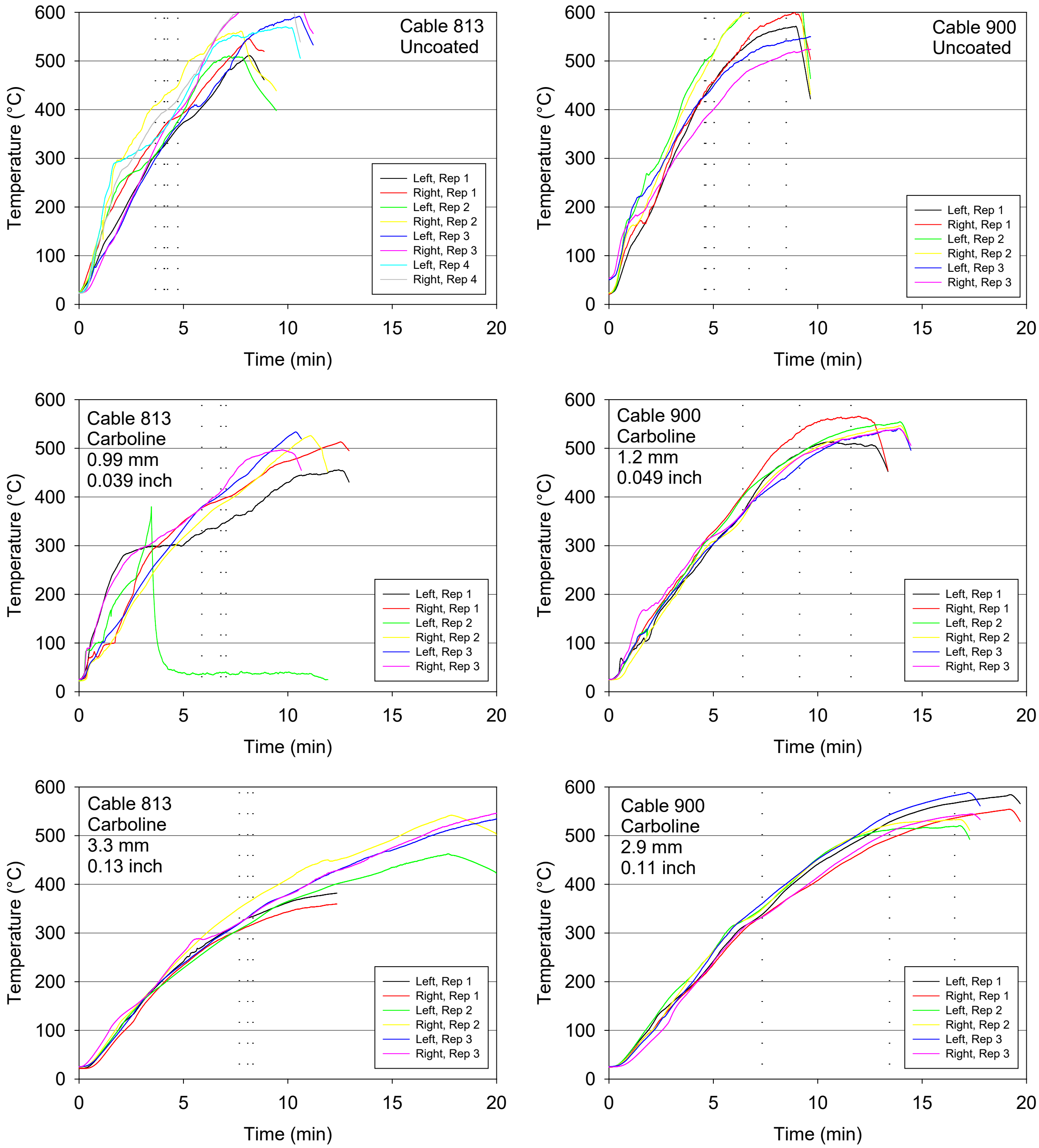


**Figure A-1. Inner temperature and time to failure for cables coated with Carboline.**

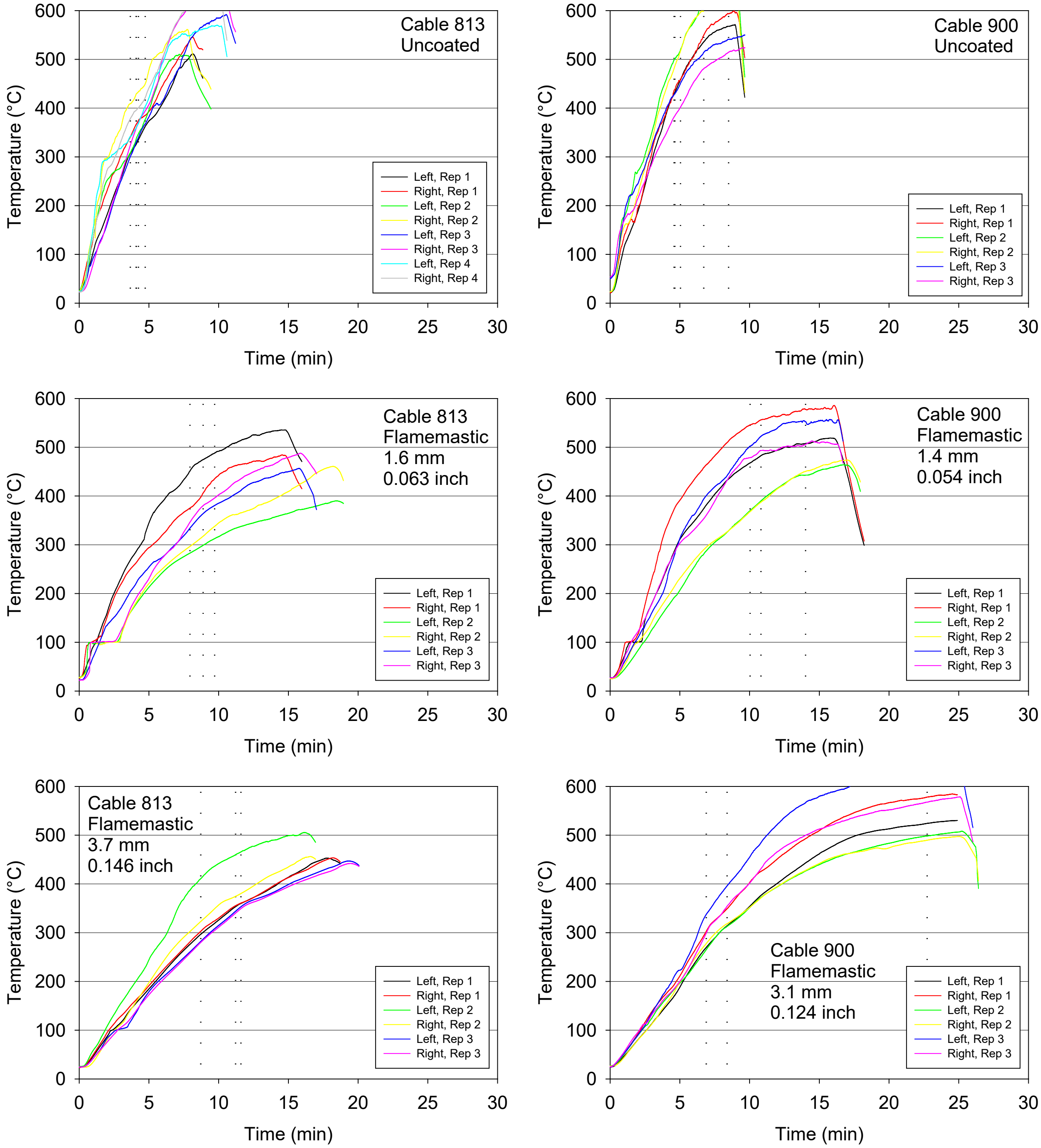


**Figure A-2. Inner temperature and time to failure for cables coated with Flamemastic.**

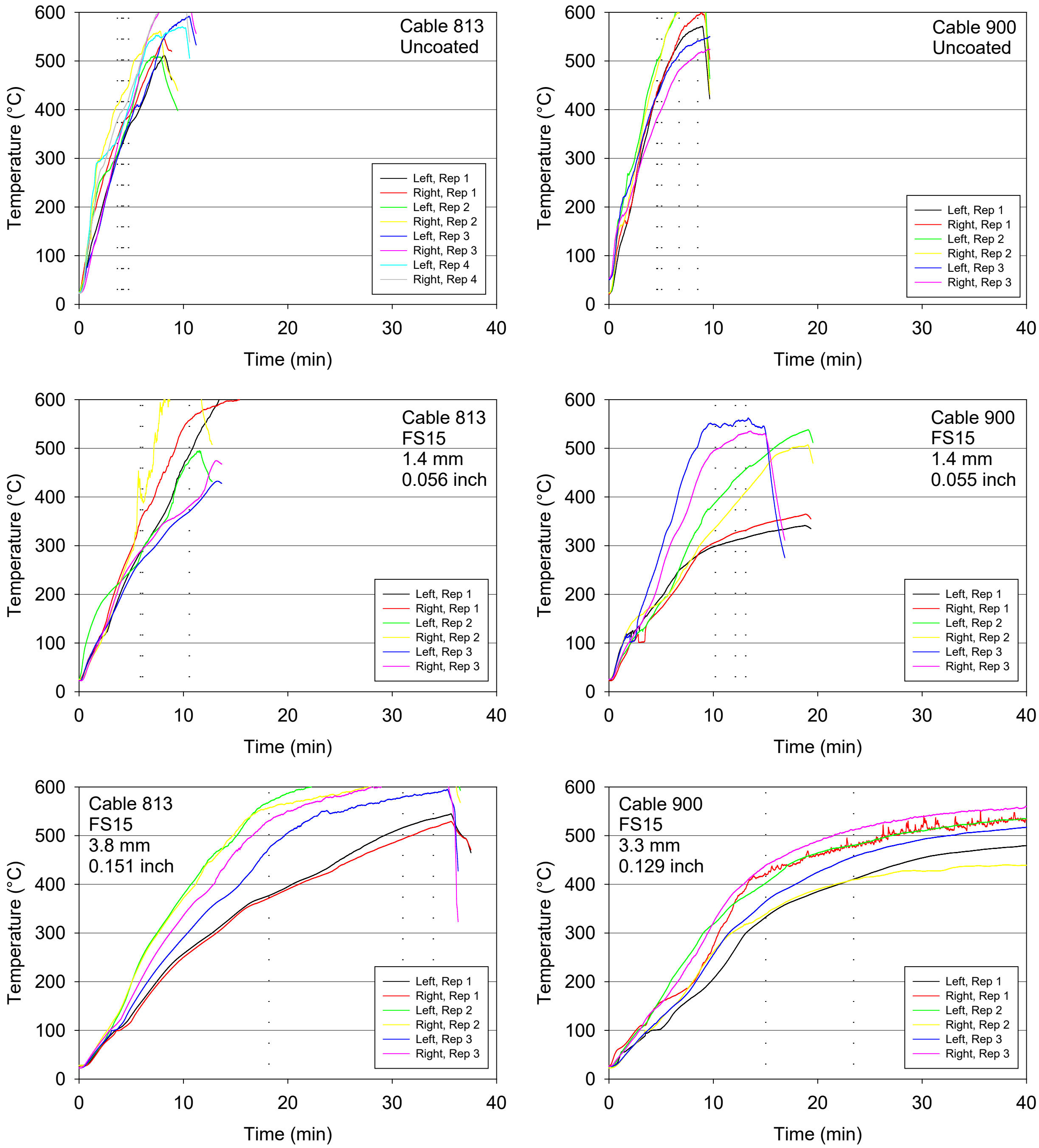


**Figure A-3. Inner temperature and time to failure for cables coated with FS15.**

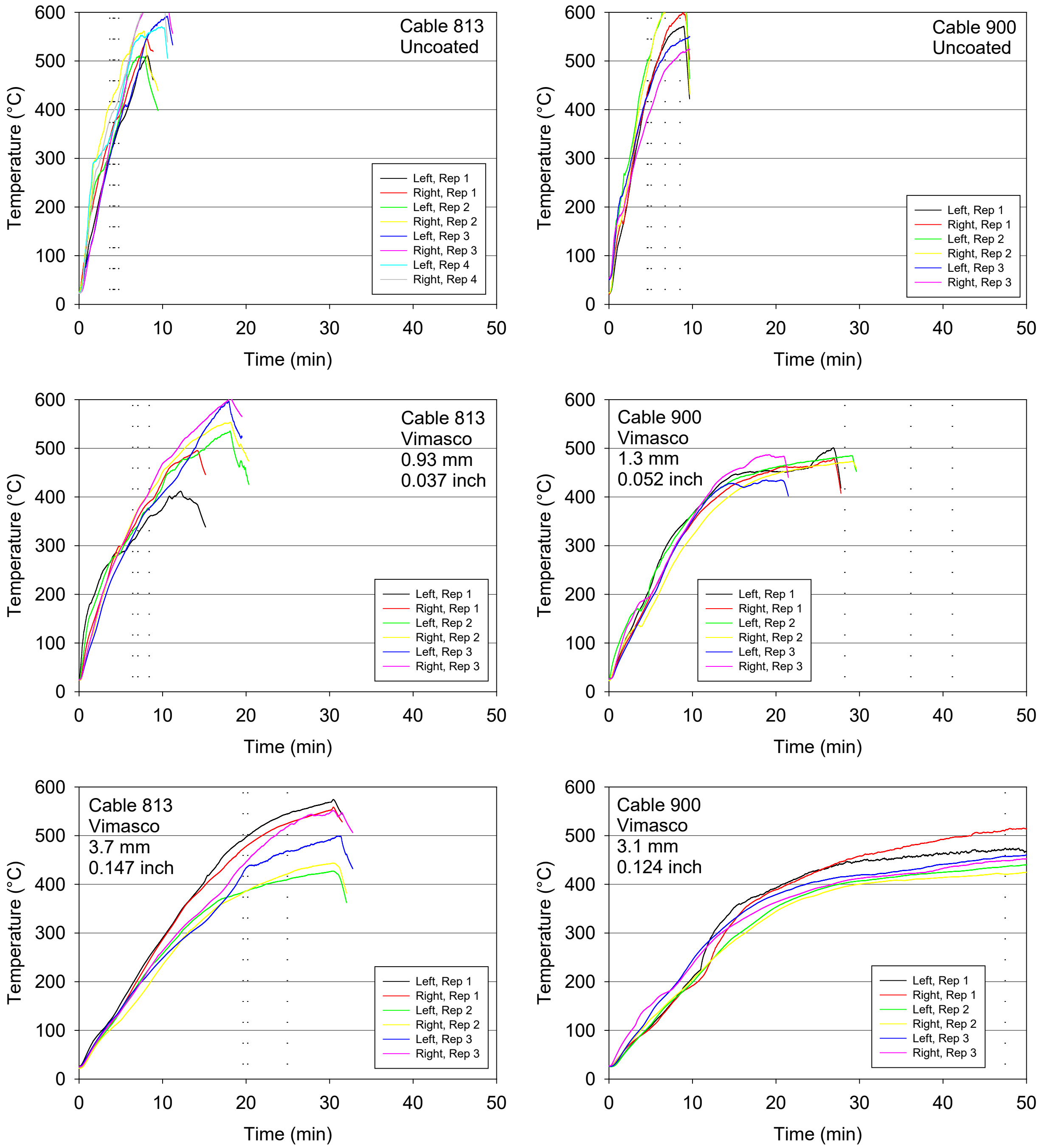


**Figure A-4. Inner temperature and time to failure for cables coated with Vimasco 3i.**