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# Response Bias of Electrical Cable Coatings at Fire Conditions (REBECCA-FIRE)

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# Response Bias of Electrical Cable Coatings at Fire Conditions (REBECCA-FIRE)

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# ABSTRACT

This report contains results of a multi-year experimental program called REBECCA-FIRE (Response Bias of Electrical Cable Coatings at Fire Conditions). Volume 2 of the three volume report focuses on the burning behavior of electrical cables that are protected with a variety of protective coatings. The experiments range from bench to full-scale. Ignition temperatures have been measured using a well-controlled convection oven. Burning rates of coated cables have been measured using a cone calorimeter in which 10 cm (4 in) by 10 cm (4 in) cable segments are exposed to a relatively high heat flux to determine their burning rate, heat of combustion, and other properties. Full-scale horizontal and vertical flame spread experiments have been conducted to determine if the coatings prevent the lateral and upward spread of fire over different types of cables, and to determine the time at which circuit integrity is lost.

# FOREWORD

To be filled in by US NRC.

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# EXECUTIVE SUMMARY

Volume 2 of the REBECCA-FIRE (Response Bias of Electrical Cable Coatings at Fire Conditions) program is focused on the burning behavior (ignition, burning rate, flame spread) of electrical cables protected with a variety of commercially-available protective coatings. This study follows on the CHRISTI-FIRE (Cable Heat Release, Ignition, and Spread in Tray Installations during Fire) research program whose objective was to quantify the burning behavior of unprotected electrical cables installed in cable trays (McGrattan *et al.* 2012).

Volume 1 of the REBECCA-FIRE program (Gonzalez *et al.*, 2017) provides a history of the use of protective cable coatings in the nuclear industry. Volume 3 (Taylor *et al*., 2017) documents the results of experiments on the electrical functionality of coated cables performed at NIST and Sandia National Laboratories.

Highlights of Volume 2 of REBECCA-FIRE include:

1. The thermal properties of four different coatings have been measured, including the density, specific heat, and thermal conductivity. Thermogravimetric analysis (TGA) and micro-combustion calorimetry (MCC) measurements have been performed on the coatings to determine the temperature at which they pyrolyze. These measurements are then used to extend a simple heat transfer model called THIEF (Thermally Induced Electrical Failure) to predict the rate of heat conduction through coated cable bundles.
2. Cone calorimeter measurements have been made on cable samples with and without protective coatings to determine the effect of the coatings on the burning rates of cables.
3. Coated and uncoated samples of cables have been heated uniformly in a convection oven to determine the temperature of ignition.
4. Full-scale vertical flame spread experiments involving trays of coated and uncoated cables have been performed to assess the claim that the coatings impede the vertical spread of fire. In some of these experiments, electrical functionality has been monitored to determine the role coatings play in delaying electrical failure in a fire.
5. Bench-scale measurements of circuit integrity have been performed in which a single energized cable, either coated or uncoated, is exposed directly to flame temperatures of approximately 750 °C (1382 °F).
6. Full-scale horizontal flame spread experiments have been performed to determine circuit failure times of coated cables undergoing slow, medium, and fast heating.

# ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| ASTM | American Society for Testing and Materials |
| AWG | American Wire Gauge |
| CAROLFIRE | Cable Response to Live Fire |
| CDRS | Conductors |
| CHRISTIFIRE | Cable Heat Release, Ignition, and Spread in Tray Installations |
| CSPE | Chloro-Sulfonated Polyethylene |
| CVTC | Continuous Vulcanization Tray Cable |
| DEG C | Degrees Celsius |
| DIR BUR | Direct Burial |
| EN | European standard test designation |
| EPR | Ethylene-Propylene Rubber |
| EPRI | Electric Power Research Institute |
| FLASH-CAT | Flame Spread over Horizontal Cable Trays |
| FMRC | Factory Mutual Research Corporation |
| FR | Flame Retardant |
| FT4 | Flame Test 4 |
| FR-XLP | Flame Retardant Cross-Linked Polyethylene |
| FR-XLPE | Flame Retardant Cross-Linked Polyethylene |
| 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 |
| ISO | International Organization for Standardization |
| LSZH | Low Smoke Zero Halogen |
| MCC | Micro-Combustion Calorimetry |
| NEC | National Electric Code |
| NIST | National Institute of Standards and Technology |
| NPP | Nuclear Power Plant |
| NRC | Nuclear Regulatory Commission |
| NRR | NRC Office of Nuclear Reactor Regulation |
| OIL RES | Oil Resistant |
| PE | Polyethylene |
| PRA | Probabilistic Risk Assessment |
| PVC | Poly-vinyl Chloride |
| REBECCA-FIRE | Response Bias of Electrical Cable Coatings at Fire Conditions |
| RES | NRC Office of Nuclear Regulatory Research |
| ROHS | Restriction of Hazardous Substances |
| SIS | Safety Instrumented System |
| SNL | Sandia National Laboratories |
| SP | Swedish National Testing and Research Institute |
| SR | Silicone Rubber |
| SUN RES | Sun Resistant |

| | |
|---|---|
| TC | Thermocouple or Tray Cable |
| TC-ER | Tray Cable - Exposed Run |
| TC/NCC | Tray Cable/Nickel Coated Copper |
| Tefzel® | DuPont ETFE (Ethylene-Tetrafluoroethylene) Resin |
| TFN | Thermoplastic Fixture wire Nylon jacketed |
| 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 |
| UL | Underwriters Laboratories |
| VNTC | Vinyl Nylon Tray Cable |
| XHHW | Cross-linked High Heat Water resistant |
| VTT | Valtion Teknillinen Tutkimuskeskus (Technical Research Centre, Finland) |
| XLPE, XLP or XPE | Cross-Linked Polyethylene |
| XLPO | Cross-Linked Polyolefin |

# 1 BACKGROUND

Electrical cables perform numerous functions in nuclear power plants (NPP). Power cables supply electricity to motors, transformers, heaters, light fixtures, fire suppression equipment, and reactor cooling equipment. Control cables connect plant equipment such as motor-operated valves (MOVs) and motor starters to remote initiating devices (e.g., switches, relays, and contacts). Instrumentation cables transmit low-voltage signals between input devices and display panels. NPPs typically contain hundreds of miles of electrical cables. A typical boiling-water reactor (BWR) requires approximately 100 km (60 mi) of power cable, 80 km (50 mi) of control cable and 400 km (250 mi) of instrument cable. A pressurized-water reactor (PWR) may require even more cables. The containment building of Waterford Steam Electric Generating Station, Unit 3 requires nearly 1,600 km (1,000 mi) of cable (US NRC, NUREG/CR-6384).

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

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

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

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

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

## 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, NUREG/CR-6931) project (Nowlen et al., 2007) 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 (McGrattan 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

The second phase of the REBECCA-FIRE program focusses 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 if one is to incorporate a coating in a thermal penetration calculation like the THIEF (Thermally Induced Electrical Failure) model described in NUREG/CR-6931, Vol. 3 (McGrattan, 2008).

In addition to these basic thermal properties, additional experiments were conducted to determine the burning behavior. These experiments include TGA (Thermogravimetric Analysis) and MCC (Micro-Combustion Calorimetry). Both of these 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 testing like that performed in the CAROLFIRE program (Nowlen *et al*., 2007). 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. As a general rule, 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 IEEE 1202, *Standard for Flame Testing of Cables for Use in Cable Tray in Industrial and Commercial Occupancies* (1991). A modified version of this test has been performed at NIST using three different cables protected by four different coatings. Two series of experiments have been performed, the first involving unenergized cables; the second energized and thermally monitored cables. The objectives of the experiments were to confirm that cable coatings prevent upward flame spread, and to quantify the delay in electrical failure afforded by this type of protection.

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

An important question regarding 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 chapter provides descriptions of 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 the “Item No.” or “Cable #” is merely an identifier and has no relevance beyond this project. Photographs of the cables are shown in Figure 3-1 and Figure 3-2. The cable markings are listed in Table 3-1. The cable properties are listed in Table 3-2. The reported cable diameter and layer thickness measurements have a combined standard uncertainty of 0.2 mm. The mass fraction measurements were obtained by dissecting 20 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. NIST guidelines for expressing measurement uncertainty are given by Taylor and Kuyatt (1994).

A cross reference of the cables used in CAROLFIRE (Nowlen et al., 2007) and those purchased and those left over from previous NRC-sponsored experiments at Brookhaven National Laboratory are listed in Table 3-1.

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

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

812 813 814 815 816 817 818 819 822 823 824

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

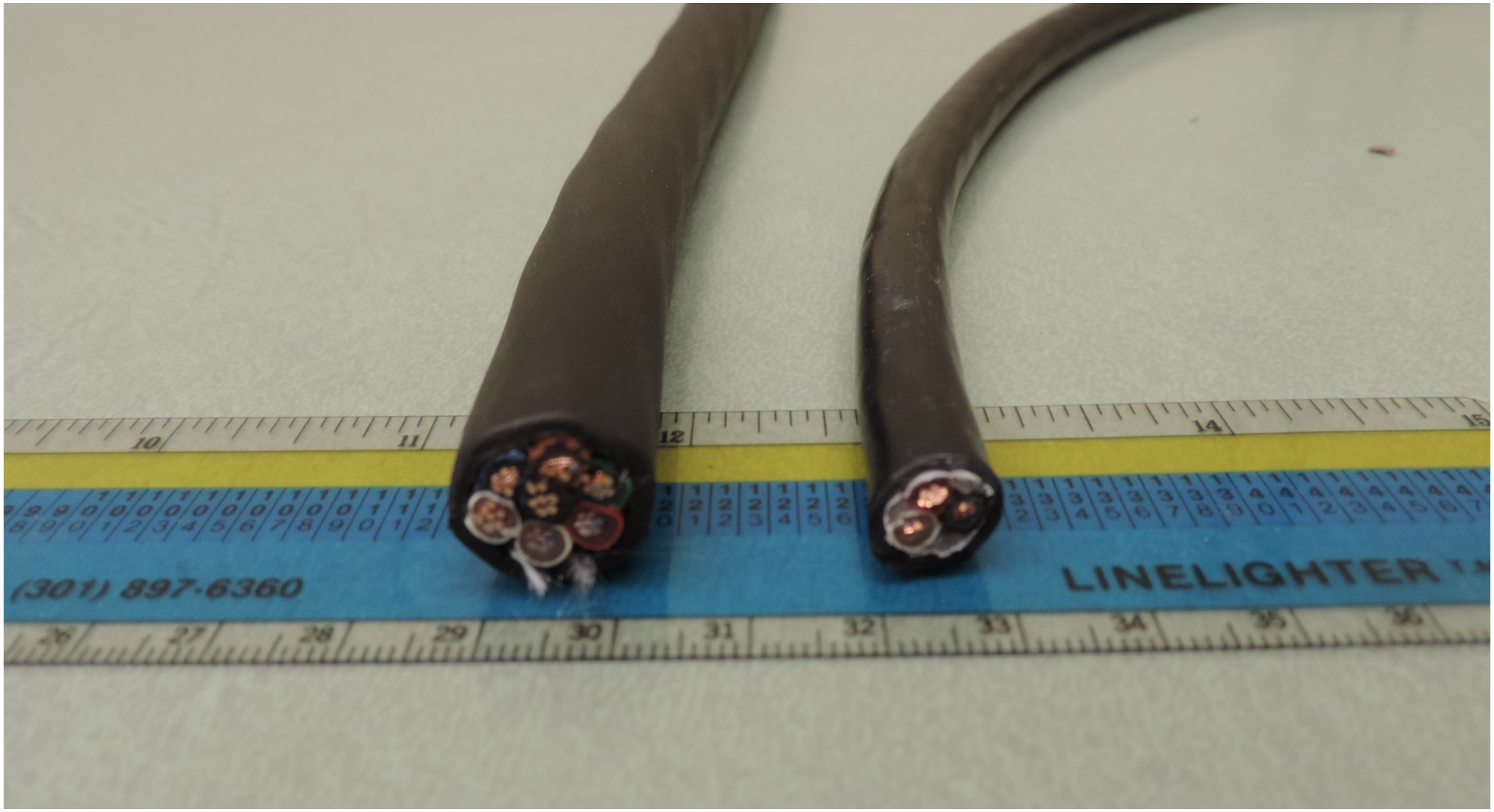


**Figure 3-3. Photograph of Cables 900 (left) and 902 (right).**

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

| 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 600V 09 MAR 2006 |
| 815 | PURCHASED | GENERAL CABLE | 2011 | GENERAL CABLE® (WC) VNTC 12/C 18AWG (UL) TYPE TC-ER TFN CDRS SUN RES DIR BUR 600V ROHS 20 JAN 2011 |
| 816 | PURCHASED | ROCKBESTOS | 2011 | 4 SHIELDED PAIRS 16 AWG COPPER ROCKBESTOS-SURPRENANT (G) 600V 90 DEG C WET OR DRY FIREWALL(R) III SUN RES DIR BUR OIL RES II NEC TYPE TC (UL) FRXLPE SHIELDED CSPE I46-5844 2011 1D-138 |
| 817 | CAROLFIRE #7 | ROCKBESTOS | 2006 | 2/C 16 AWG COPPER ROCKBESTOS-SURPRENANT (G) 600V 90 DEG C WET OR DRY FIREWALL(R) III SUN RES DIR BUR OIL RES II NEC TYPE TC (UL) FRXLPE SHIELDED CSPE I46-0021 2006 6C-191 |
| 818 | BROOKHAVEN | ROCKBESTOS | 1981 | ROCKBESTOS® RSS-6-104 1981 |
| 819 | | FIRST CAPITOL | 2003 | NO MARKINGS |
| 822 | BROOKHAVEN | ROCKBESTOS | UNKNOWN | NO MARKINGS |
| 823 | BROOKHAVEN | ROCKBESTOS | UNKNOWN | 12 AWG ROCKBESTOS® FIREWALL® TYPE SIS 600V (UL) NUCLEAR |
| 824 | | KERITE | 1989 | KERITE 1989 #12 AWG CU 600V FR3 TEST # A6272 |
| 900 | PURCHASED | LAKE CABLE | 2015 | #2582 FT. TPT127 LAKE CABLE 12AWG 7C PE/PVC2010 CONTROL CABLE 600V 75$^0$ C 2015 “ROHS 11” REACH MADE IN USA 280547 |
| 902 | TVA | CYPRUS WIRE & CABLE | 1975 | 3460 FEET CYPRUS WIRE & CABLE 75K/-8615U-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 the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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

| Cable No. | Insulation Material | Jacket Material | Class. | Conductors | Diameter (mm) | Jacket Thickness (mm) | Insulator Thickness (mm) | Mass per Length (kg/m) | Copper Mass Fraction | Jacket Mass Fraction | Insulation Mass Fraction | Filler Mass Fraction |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 800 | PVC | PVC | TP | 7 | 12.4 | 1.3 | 0.7 | 0.31 | 0.66 | 0.19 | 0.11 | 0.01 |
| 801 | PVC/Nylon | PVC | TP | 7 | 12.5 | 1.3 | 0.6 | 0.31 | 0.66 | 0.19 | 0.11 | 0.01 |
| 802 | XLPE | CSPE | TS | 7 | 15.0 | 2.3 | 1.2 | 0.42 | 0.50 | 0.30 | 0.20 | 0.01 |
| 803 | XLPE | CSPE | TS | 7 | 15.0 | 2.4 | 1.0 | 0.44 | 0.48 | 0.32 | 0.19 | 0.01 |
| 804 | XLPE | PVC | Mix | 7 | 15.1 | 1.6 | 1.0 | 0.41 | 0.52 | 0.23 | 0.22 | 0.01 |
| 805 | Tefzel® | | TP | 7 | 10.2 | 0.8 | 0.5 | 0.29 | 0.74 | 0.08 | 0.15 | 0.02 |
| 806 | XLPE | XLPO | TS | 7 | 12.2 | 1.2 | 0.8 | 0.32 | 0.66 | 0.18 | 0.17 | 0.00 |
| 807 | PE | PVC | TP | 7 | 14.0 | 1.5 | 0.3 | 0.37 | 0.59 | 0.24 | 0.15 | 0.01 |
| 808 | VITA-LINK® | | TS | 7 | 19.6 | 2.4 | 1.7 | 0.48 | 0.26 | 0.33 | 0.43 | 0.01 |
| 809 | SR | Aramid Braid | TS | 7 | 14.5 | 1.2 | 1.1 | 0.35 | 0.62 | 0.08 | 0.31 | 0.01 |
| 810 | PVC/Nylon | PVC | TP | 3 | 15.2 | 1.7 | 1.1 | 0.43 | 0.63 | 0.23 | 0.12 | 0.01 |
| 811 | XLPE | CSPE | TS | 3 | 16.3 | 1.9 | 1.72 | 0.43 | 0.55 | 0.29 | 0.16 | 0.03 |
| 812 | XLPE | CSPE | TS | 3 | 16.3 | 2.5 | 1.7 | 0.54 | 0.53 | 0.29 | 0.14 | 0.03 |
| 813 | XLPE | CSPE | TS | 12 | 12.7 | 1.5 | 1.2 | 0.25 | 0.37 | 0.33 | 0.29 | 0.01 |
| 814 | PVC | PVC | TP | 12 | 11.3 | 1.2 | 0.5 | 0.19 | 0.56 | 0.03 | 0.40 | 0.00 |
| 815 | PVC/Nylon | PVC | TP | 12 | 11.3 | 1.2 | 0.5 | 0.19 | 0.59 | 0.02 | 0.29 | 0.06 |
| 816 | XLPE | CSPE | TS | 4 | 16.7 | 2.9 | 1.1 | 0.42 | 0.26 | 0.45 | 0.22 | 0.07 |
| 817 | XLPE | CSPE | TS | 2 | 7.8 | 1.6 | 0.9 | 0.11 | 0.24 | 0.58 | 0.15 | 0.00 |
| 818 | PE | PVC | TP | 1 | 6.3 | 1.4 | 1.4 | 0.06 | 0.38 | 0.40 | 0.07 | 0.15 |
| 819 | SR | Glass Braid | TS | 3 | 16.3 | 1.4 | 20.1 | 0.52 | 0.47 | 0.08 | 0.24 | 0.19 |

| Cable No. | Insulation Material | Jacket Material | Class. | Conductors | Diameter (mm) | Jacket Thickness (mm) | Insulator Thickness (mm) | Mass per Length (kg/m) | Copper Mass Fraction | Jacket Mass Fraction | Insulation Mass Fraction | Filler Mass Fraction |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 822 | SR | Glass Braid | TS | 1 | 3.7 | 0.3 | 1.0 | 0.03 | 0.48 | 0.18 | 0.31 | 0.01 |
| 823 | XLPE | | TS | 1 | 3.8 | 1.2 | N/A | 0.04 | 0.70 | 0.30 | 0.00 | 0.00 |
| 824 | EPR | CSPE | TS | 1 | 5.1 | 1.4 | 1.1 | 0.08 | 0.34 | 0.46 | 0.20 | 0.00 |
| 900 | PE | PVC | TP | 7 | 15.9 | 1.9 | 1.1 | 0.38 | 0.55 | 0.27 | 0.10 | 0.08 |
| 902 | PE | PVC | 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 is performed with techniques similar to those used in the THIEF (Thermally-Induced Electrical Failure) model (McGrattan 2008).

### 3.2.1 Carboline Intumastic 285

Carboline Intumastic 285 is a registered product of the Carboline Company (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 (flamemaster.com). According to manufacturer literature, the coating material consists of water-based thermoplastic 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 of which 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 (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 (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 testing. The samples were approximately 10 cm by 10 cm by 1.5 cm thick. The uncertainty in the bulk density is mainly due to the uncertainty in the measurement of the sample thickness, which is ±1 mm (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 only measures the volume of the solid material as opposed to void spaces within the solid. Three samples of each material were measured. The results are summarized in Table 3-3. 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 | 1740 ± 10 |
| Vimasco 3i | 852 ± 60 | 1480 ± 20 |
| Flamemastic 77 | 1033 ± 72 | 2030 ± 10 |
| FS15 | Not measured | 1660 ± 20 |

### 3.2.6 Heat Capacity

Specific heat capacities at room temperature were measured using differential scanning calorimetry (DSC) according to ASTM E1269-11 (ASTM 2011), but at a heating rate of 10 °C/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. The results are presented in Table 3-4.

**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 |
| FS 15 | 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 $T_g$, 2σ = ± 2.4 °C
b – $T$ is in K for calculation of specific heat
c – Vimasco begins to degrade at approximately 160 (°C)

### 3.2.7 Thermal Conductivity

Room temperature (20 °C, 68 °F) thermal conductivities were measured using a Hot Disk TPS thermal constants analyzer. For each coating material, two measurements were taken at three different locations for a total of 6 measurements per material. A nominal 6.4 mm Kapton probe was used with typical probing depths of 5 mm to 7 mm. The results are summarized in Table 3-5.

**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 |
| FS 15 | 0.642 | 0.022 |

### 3.2.8 Thermogravimetric Analysis (TGA)

The thermal degradation of the three coating samples was studied using thermogravimetric analysis (ASTM E1131-08, 2014). In this test method, approximately 10 mg of each coating was placed on a small load cell in heated chamber whose temperature was increased at a rate of 5 ºC/min up to 800 °C. The relative mass of the sample as a function of temperature is shown in Figure 3-4. Note that each coating leaves a residue behind, as indicated by the right hand tail of each plot.

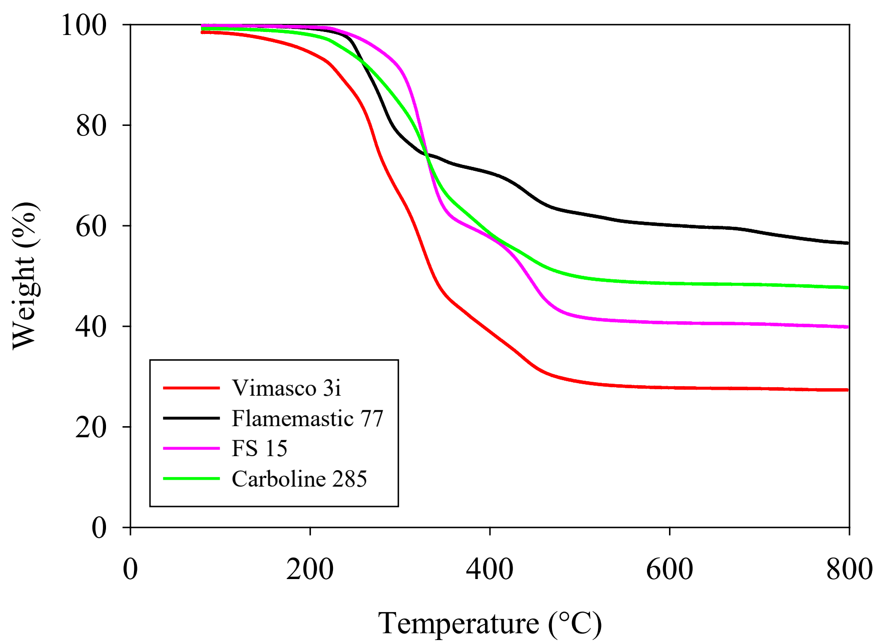


**Figure 3-4. Results of the thermogravimetric analysis (TGA) of the four cable coatings.**

The TGA results indicate that there are two significant reactions that occur; the first at approximately 300 ºC and the second at approximately 450 ºC. 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. (Lyon, 2012), the relative standard uncertainty of the reaction rate is 3 %.

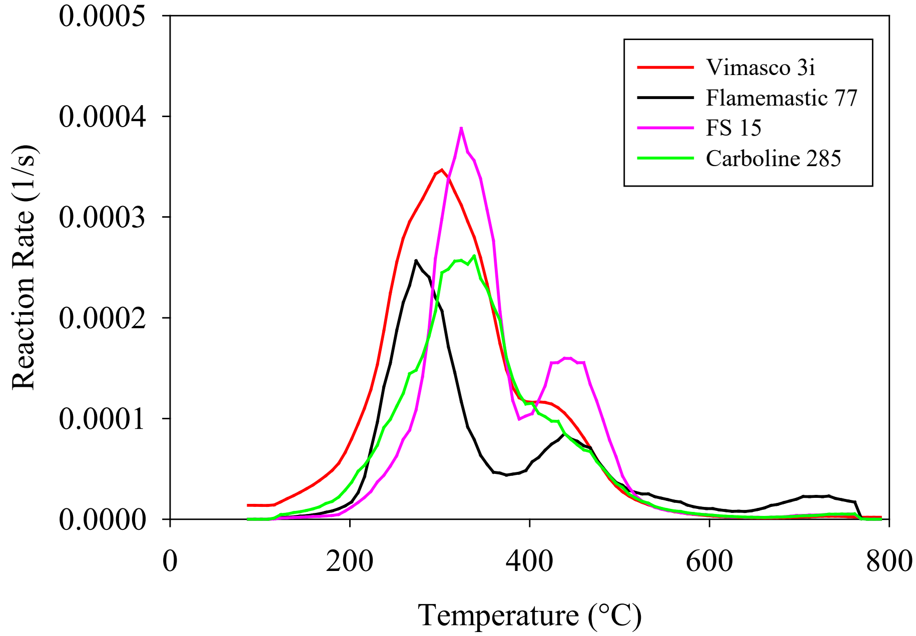


**Figure 3-5. TGA results for the cable coatings, expressed in terms of a reaction rate.**

### 3.2.9 Micro-Combustion Calorimetry (MCC)

One drawback of TGA is that it only indicates the temperatures at which the sample off-gases. It does not indicate whether these gases are combustible. However, there is a similar technique, called micro-combustion calorimetry (MCC), which indicates the relative flammability of the off-gas (ASTM D7309-13, 2013). For each material, three replicate tests were performed at a nitrogen purge gas flow rate of approximately 80 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. There is a difference in the location of the peaks between the TGA and MCC, which is partly explained by the fact that the heating rate in the two tests differs by an order of magnitude. The TGA is typically operated with a heating rate of 5 ºC/min, whereas the MCC is operated at a rate of 60 ºC/min. In any event, these tests indicate that all four coatings do burn, leaving a relatively large amount of residue. According to an analysis by Lyon et al. (Lyon, 2012), the relative standard uncertainty of the heat release rate (HRR) is 22 %.

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

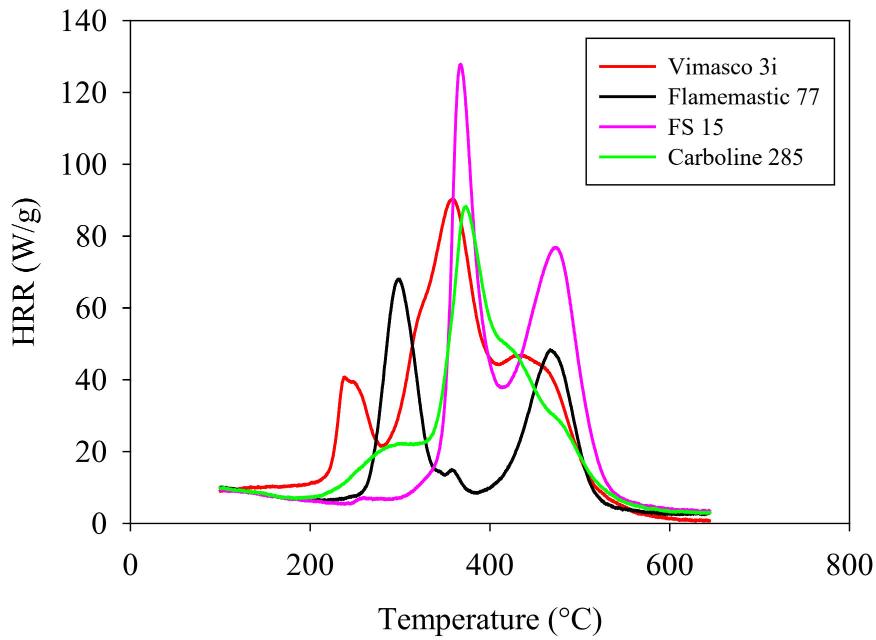


**Figure 3-6. MCC results for the cable coatings.**

**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 kW/m$^2$. A description of the cone calorimeter and its uncertainty is given in Chapter 4. Only one replicate was performed for each sample. Each was approximately 10 cm by 10 cm. The sample thickness and mass were:

Flamemastic 77: thickness 14.8 mm ± 1 mm, mass 153.0 g ± 0.05 g (standard uncertainty)

Vimasco 3i: thickness 13.4 mm ± 1 mm, mass 114.2 g ± 0.05 g

Carboline 285: thickness 16.1 mm ± 1 mm, mass 129.5 g ± 0.05 g

Note that FS15 was not evaluated in this exercise. The heat release rates of the samples are shown in Figure 3-7 through Figure 3-9. 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, owing to the fact that it undergoes thermal degradation at lower temperatures, according to the TGA and MCC measurements, Figure 3-5 and Figure 3-6.

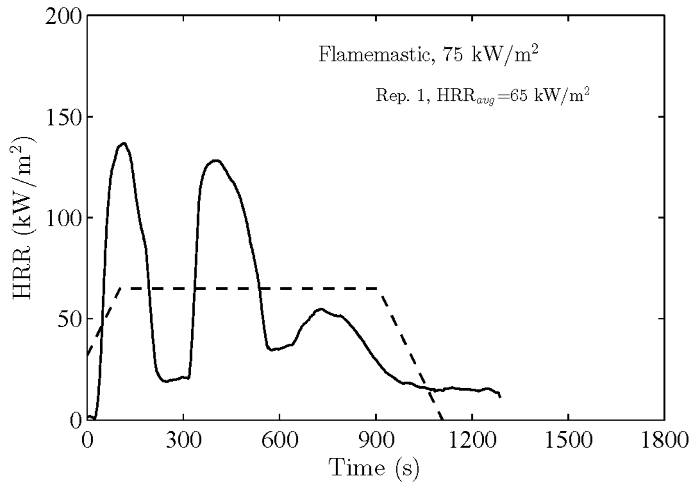


**Figure 3-7. Cone calorimeter results for Flamemastic 77.**

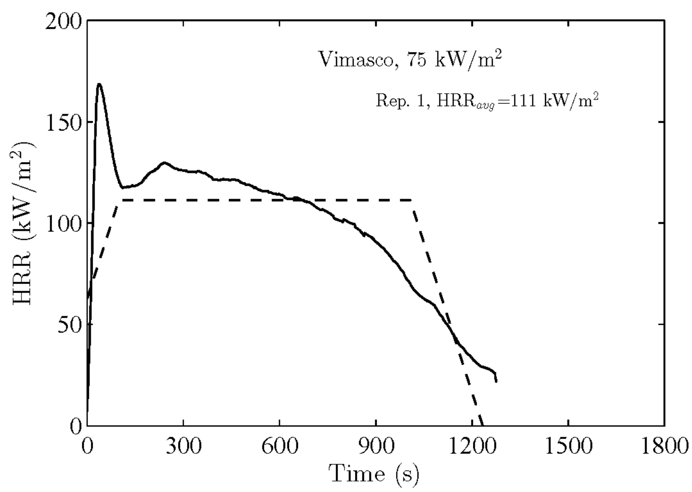


**Figure 3-8. Cone calorimeter results for Vimasco 3i.**

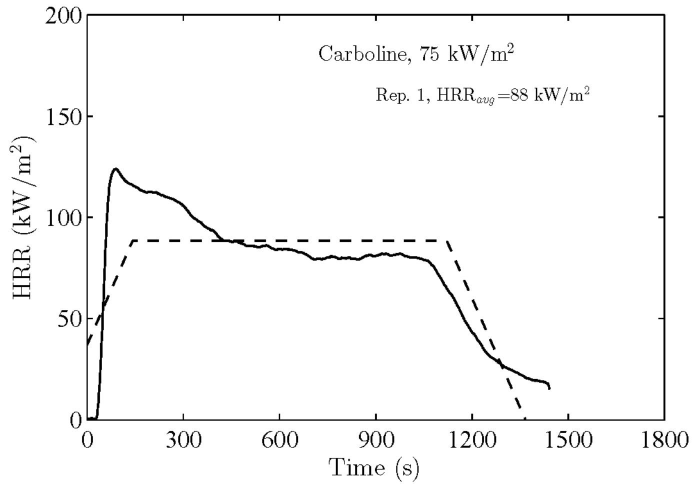


**Figure 3-9. Cone calorimeter results for Carboline 285.**

### 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 ten 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]. The bundle configuration is shown in Figure 3-10. 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.

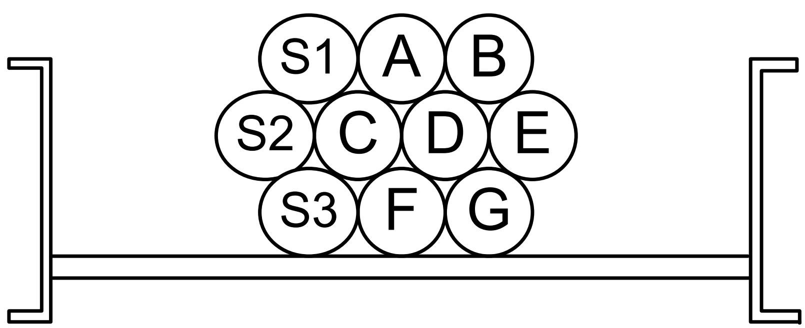


**Figure 3-10. Ten-cable bundle configuration tested at Sandia National Laboratories**

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.

There are a number of ways that the heat transfer within the bundle can be modeled. A two or three-dimensional model could account for the different materials (coating, plastics, copper) and

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

the overall configuration. However, such a calculation requires a considerable effort and it is not always possible to measure the thermal properties of all the materials. Instead, a one-dimensional heat conduction model was developed called THIEF (Thermally-Induced Electrical Failure) 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 ten 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. The measured[2] and predicted temperatures of Cables A, B, and C are shown in Figure 3-11 through Figure 3-13. The THIEF model assumes that the bundle is circular in cross section with a diameter of 4 cm. Its density, based on the mass of the cables per unit length and its assumed total cross sectional area, is 2321 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. In the coated case, the depth is 4.0 mm. The actual measured properties of the coatings are not actually used in this calculation; only the relative depths. For Cables A and B, the difference in depth alone explains the difference in temperature between the uncoated and coated bundles. Cable C is more difficult to predict. 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 A and B for the coated bundles.

In the SNL experiments, the uncoated bundles ignited after approximately 24 min (1440 s). 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 1800 s simply because the TC measurements became increasingly erratic as the cables and coatings approached their ignition temperatures which are in the range between 300 ºC and 400 ºC. It is not obvious, based on the measured thermal properties, why the Carboline coating delays ignition more than 20 min beyond that of the other two coatings. One possible explanation is simply that the temperature at which the Carboline coating undergoes peak pyrolysis is higher than the other two coatings, as shown in Figure 3-5 and Figure 3-6. A second possibility is that the Carboline coating was difficult to apply consistently because of its rough texture.

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

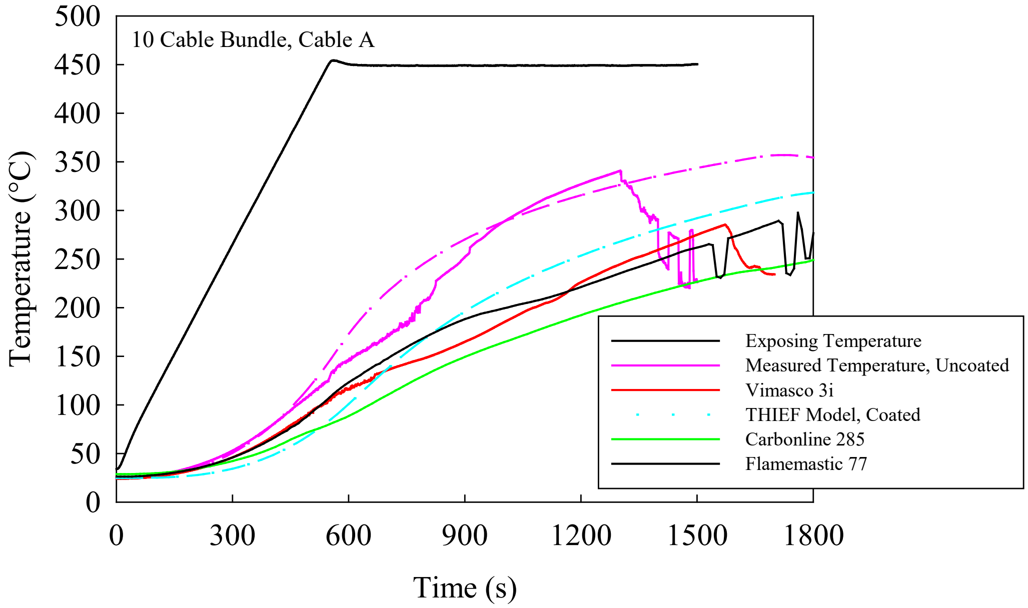


**Figure 3-11. Measured and predicted temperatures inside 10-cable bundle, Cable A.**

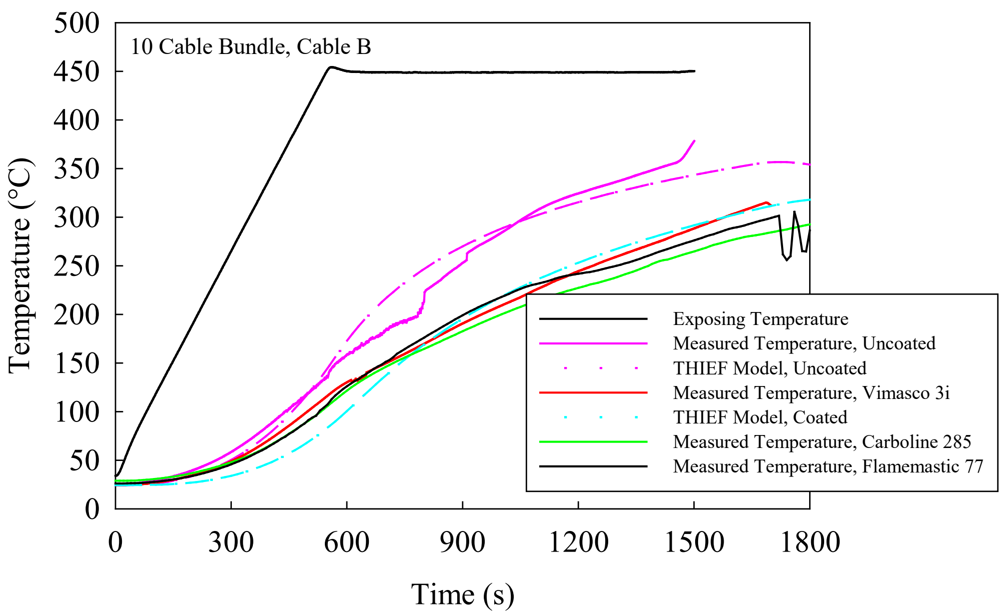


**Figure 3-12. Measured and predicted temperatures inside 10-cable bundle, Cable B.**

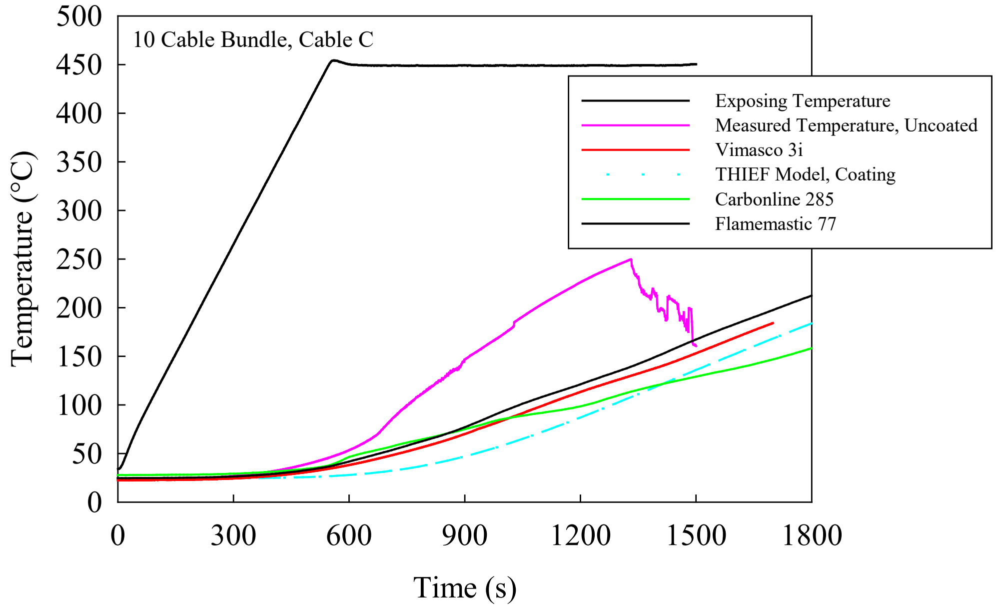


**Figure 3-13. Measured and predicted temperatures inside 10-cable bundle, Cable C.**

The results shown in this section demonstrate 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 chapter 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 heat release rate of a material sample under a constant imposed heat flux. In Phase 1 of the CHRISTIFIRE program (McGrattan *et al.*, 2012), 12 cable samples were tested at 3 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 heat release rates consistent with larger scale experiments; thus, in subsequent testing only heat fluxes of 50 kW/m$^2$ or 75 kW/m$^2$ were used.

The cone calorimeter measurements were conducted using the standardized procedure for cables, ASTM D 6113-03 (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 in width, 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 upwards when heated. The entire assembly is shown in Figure 4-3. The coated samples are shown in Figure 4-4 through Figure 4-6.

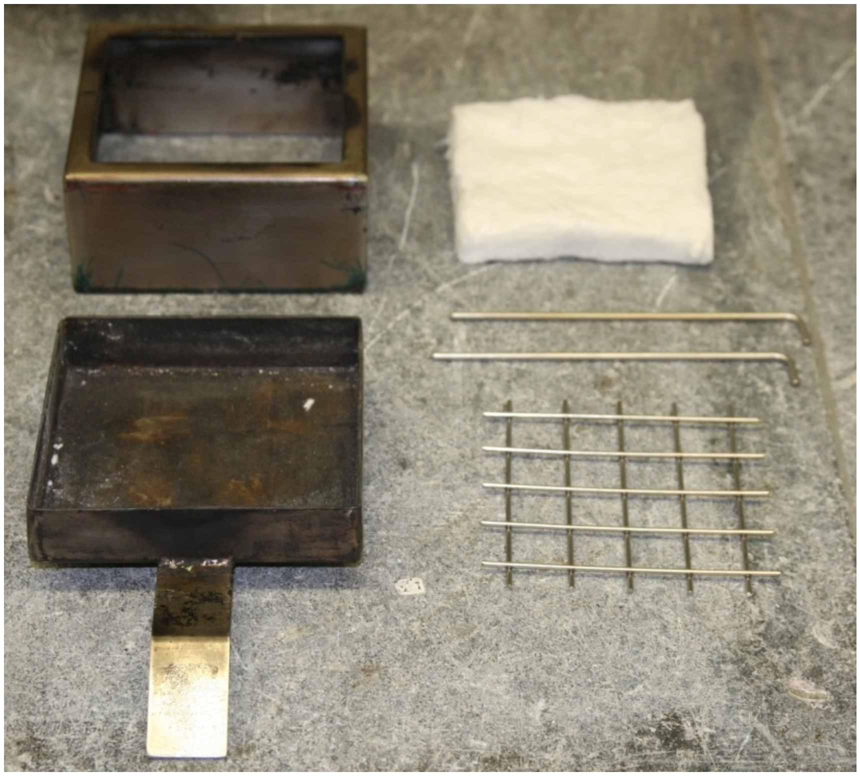

**Figure 4-2. Components of the cone calorimeter sample holder.**

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

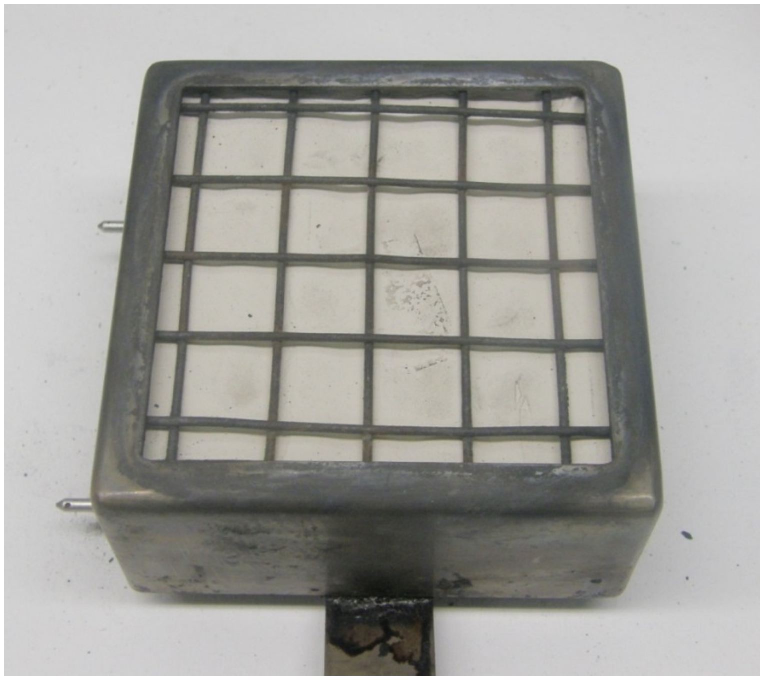

**Figure 4-4. Cable 802 coated with Flamemastic F-77.**

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

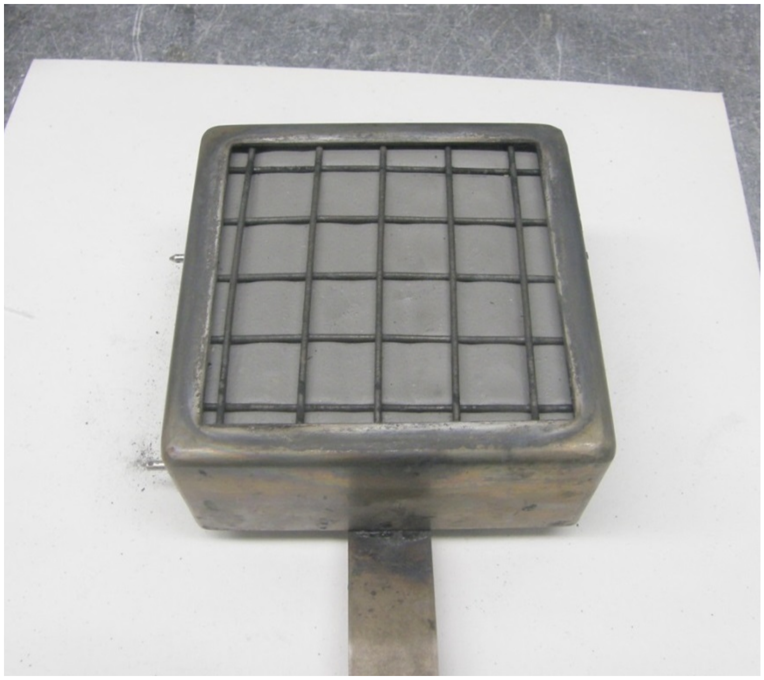

**Figure 4-6. Cable 802 coated with Vimasco 3i.**

## 4.2 Uncertainty

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

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

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

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

## 4.3 Results

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

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

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

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

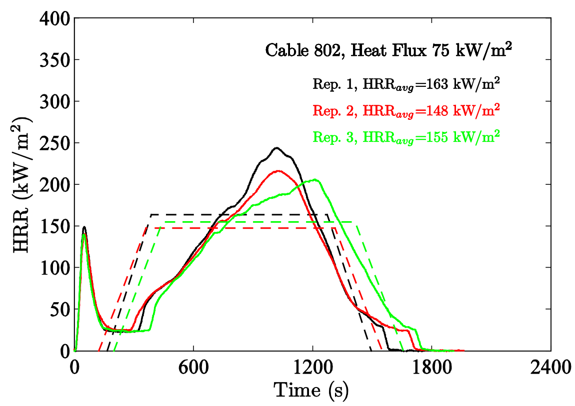


**Figure 4-7. Sample output from cone calorimeter.**

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

$$\overline{\dot{q}''} = \frac{\int_{t_1}^{t_2} \dot{q}''\, dt}{t_2 - t_1} \qquad (4\text{-}3)$$

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

### 4.3.1 Cable 802

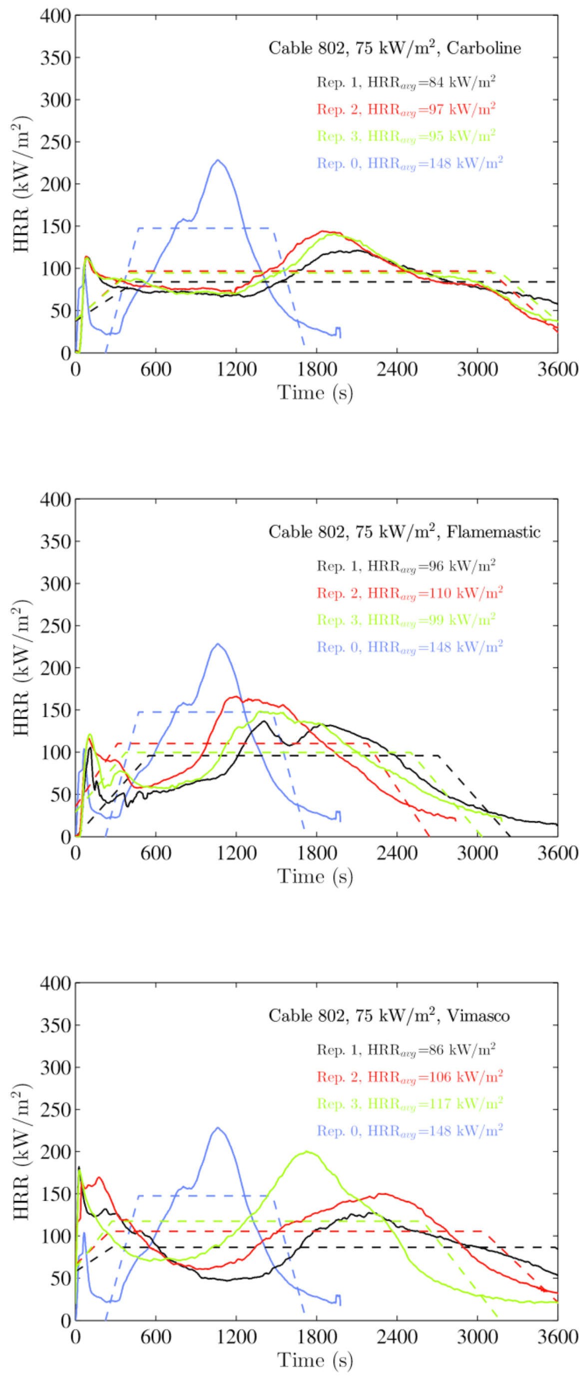


**Figure 4-8. Cone calorimeter results for Cable 802. Rep 0 denotes the uncoated sample.**

### 4.3.2 Cable 802 and Cable 807, mixed

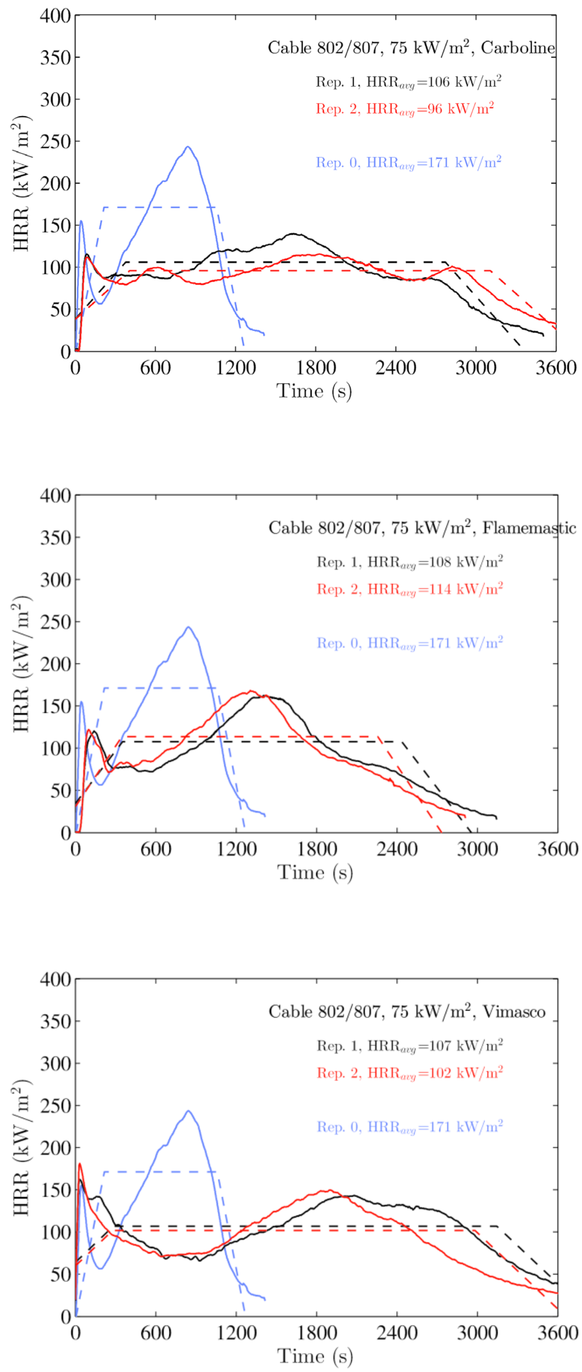


**Figure 4-9. Cone calorimeter results for Cables 802 and 807, mixed. Rep 0 denotes the uncoated sample.**

### 4.3.3 Cable 804

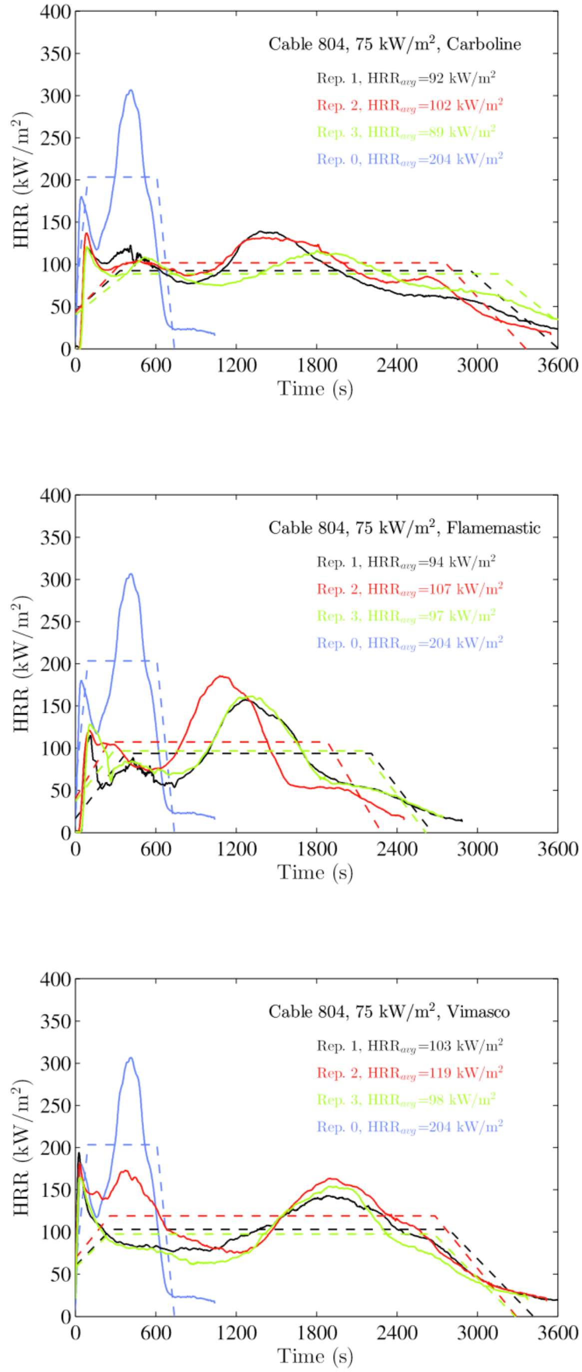


**Figure 4-10. Cone calorimeter results for Cable 804. Rep 0 denotes the uncoated sample.**

### 4.3.4 Cable 805

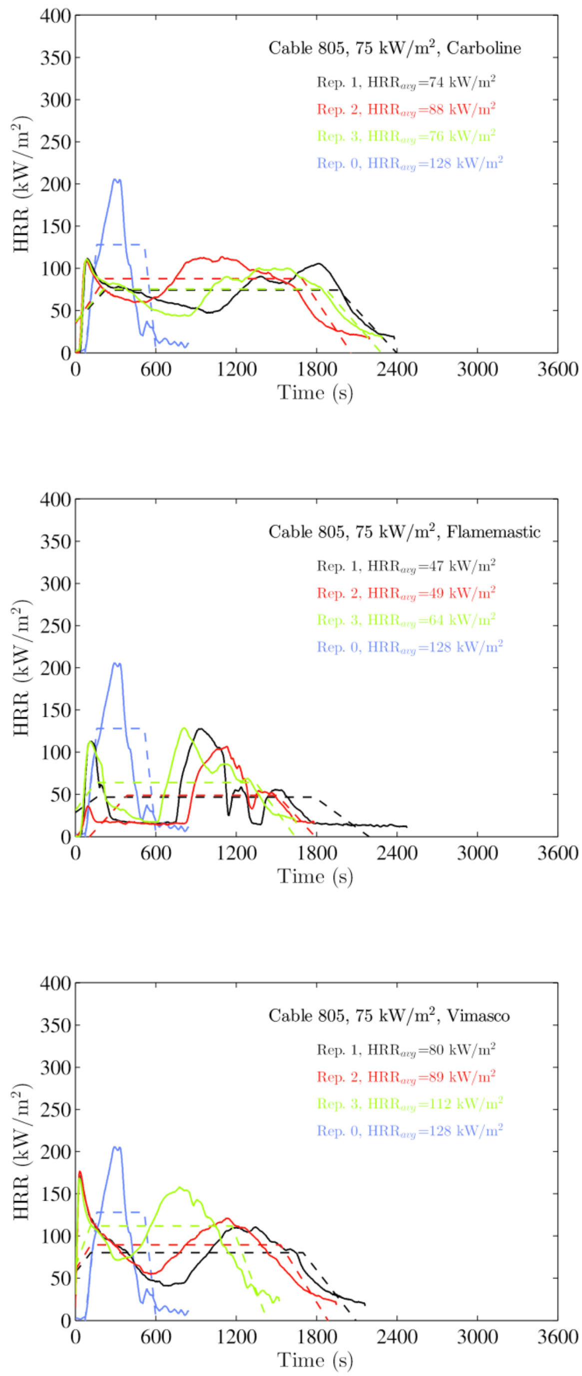


**Figure 4-11. Cone calorimeter results for Cable 805. Rep 0 denotes the uncoated sample.**

### 4.3.5 Cable 806

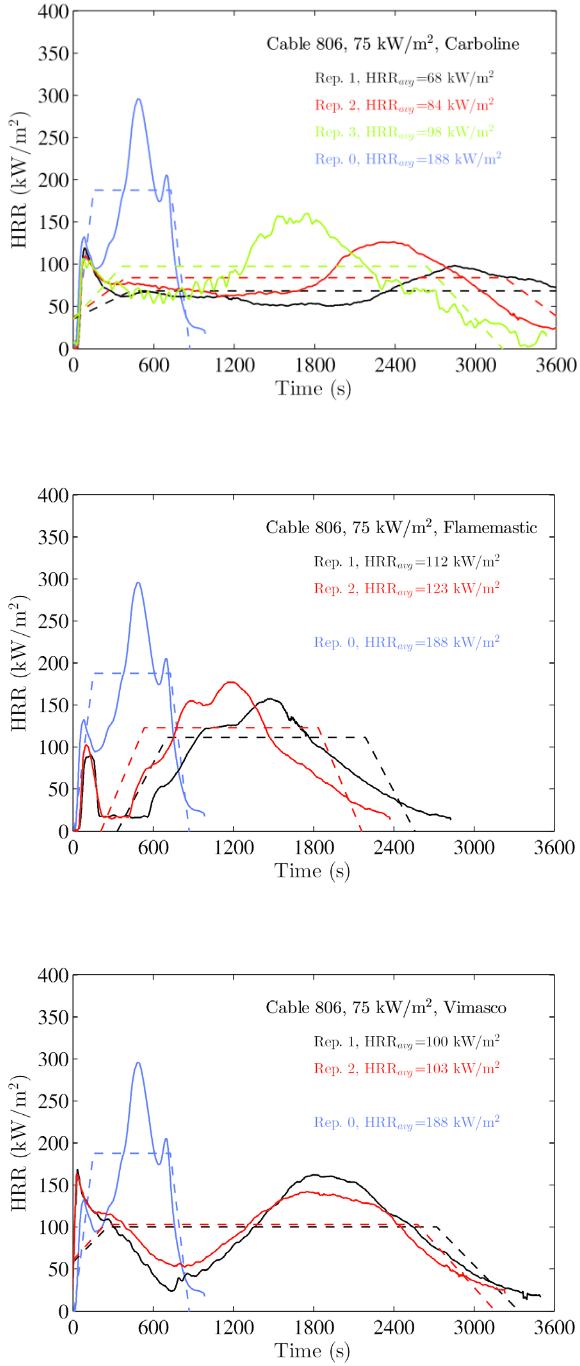


**Figure 4-12. Cone calorimeter results for Cable 806. Rep 0 denotes the uncoated sample.**

### 4.3.6 Cable 807

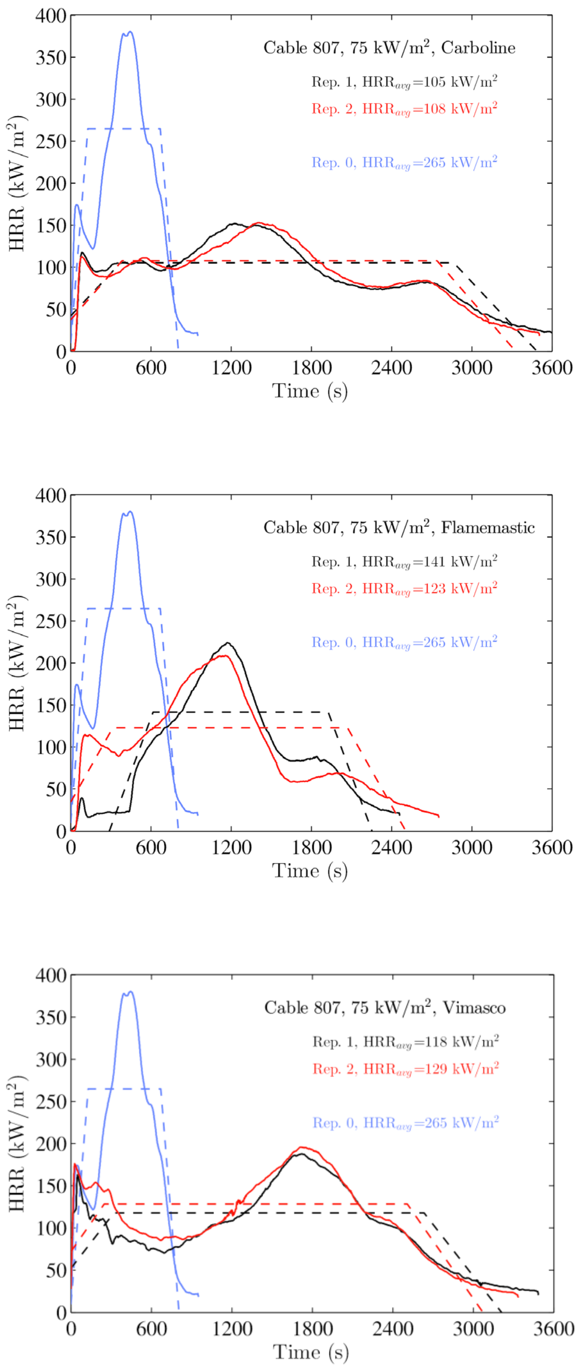


**Figure 4-13. Cone calorimeter results for Cable 807. Rep 0 denotes the uncoated sample.**

### 4.3.7 Cable 808

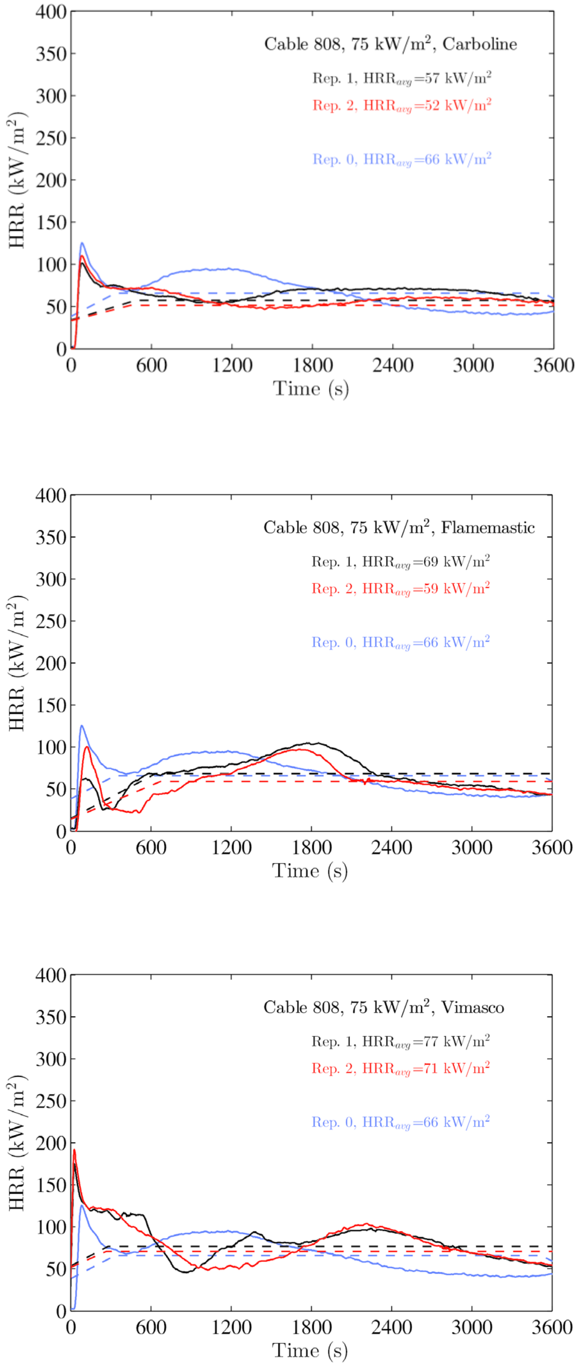


**Figure 4-14. Cone calorimeter results for Cable 808. Rep 0 denotes the uncoated sample.**

### 4.3.8 Cable 809

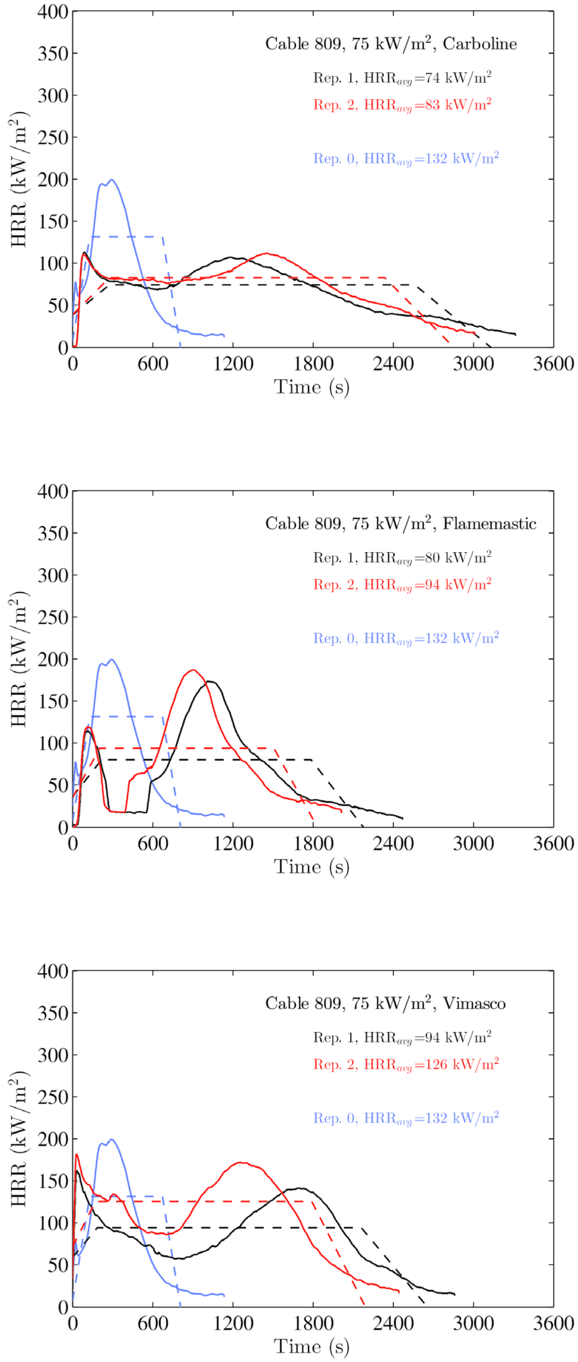


**Figure 4-15. Cone calorimeter results for Cable 809. Rep 0 denotes the uncoated sample.**

### 4.3.9 Cable 811

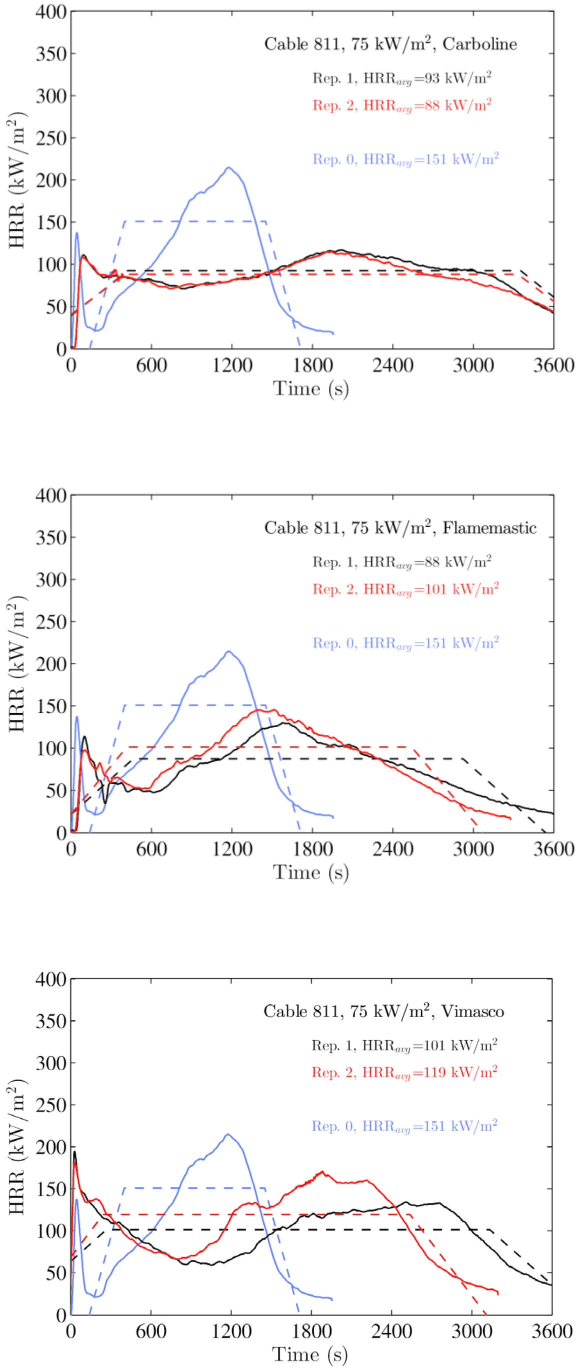


**Figure 4-16. Cone calorimeter results for Cable 811. Rep 0 denotes the uncoated sample.**

### 4.3.10 Cable 813

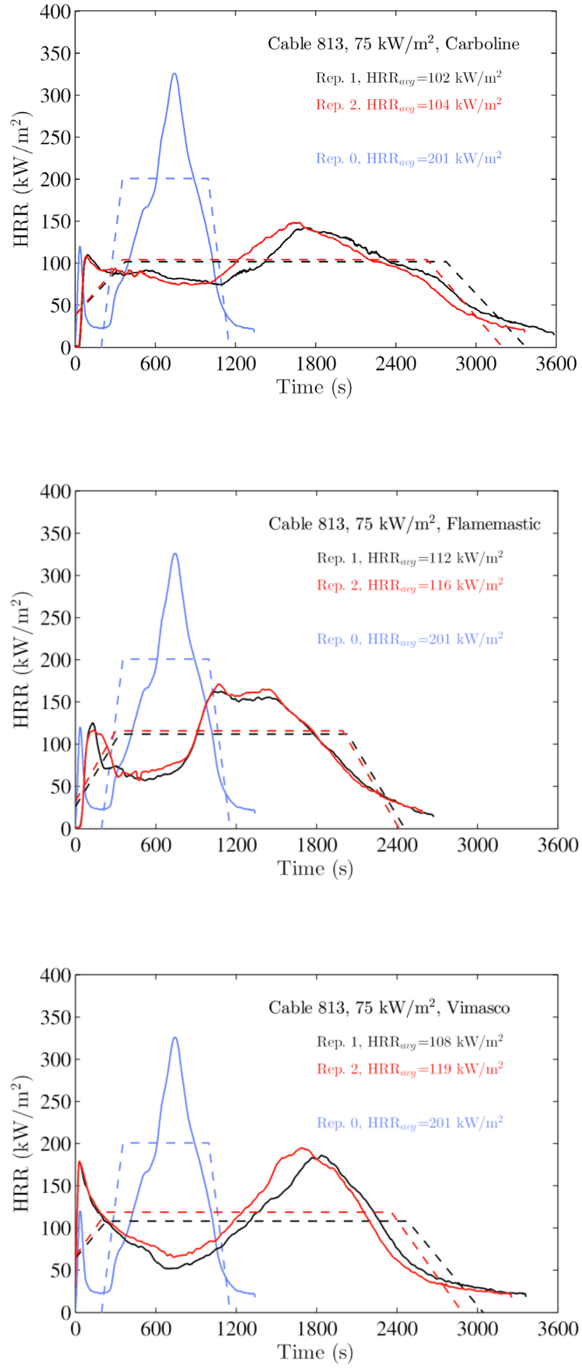


**Figure 4-17. Cone calorimeter results for Cable 813. Rep 0 denotes the uncoated sample.**

### 4.3.11 Cable 803 and 814, mixed

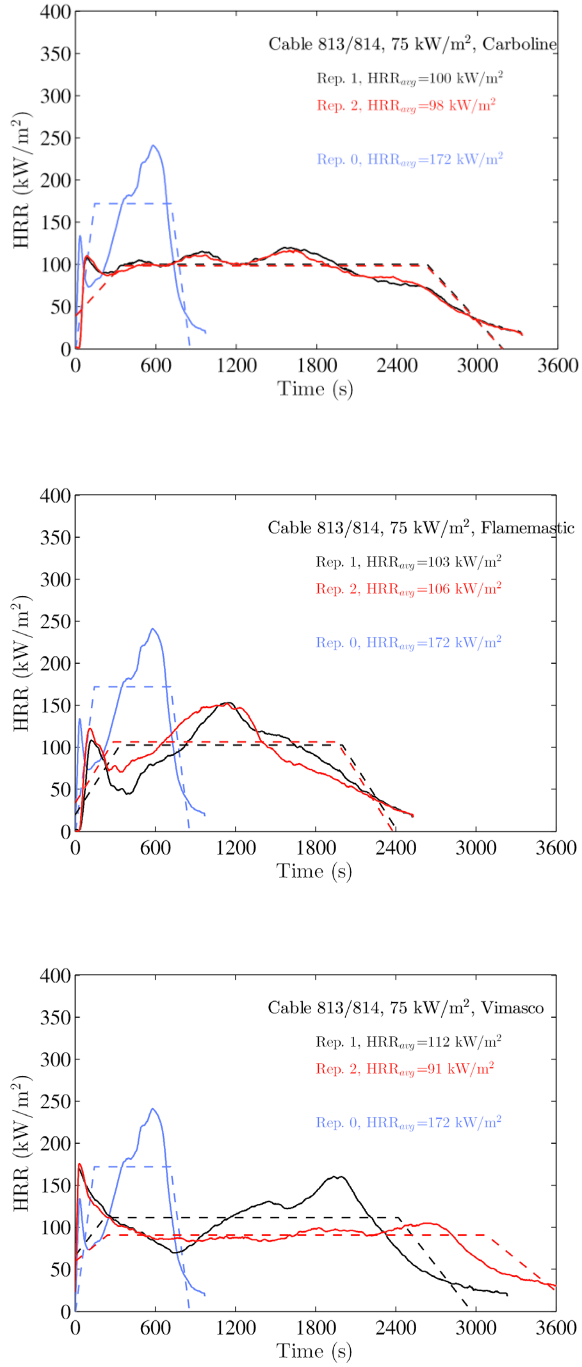


**Figure 4-18. Cone calorimeter results for Cables 813 and 814, mixed. Rep 0 denotes the uncoated sample.**

### 4.3.12 Cable 814

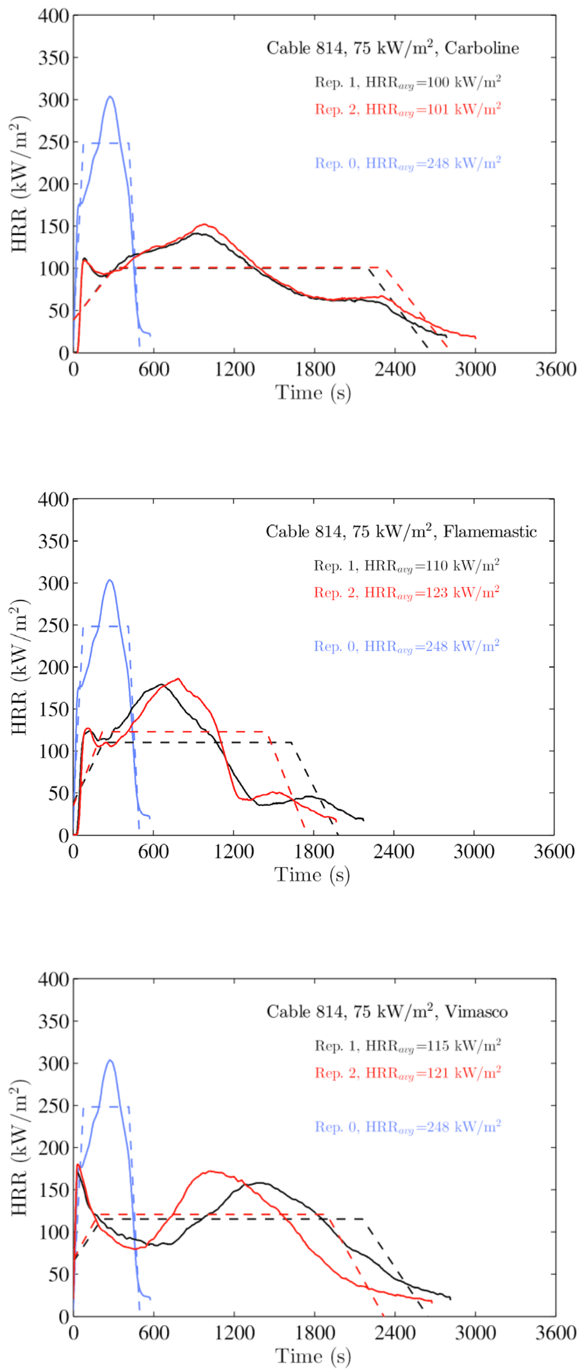


**Figure 4-19. Cone calorimeter results for Cable 814. Rep 0 denotes the uncoated sample.**

## 4.4 <u>Summary</u>

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

In general, the coatings delay the time to ignition, decrease the peak heat release rate, and increase the total energy released because the coatings do add to the fuel load. 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/m$^2$) | | | | Average Energy Released (MJ/m$^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 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 chapter describes the experiments conducted to determine the ignition temperature of coated and uncoated cable samples.

## 5.1 Experimental Description

Measurements of cable ignition temperatures were conducted in a Carbolite LHT 660 convection oven with a maximum operating temperature of 600 °C (1112 °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. In order 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 kV to 45 kV. The spark energy from this type of ignitor is on the order of 0.1 J.

After initial testing of 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 photographs in Figure 5-2 and Figure 5-3.

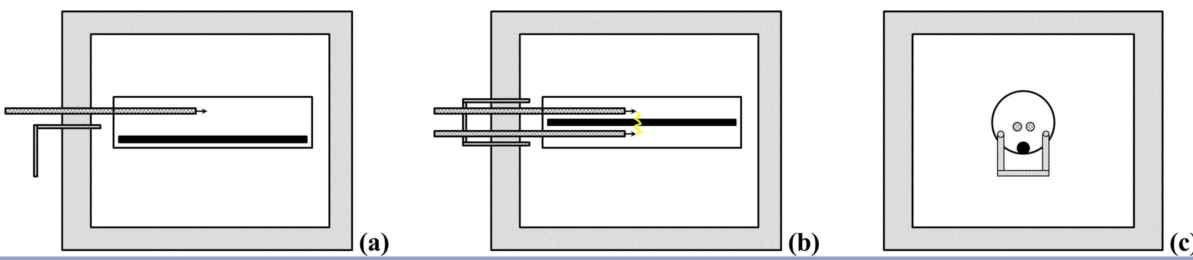


**Figure 5-1: Oven configuration showing electrodes, gas inlets, cylindrical shroud, and cable.**

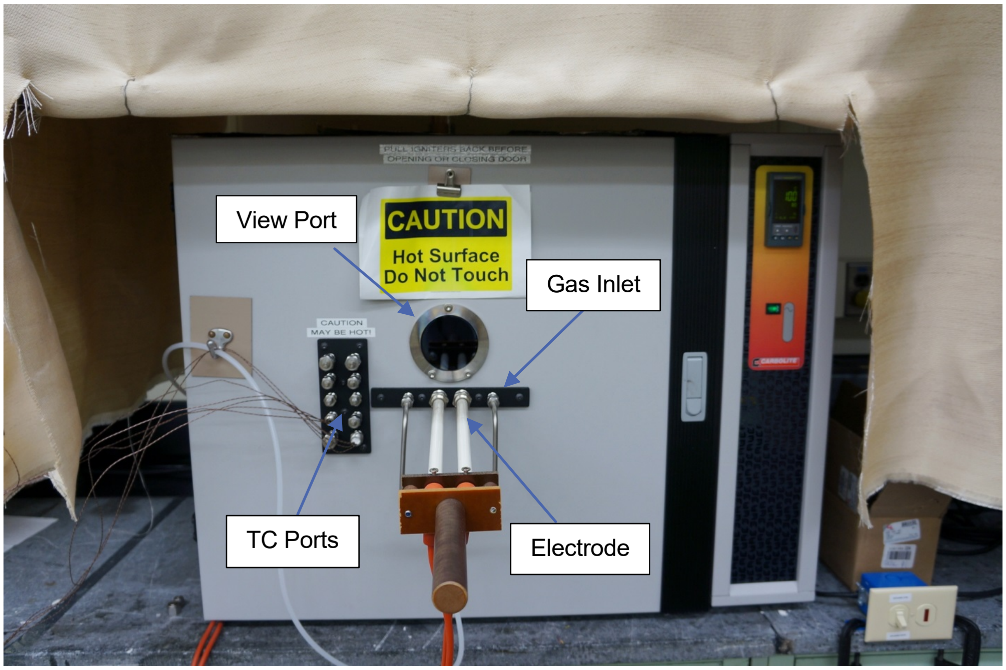


**Figure 5-2: Oven exterior showing electrodes, gas inlets, and thermocouple wire ports.**

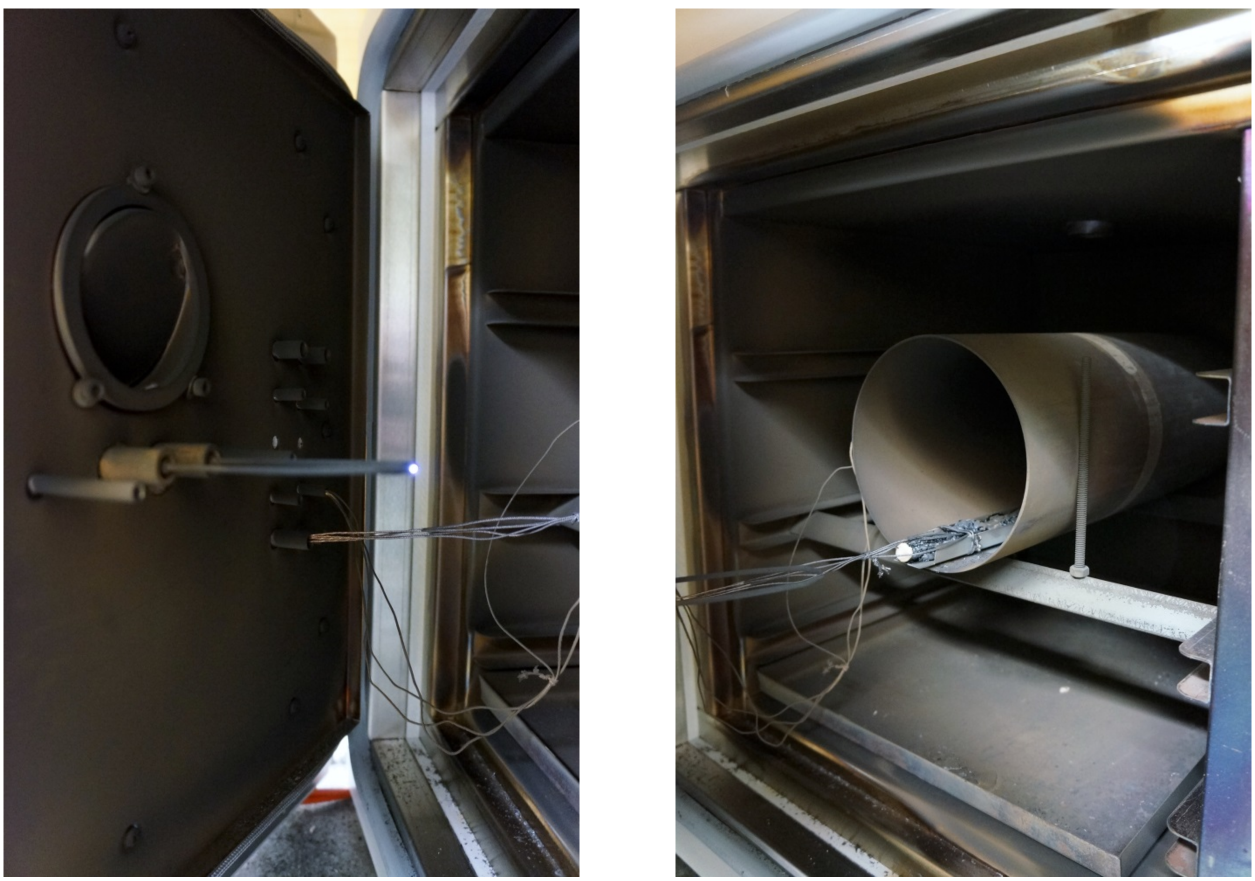

**Figure 5-3: Oven interior showing electrodes, gas inlets, thermocouples, shroud, and cable.**

Cable specimens were prepared in approximately 30 cm 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:

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

2. 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 from the cable end.

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

An example of a cable specimen prepared for testing is shown in Figure 5-4.

**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 testing, 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 was acquired at 1 Hz. 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.

## 5.2 Ignition Temperature of Uncoated Cables

Cable ignition temperatures fell into 4 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 tested individually, but ignited at a much lower temperature (325 °C, 617 °F) when multiple lengths were tested

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

Ignition temperatures for cables from the first 3 categories are shown in Figure 5-5. For each cable, the temperature was recorded on the surface, under the jacket, near the center of the cable, and 1 cm 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 3rd category, cable 817. When heated as a single 30 cm length, the cable does not ignite until a relatively high temperature of 430 °C. However, if a second cable segment is added (817 x2), the ignition temperature falls to 345 °C. It is notable that this cable is relatively small in diameter compared to most of the others tested (the other relatively small cable is 818). It is possible that a flammable component of the polymer is released at the lower temp, but not in sufficient quantity per unit length to sustain ignition. The addition of the second cable segment doubles the output of fuel per unit length, sustaining ignition. A similar behavior is observed for cable 809, which has a silicone rubber insulator and a braided fiber jacket, even though its diameter similar to most of those tested. When tested individually, it does not ignite at all; however, when two lengths are tested together, they ignite at a little over 400 °C. 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).

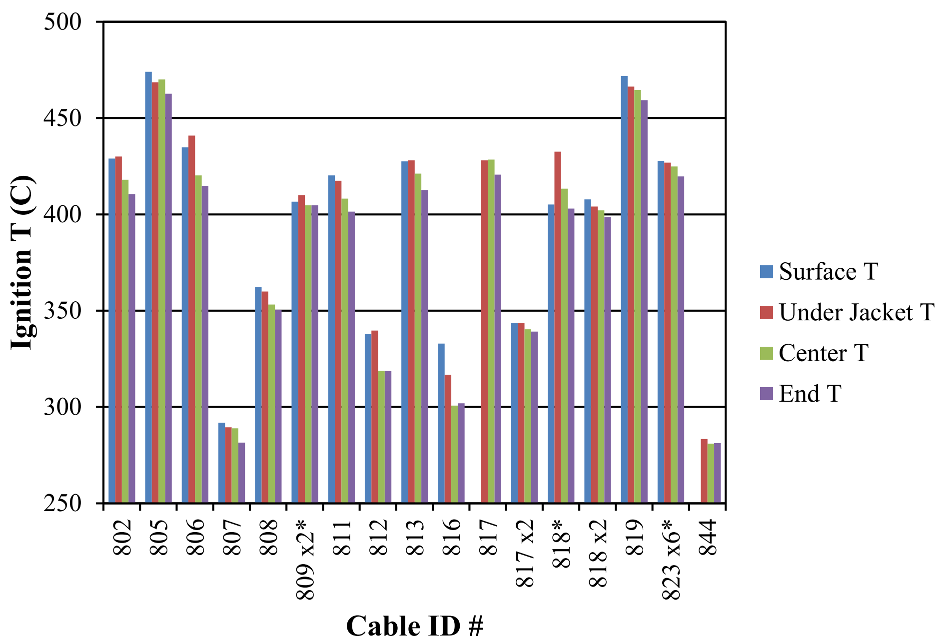


**Figure 5-5: Average measured temperatures at the time of ignition. An asterisk indicates a single cable. Except where noted in the text, uncertainties are 1 % to 3 %.**

Ignition temperatures for cables from the 4th category, intermittent ignition transitioning to sustained ignition, are shown in Figure 5-6. 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 of these cables contained PVC in one or both of the 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 PE for the insulation. Of these two, 807 ignited near 300 °C and 818 near 400 °C. However, despite the fact that the latter (818) was relatively small in diameter, increasing the cable loading had little effect on ignition temperature.

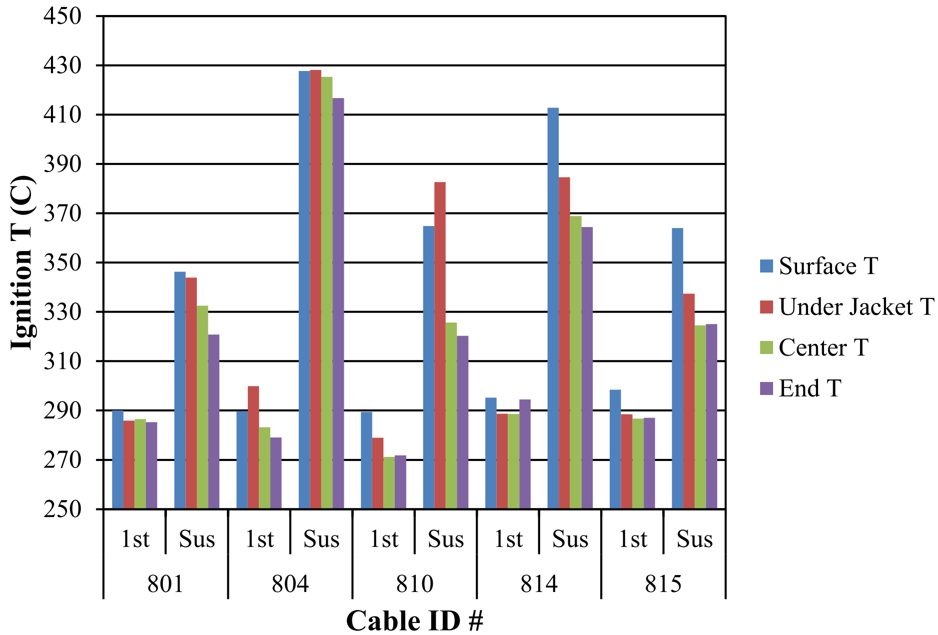


**Figure 5-6: Measured temperatures at the time of ignition—1st temperature rise and sustained temperature rise. Except where noted in the text, uncertainties are 1 % to 3 %.**

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 prior to 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, in the course of 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, where 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 that that measured at the actual time of sustained ignition.

There is no strong correlation between the results presented in this chapter and those from the cone calorimeter tests (HRR and time to ignition). This is not wholly unexpected, as HRR is more indicative of the consequence of ignition rather than 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 vs. material properties) is different. Within category 1 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, cable 844 never ignited, but did experience significant self-heating as the oven reached 400 °C.

### 5.2.2 Repeatability / Uncertainty:

With the exception of 809 x2, 818, and 823 x6, all cable tests 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 %, with the exceptions of 808, 812, 817 x2, and 819, which were 6 %.

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) where thermocouples were installed under the cable jacket at the top, bottom, and lateral locations. In the axial direction they were spaced evenly along the cable. The results from these experiments are shown in Figure 5-7. These results show that the variation in temperature around the cable is no greater than the variation between runs for any given location, and therefore the effect of rotation orientation is insignificant.

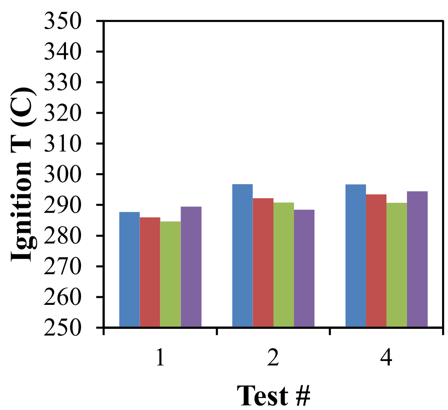


**Figure 5-7: Measured temperature at the time of ignition for the unrated residential cables. Colored bars indicate TC azimuth position at 90° intervals.**

### 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; 2) ignition temperatures around 400 °C; 3) an ignition temperature around 400 °C when tested individually, but with a much lower ignition temperature, 325 °C, when multiple lengths were tested; and 4) intermittent ignition around 300 °C, followed by heating until sustained ignition was achieved around 350 °C. Polymer material was an indicator only of the 4$^{th}$ category, including all cables with PVC and without polyethylene. 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.

Summaries of the cable surface temperature at the time of ignition are presented in Table 5-1 through Table 5-3.

**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

Measurements of coated cable ignition temperatures were conducted 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 thermocouples (TCs) with bead diameters of approximately 0.5 mm (0.02 in). An example of a cable segment prepared for testing without coatings is shown in Figure 5-8. 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 non-instrumented cables, was coated with one of the four coating materials. This configuration represents cables lined up 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. Ignition was indicated by a sudden rise in temperature of the various TCs, and a visual observation of flames through the oven window.

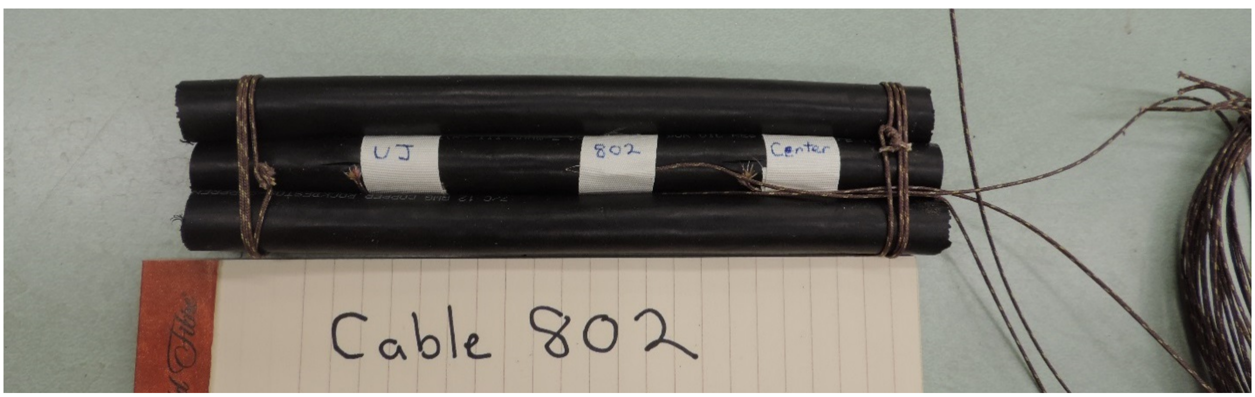


**Figure 5-8. Instrumentation of a cable segment for an uncoated test.**

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

### 5.3.2 Results

Four different cables and four different cable coatings were tested. The cables are listed in Table 3-2. Cable 802 is a thermoset cable with a relatively high ignition temperature. Cables 805 and 807 are thermoplastic cables with a significant difference in ignition temperature when uncoated. Cable 814 is a thermoplastic with a relatively low ignition temperature.

Table 5-4 summarizes the results of the ignition testing.

**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 |
| 814 | FS15 | 309 | 320 | 314 |
| 814 | Vimasco | 288 | 288 | 288 |

# 6 FULL-SCALE VERTICAL FLAME SPREAD EXPERIMENTS

This chapter includes the results of a modified version of IEEE 1202, *Standard for Flame Testing of Cables for Use in Cable Tray in Industrial and Commercial Occupancies* (1991).

## 6.1 Experimental Description

The vertical flame spread apparatus is shown in Figure 6-1. An approximately 0.3 m (12 in) wide, 2.4 m (8 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 standard IEEE 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). The number of cable segments was dictated by the IEEE 1202 standard. 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 1280 $cm^3/s$ ± 80 $cm^3/s$ (163 $ft^3/h$ ± 10 $ft^3/h$). The temperature in the laboratory during testing was approximately 25 °C (77 °F). This air/fuel mixture produced a flame with a heat release rate 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 the IEEE 1202 standard. As shown in Figure 6-4, the burner was angled upwards 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 heat release rate 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 considerably 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 two test series, I and II. The test matrix is shown in Table 6-1. and the cables were exposed to flames for 20 min.

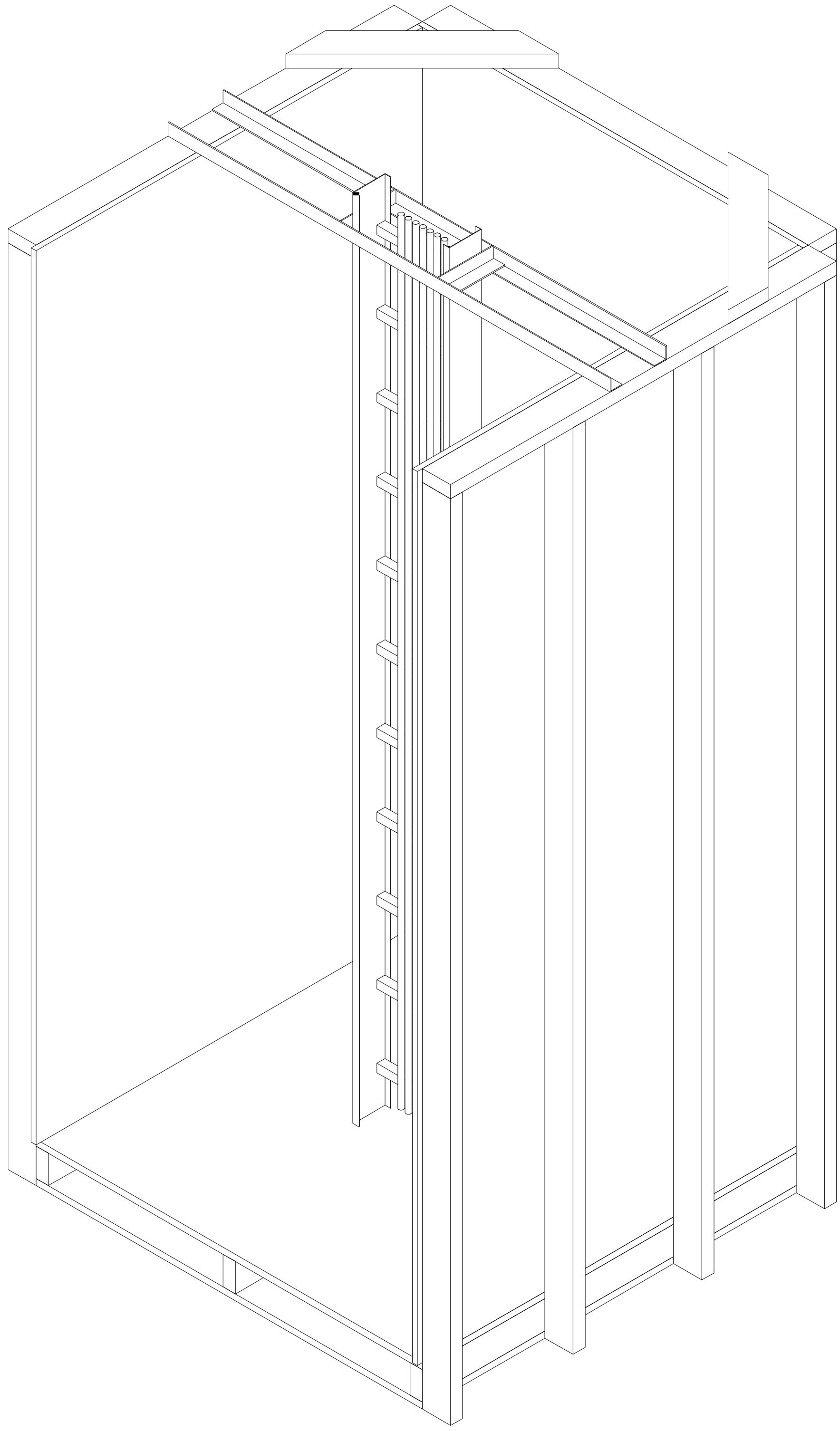

**Figure 6-1. Drawing of the vertical flame test apparatus.**

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

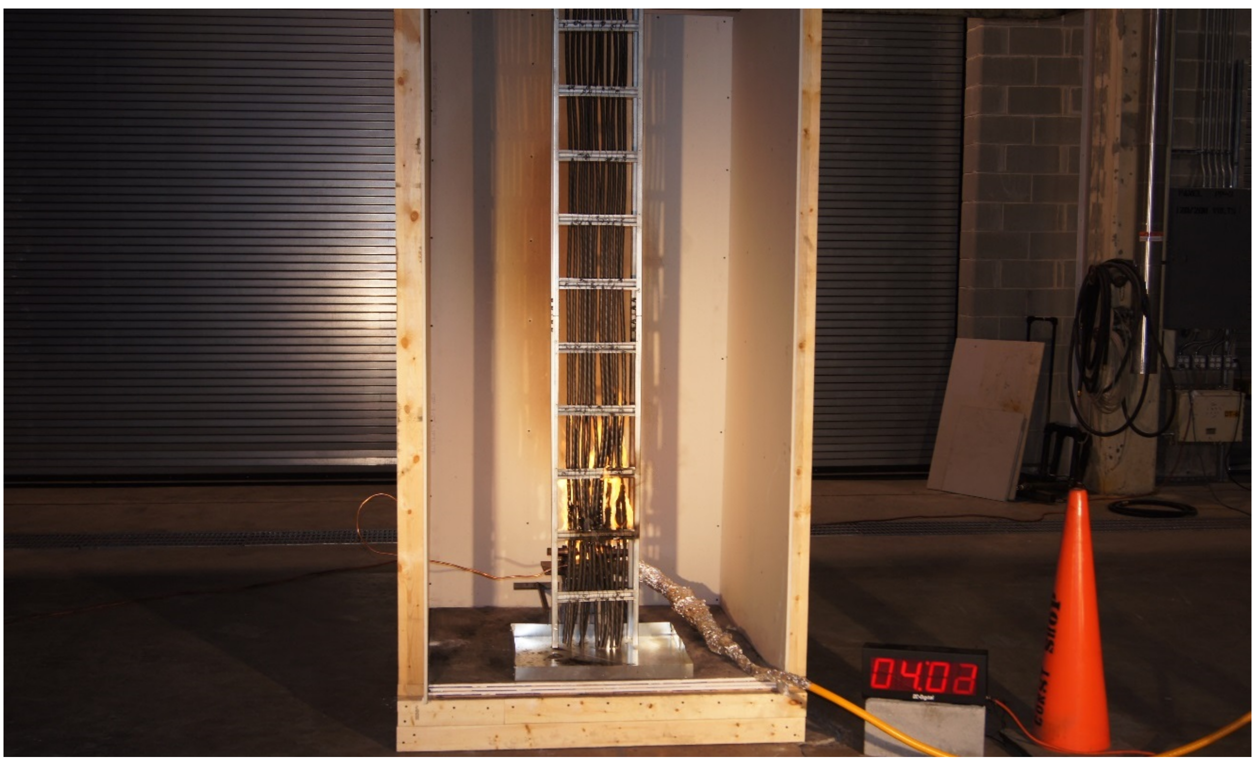

**Figure 6-3. Photograph of vertical flame spread test apparatus.**

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

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

**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.**

| Test 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 measured heat release rates (HRR) of the vertical flame spread testing are shown on the following pages. The cables selected for the experiments were as follows:

**Cable 900**, a PE insulated, PVC jacketed, 7 conductor control cable. It is not IEEE-383 qualified, and it was selected specifically because it fails the modified IEEE-1202 flame spread test.

**Cable 902**, a PE insulated, PVC jacketed, 3 conductor instrument cable. It was manufactured in 1975 and is not IEEE-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 IEEE-383 qualified. 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 heat release rate of Cable 900 with no coating applied. In Test I-3, the burner was positioned on the side of the tray where the rungs are attached. For all other tests, the burner was positioned opposite to the rung side, as called for in IEEE-1202. In Test 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.

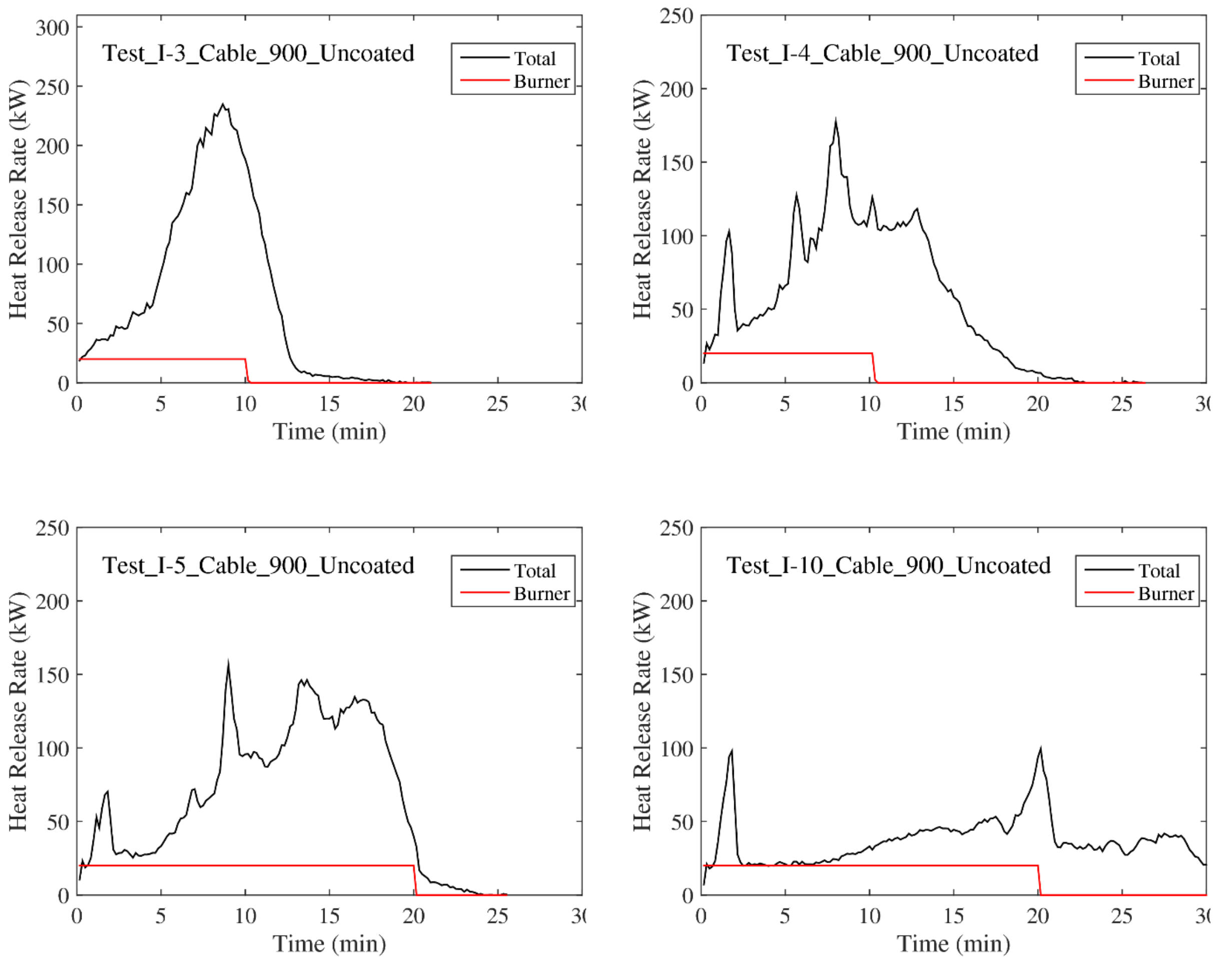


**Figure 6-8. HRR of vertical flame spread tests for Cable 900 with no coating applied.**

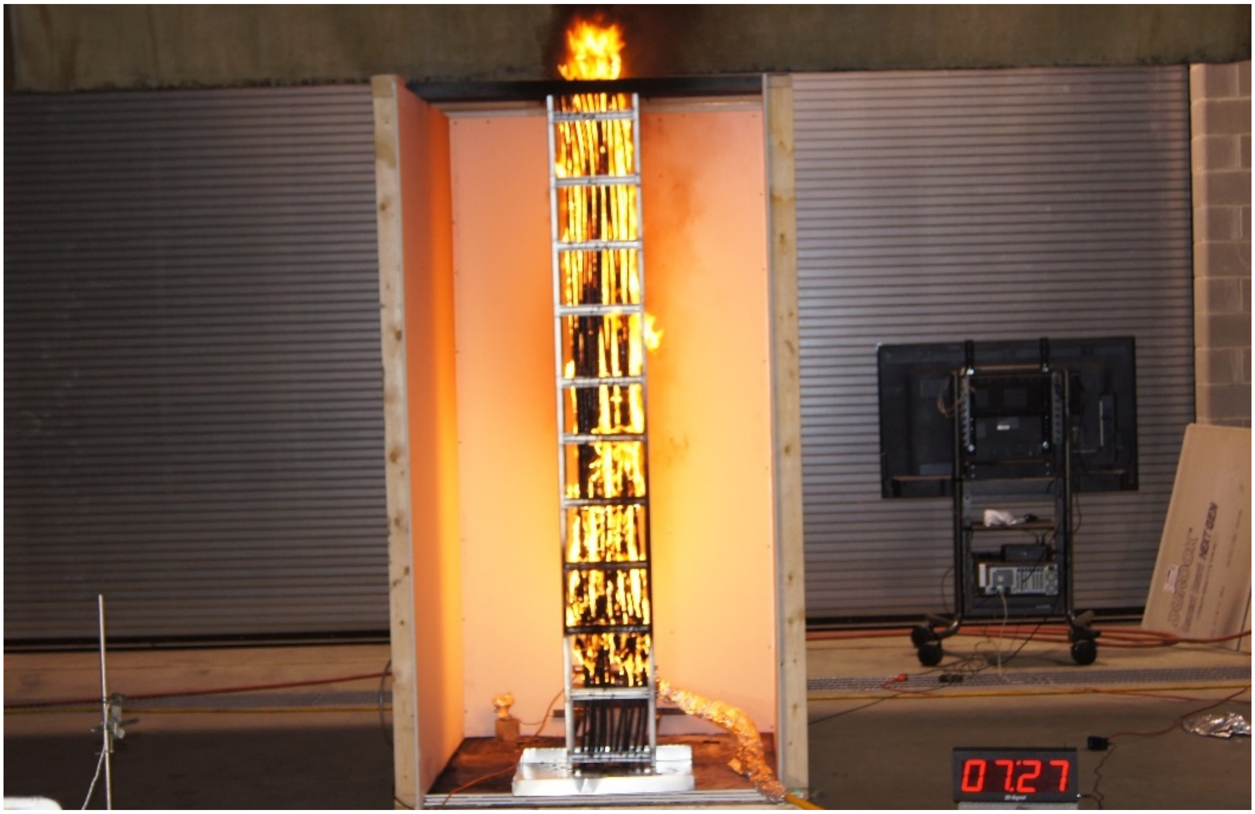


**Figure 6-9. Photograph of Test I-4, Cable 900, uncoated.**

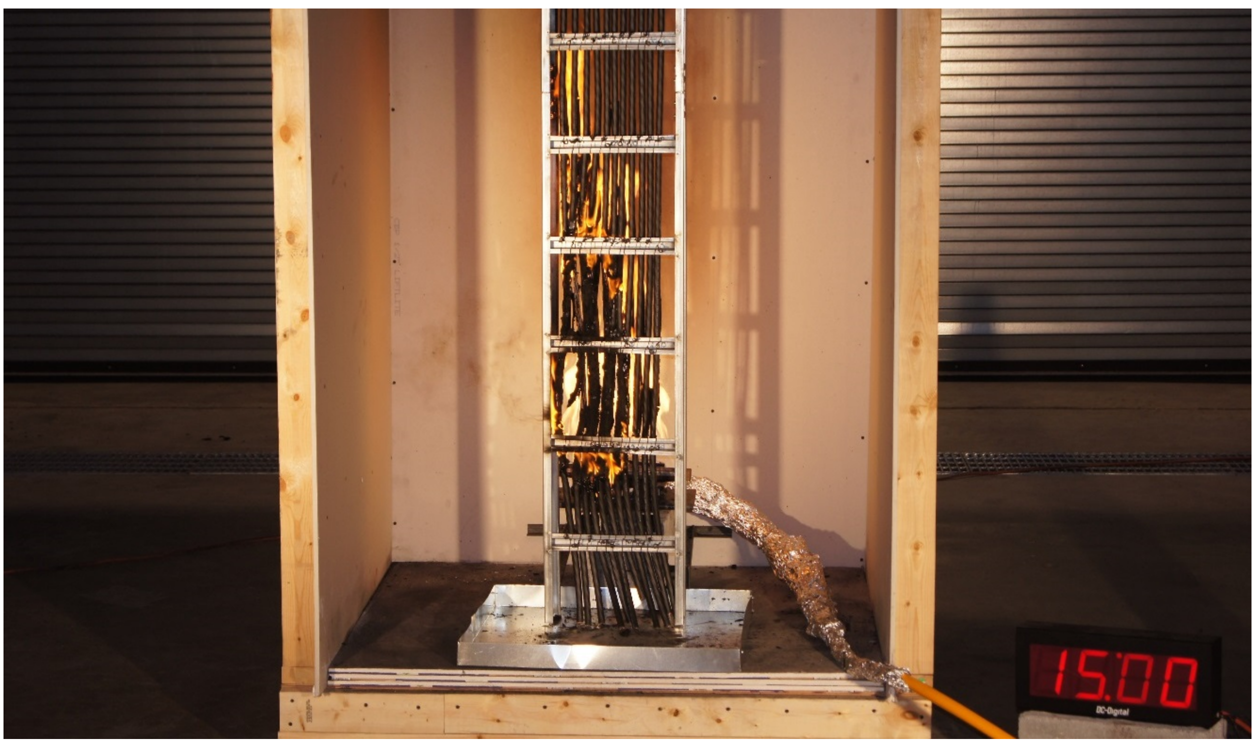


**Figure 6-10. Photograph of Test I-10, showing the shift of fire spread to the left of the tray.**

### 6.2.2 Cable 900 coated with FS15

Figure 6-11 displays the heat release rates for Cable 900 coated with FS15. In only one case, Test 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 Test I-8, both during and after the exposure to the burner. There was a noticeable swelling (intumescence) of the coating.

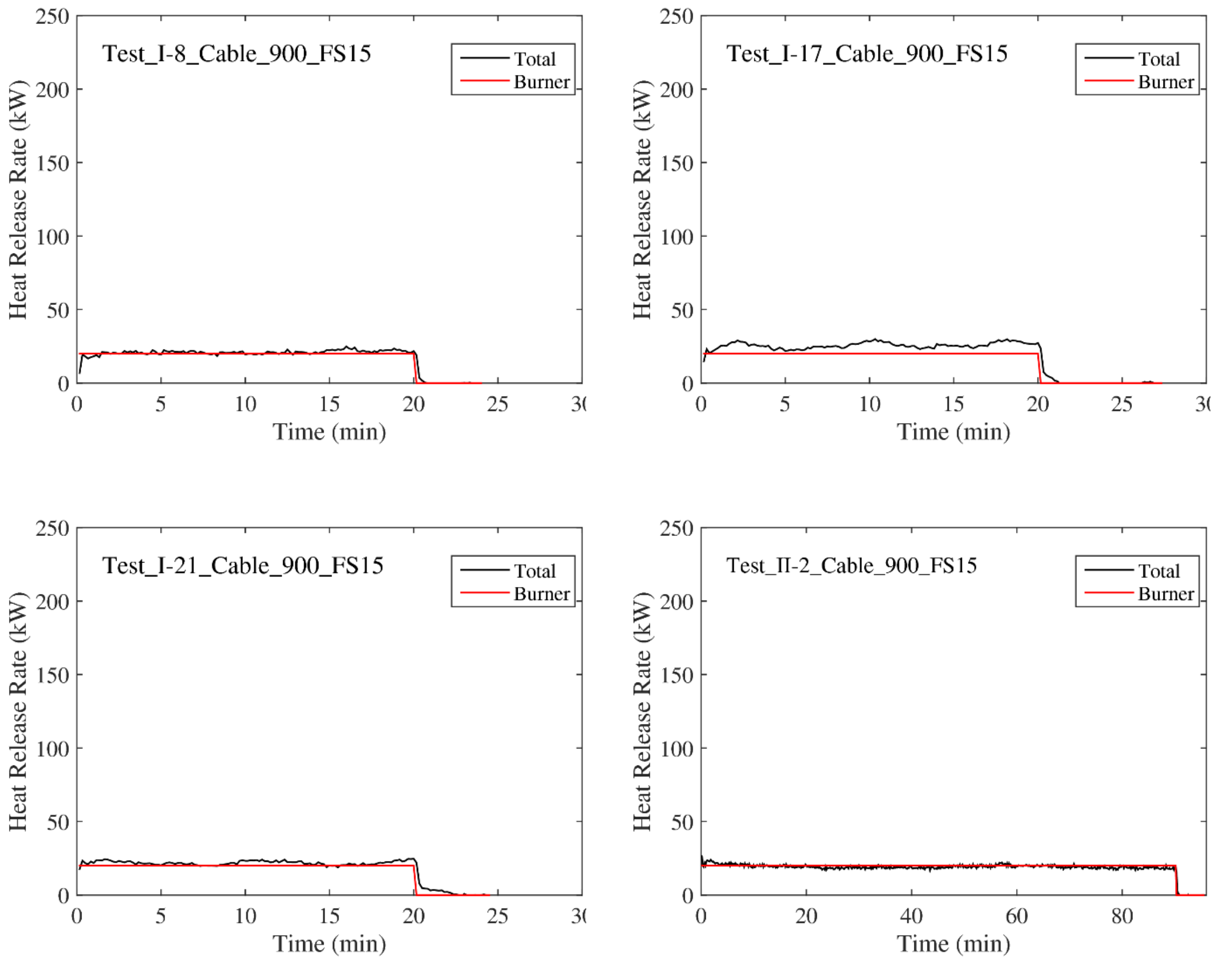


**Figure 6-11. HRR of vertical flame spread tests for Cable 900 coated with FS15.**

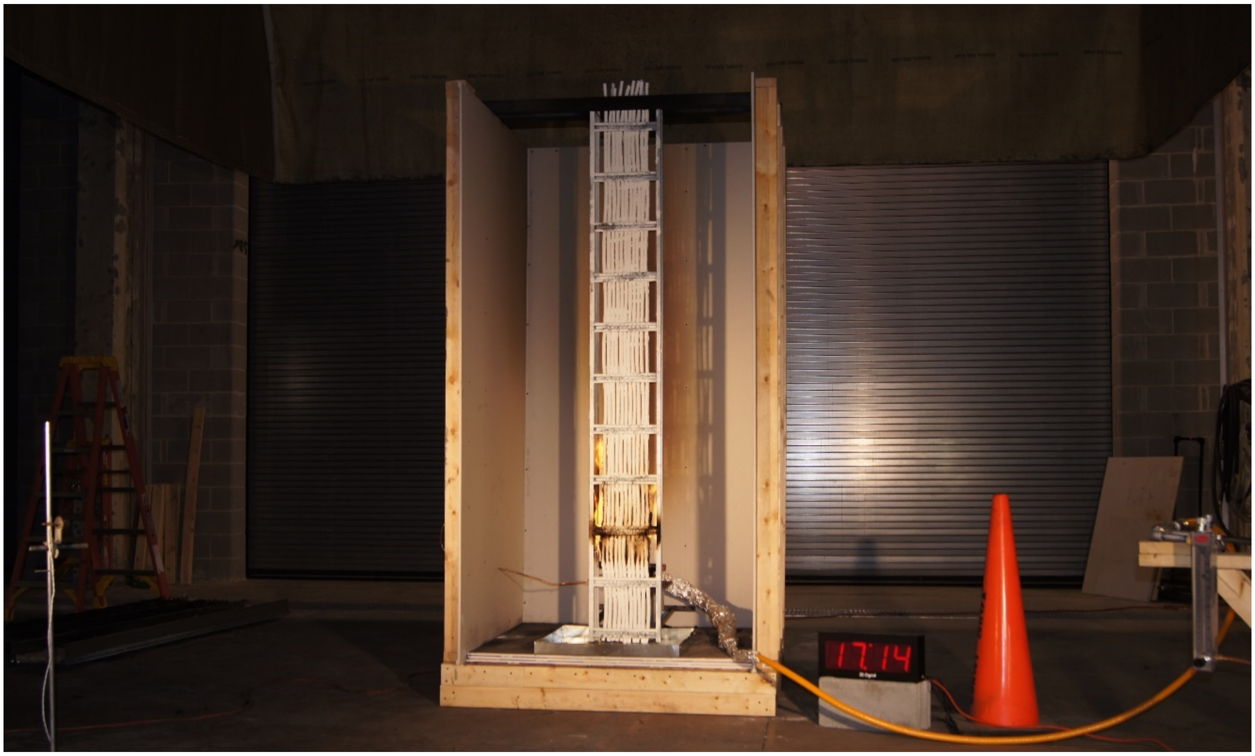


**Figure 6-12. Photograph of Test I-8, Cable 900 coated with FS15.**

**Figure 6-13. Photograph of Cable 900 coated with FS15 after Test I-8.**

### 6.2.3 Cable 900 coated with Flamemastic 77

Figure 6-16 displays the HRR of Cable 900 coated with Flamemastic 77. In one of the three tests, 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 tests had only slight increases in heat release and no upward spread.

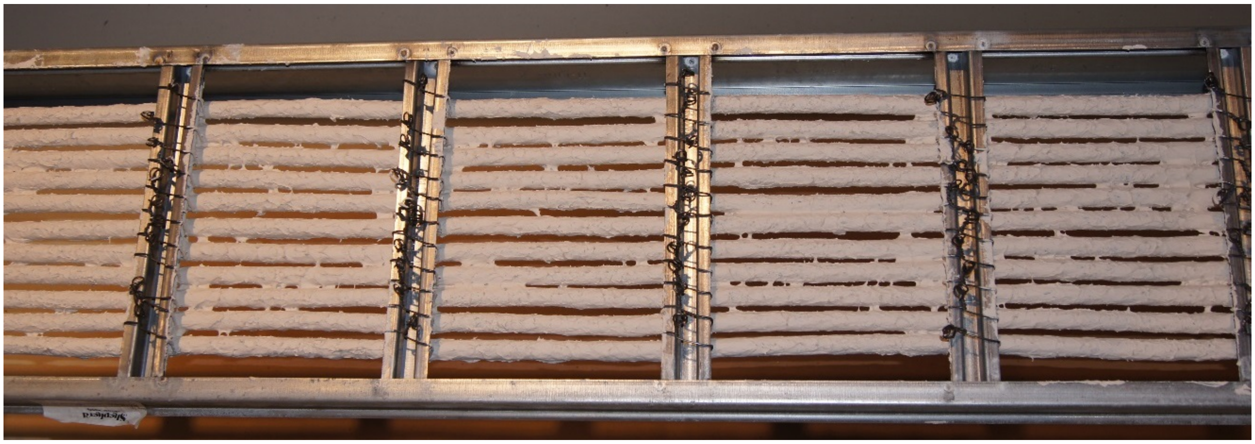

**Figure 6-14. Photograph of Cable 900 coated with Flamemastic 77.**

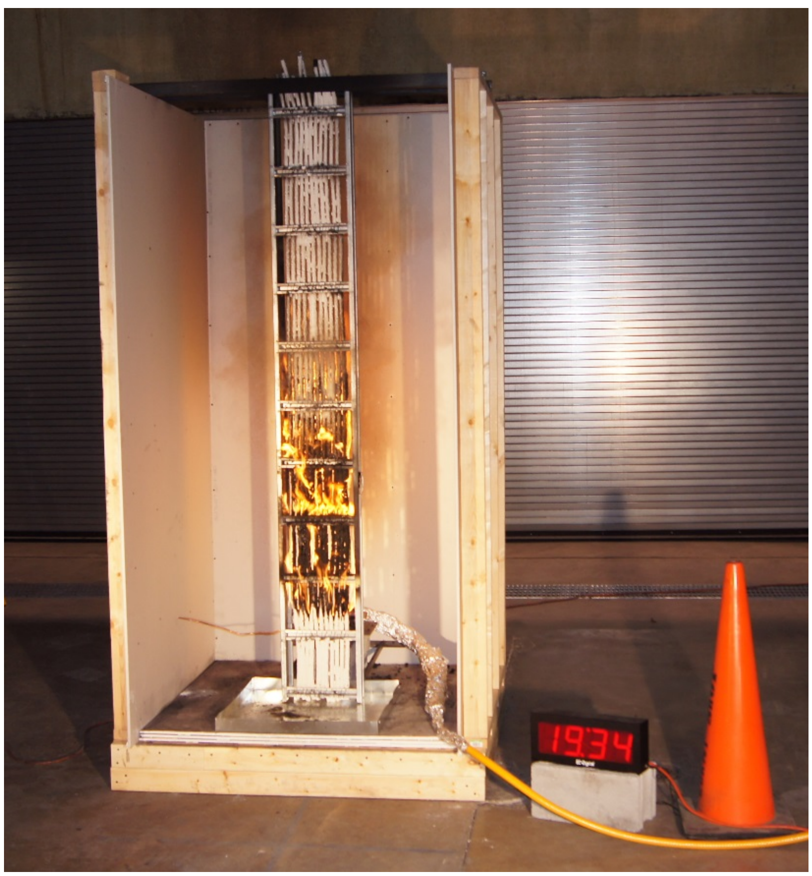


**Figure 6-15. Photograph of Test 6, Cable 900 coated with Flamemastic 77.**

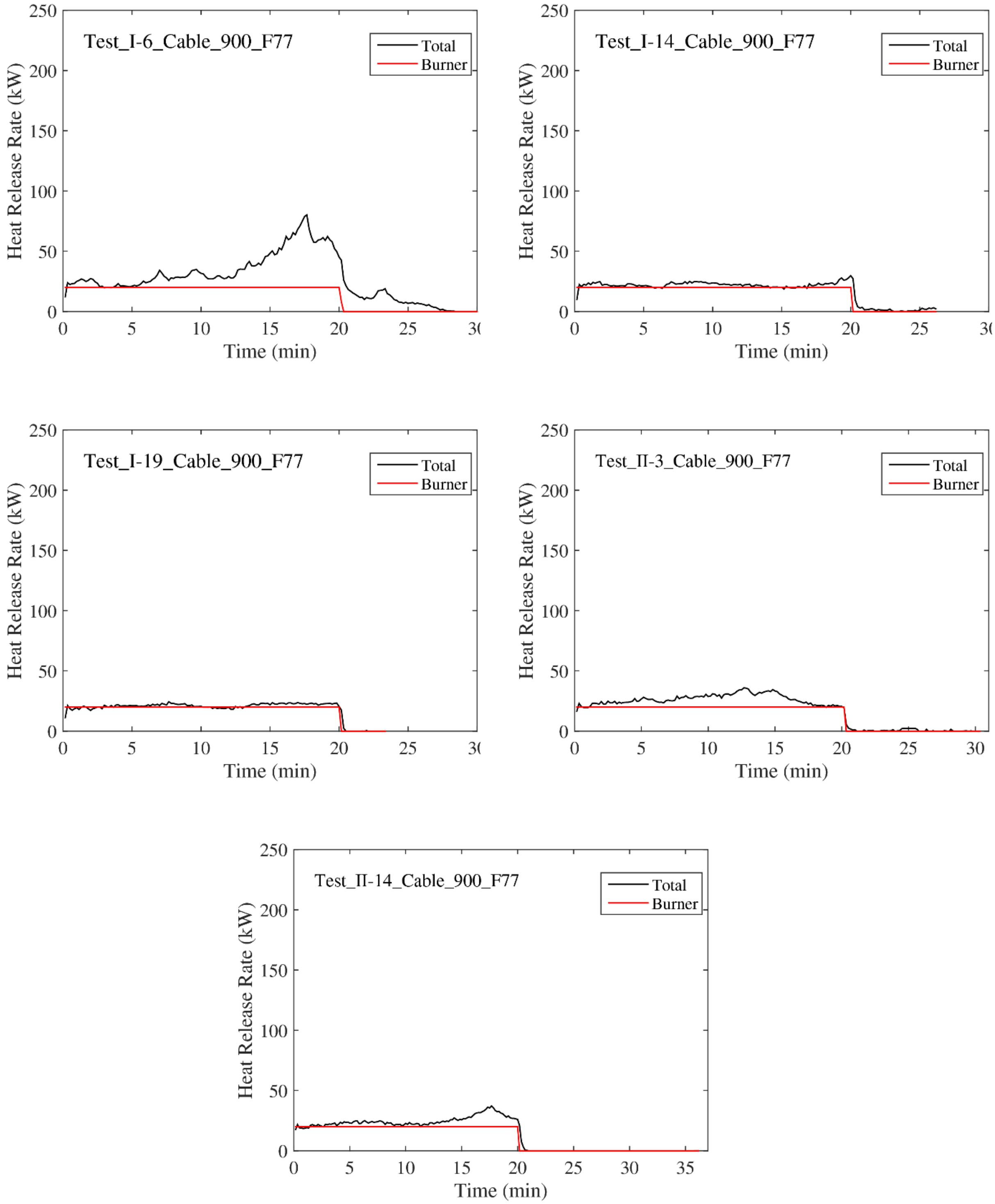


**Figure 6-16. HRR of vertical flame spread tests for Cable 900 coated with Flamemastic 77.**

### 6.2.4 Cable 900 coated with Vimasco 3i

Figure 6-19 displays the HRR for tests of Cable 900 coated with Vimasco 3i. During Test 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 tests 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 manufactures suggested dry thickness of 1.6 mm (1/16 in). In preparation for Series II, the coating was applied in a slightly thicker layer, and none of the three Series II tests exhibited any significant heat release or spread.

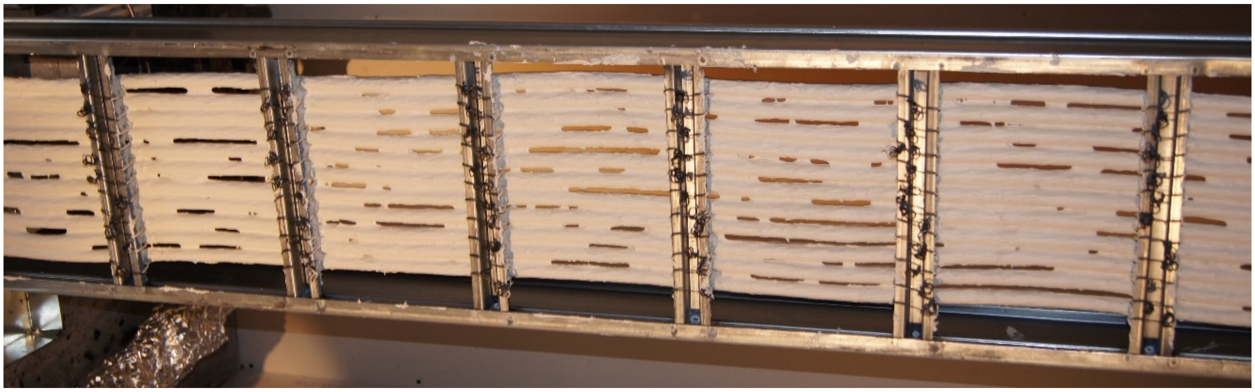

**Figure 6-17. Photograph of Cable 900 coated with Vimasco 3i.**


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

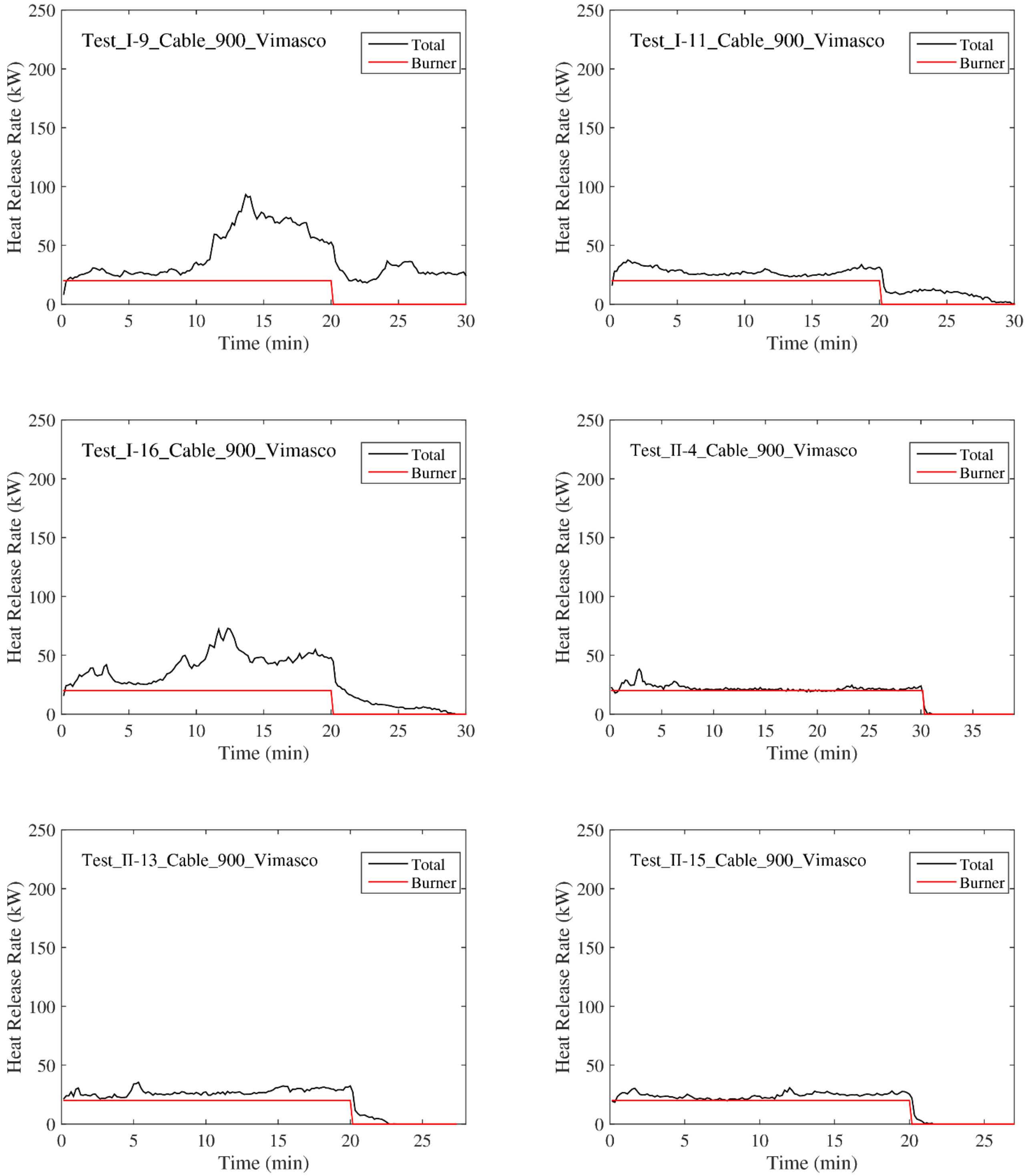


**Figure 6-19. HRR of vertical flame spread tests for Cable 900 coated with Vimasco 3i.**

### 6.2.5 Cable 900 coated with Carboline 285

Figure 6-20 displays the HRR for the tests of 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 fairly 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 Test I-7. The burner flame is barely perceptible behind the block of coated cables.

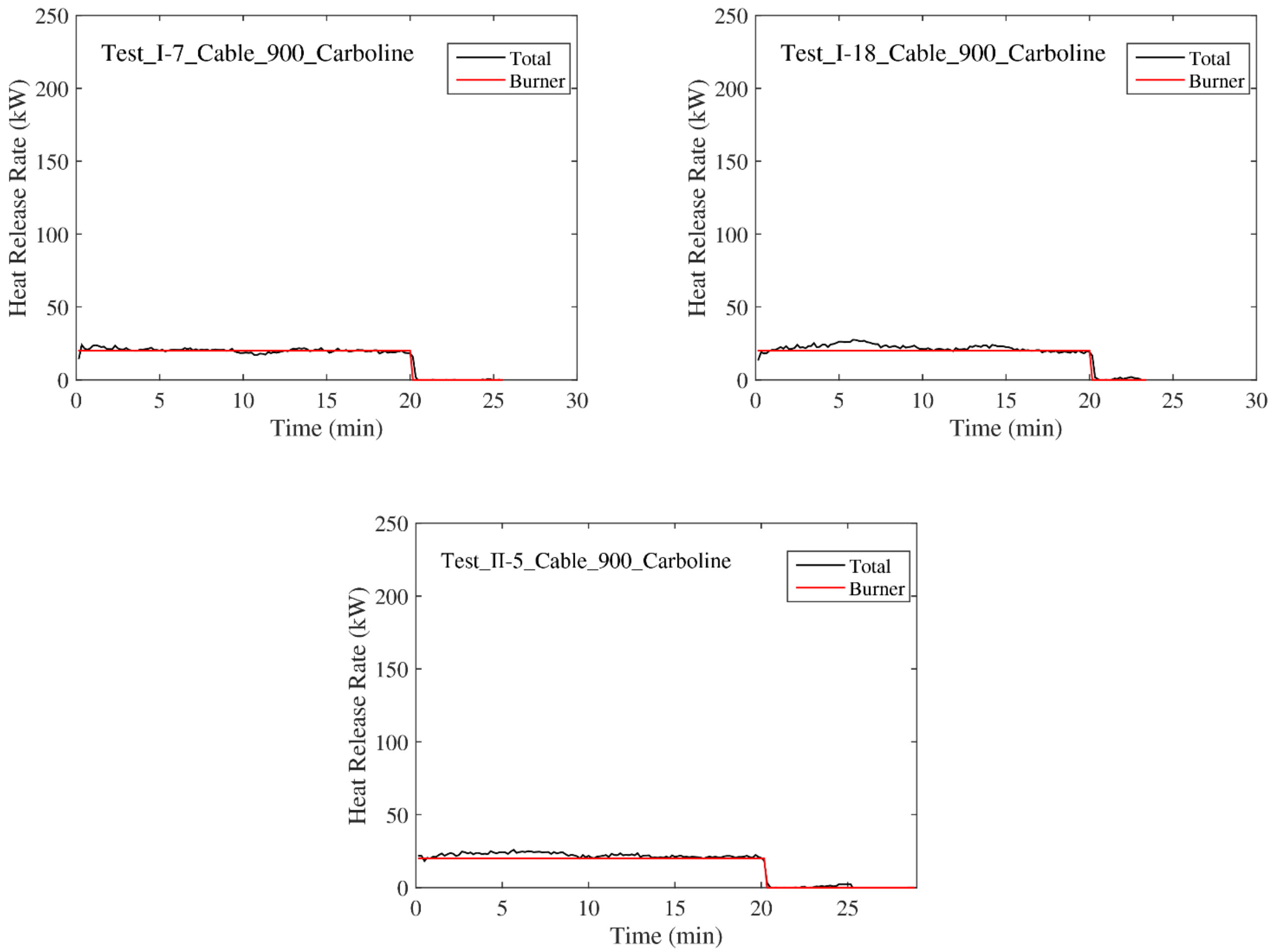


**Figure 6-20. HRR of vertical flame spread tests for Cable 900 coated with Carbonline 285.**

**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. A photograph of one of the experiments in shown in Figure 6-23.

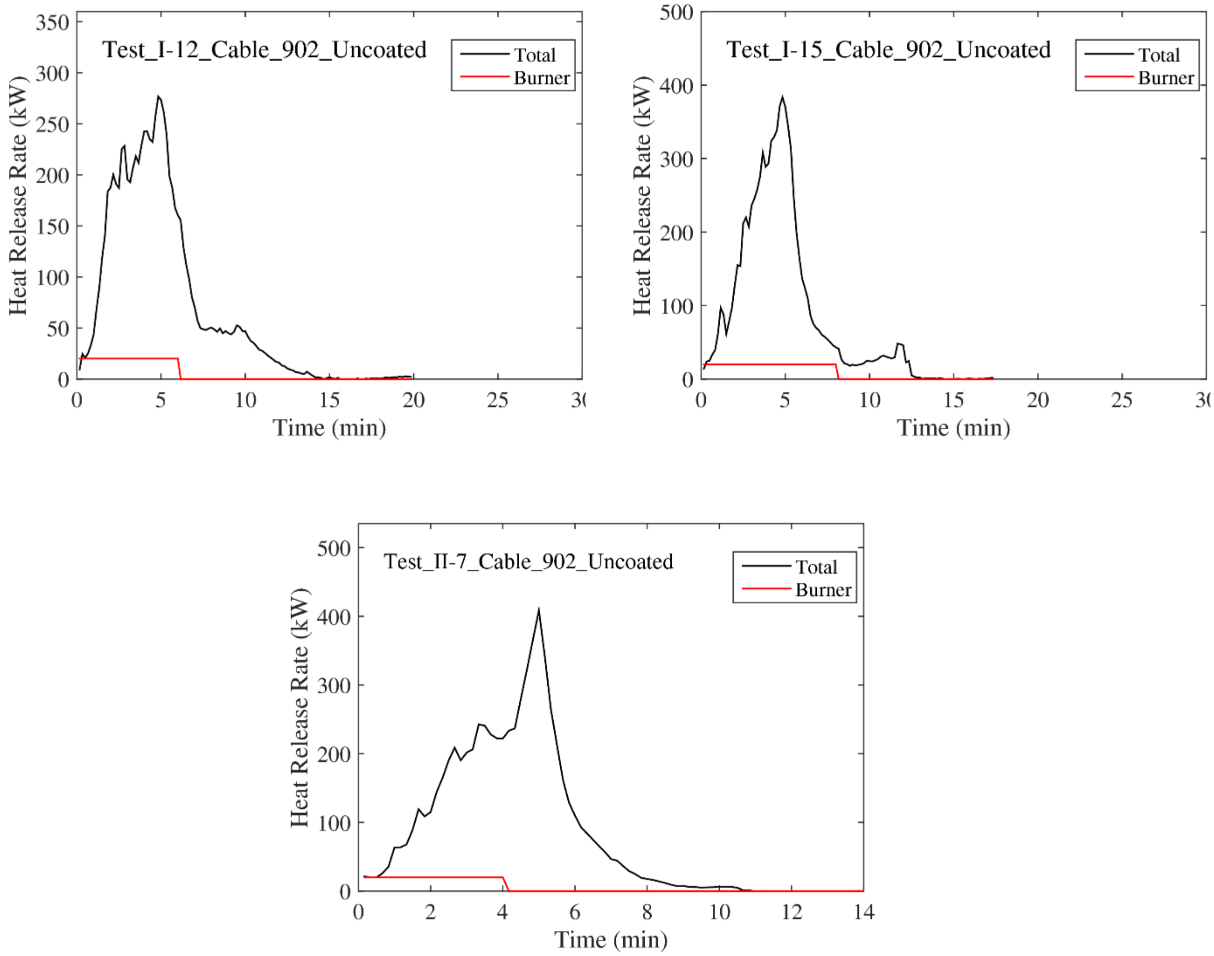


**Figure 6-22. HRR of vertical flame spread tests for Cable 902.**


**Figure 6-23. Photograph of Test II-7, Cable 902, uncoated.**

### 6.2.7 Cable 902, Coated

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

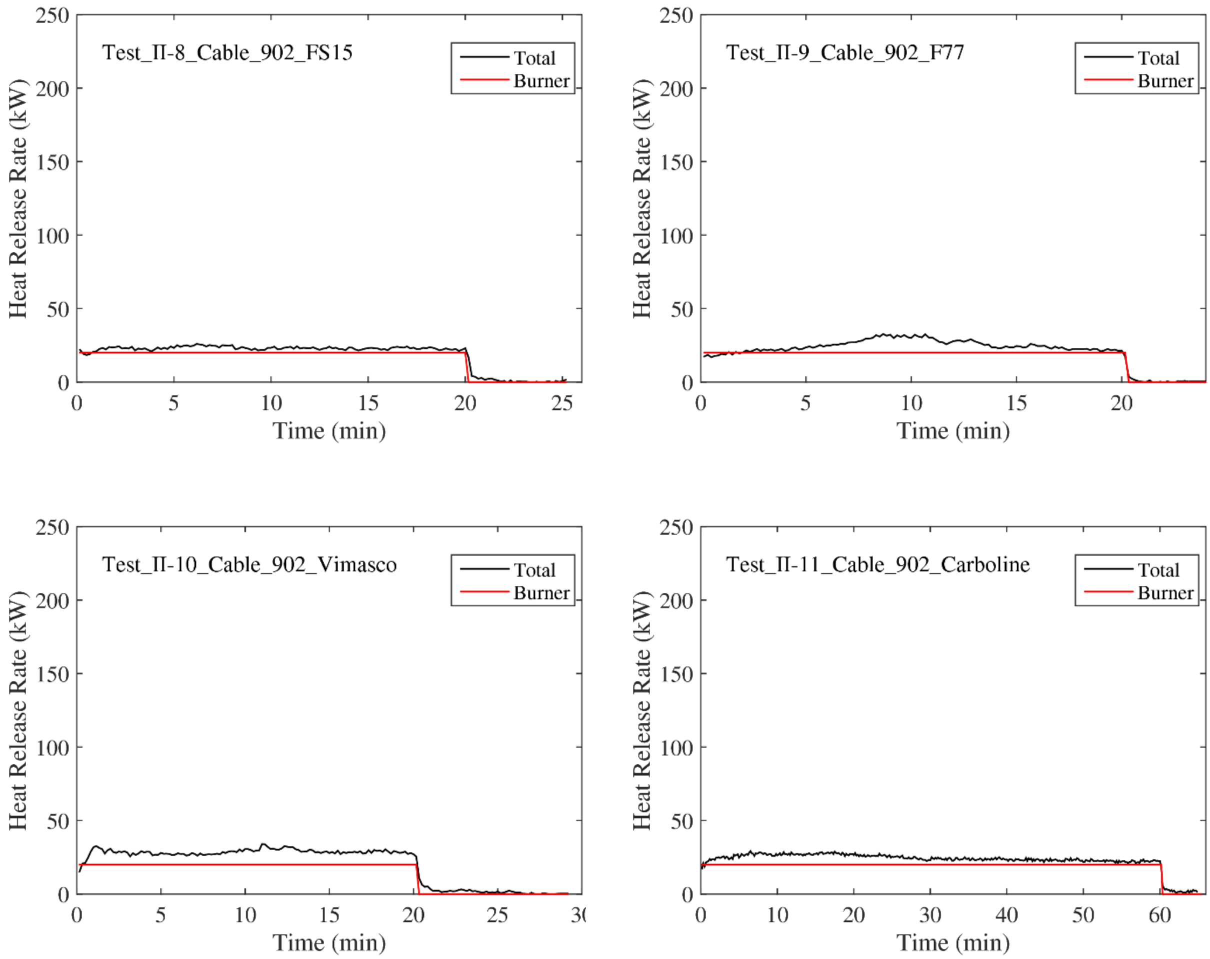


**Figure 6-24. HRR of vertical flame spread tests for Cable 902.**

## 6.3 Cable Temperatures and Electrical Failure Times

During the Series II experiments, the cables were instrumented with thermocouples (at the cable center) to measure their inner temperature during the vertical flame spread tests. 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 cooatings cover the cable like a thermal blanket, whereas the FS15 coating appears to have the additional feature of intumescence, at least it is far more apparent to the naked eye than the other three coatings.

### 6.3.1 Cable 900

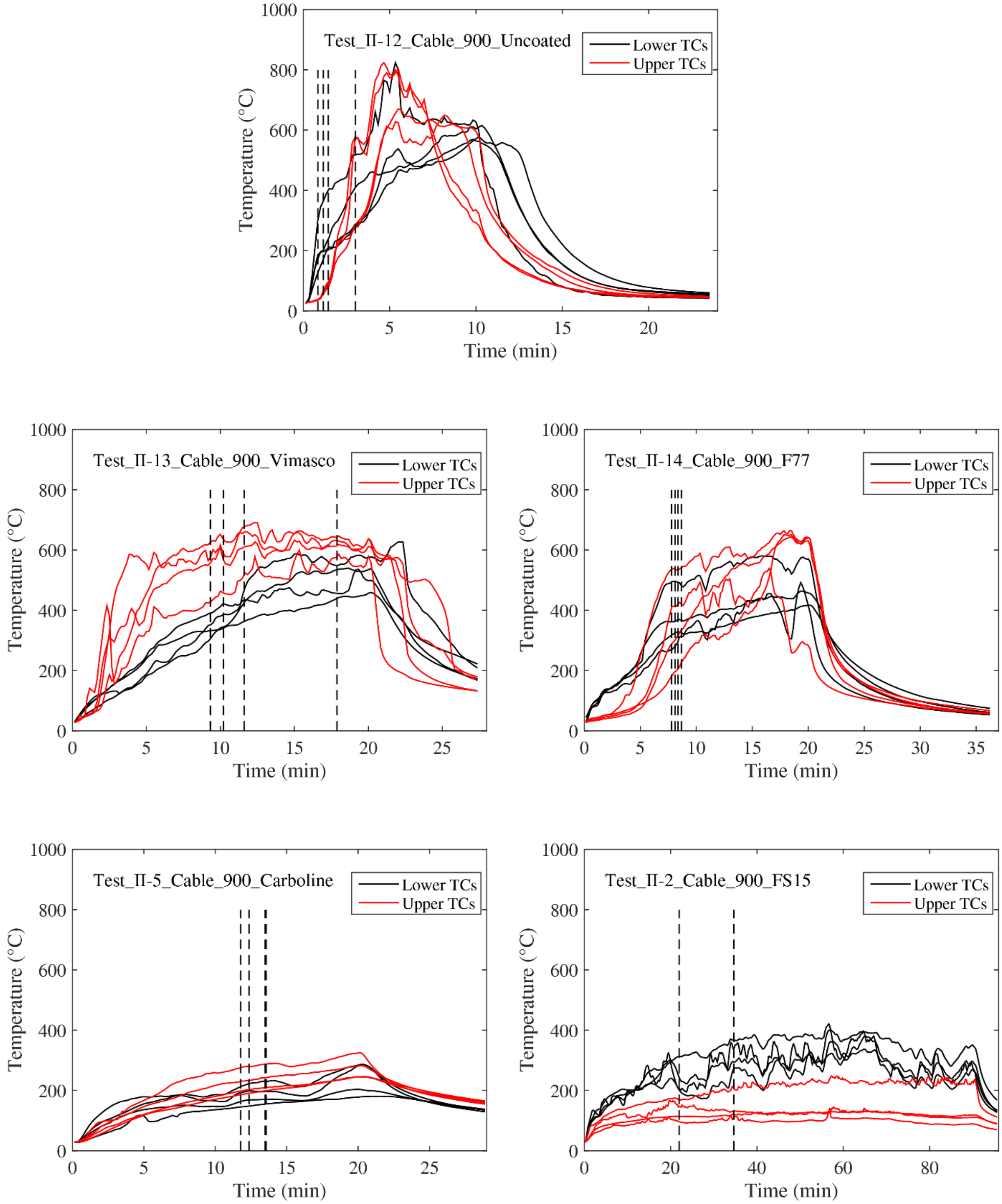


**Figure 6-25. Inner cable temperatures, Cable 900.**

### 6.3.2 Cable 902

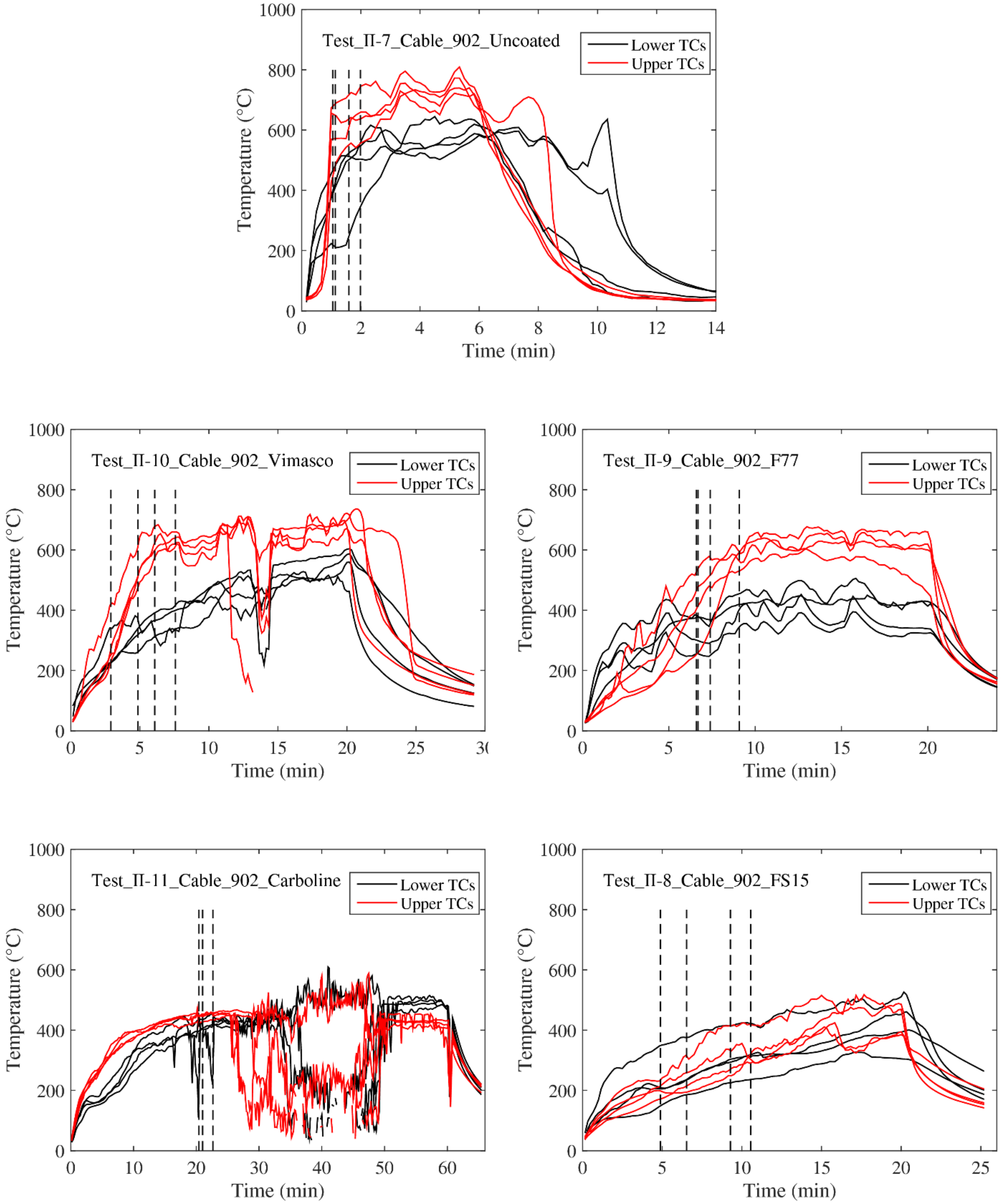


**Figure 6-26. Inner cable temperatures, Cable 902.**

### 6.3.3 Cable 813

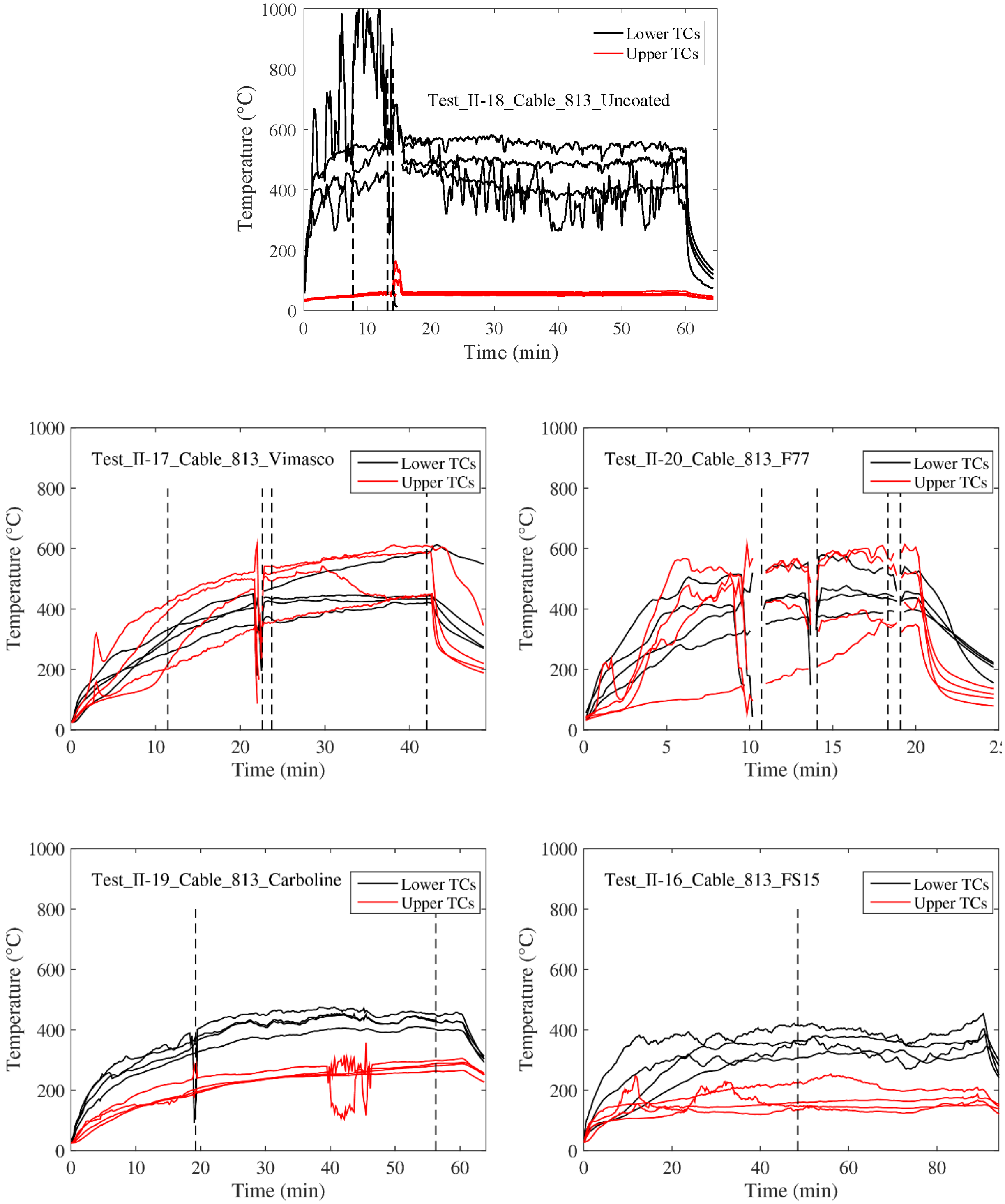


**Figure 6-27. Inner cable temperatures, Cable 813.**

## 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 where the coatings were applied at a thickness just less than the recommended value, the fire did spread upwards 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 thermocouples, it was not possible to discern a definitive temperature at which the cables failed electrically. There are several reasons for this:

1. The thermocouples were not necessarily placed at the location of peak heat flux from the fire.
2. The coating thickness varied from point to point and cable to cable.
3. The thermocouples 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 used 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 chapter describes experiments in which uncoated and coated electrical cables were exposed directly to a pre-mixed air-propane flame with a nominal temperature of 750 °C (1382 °F) at the point of impingement.

## 7.1 Experimental Description

The experiments are similar to those described in the IEC International Standard 60331-11 (IEC 2009). A typical experiment is shown in Figure 7-1.

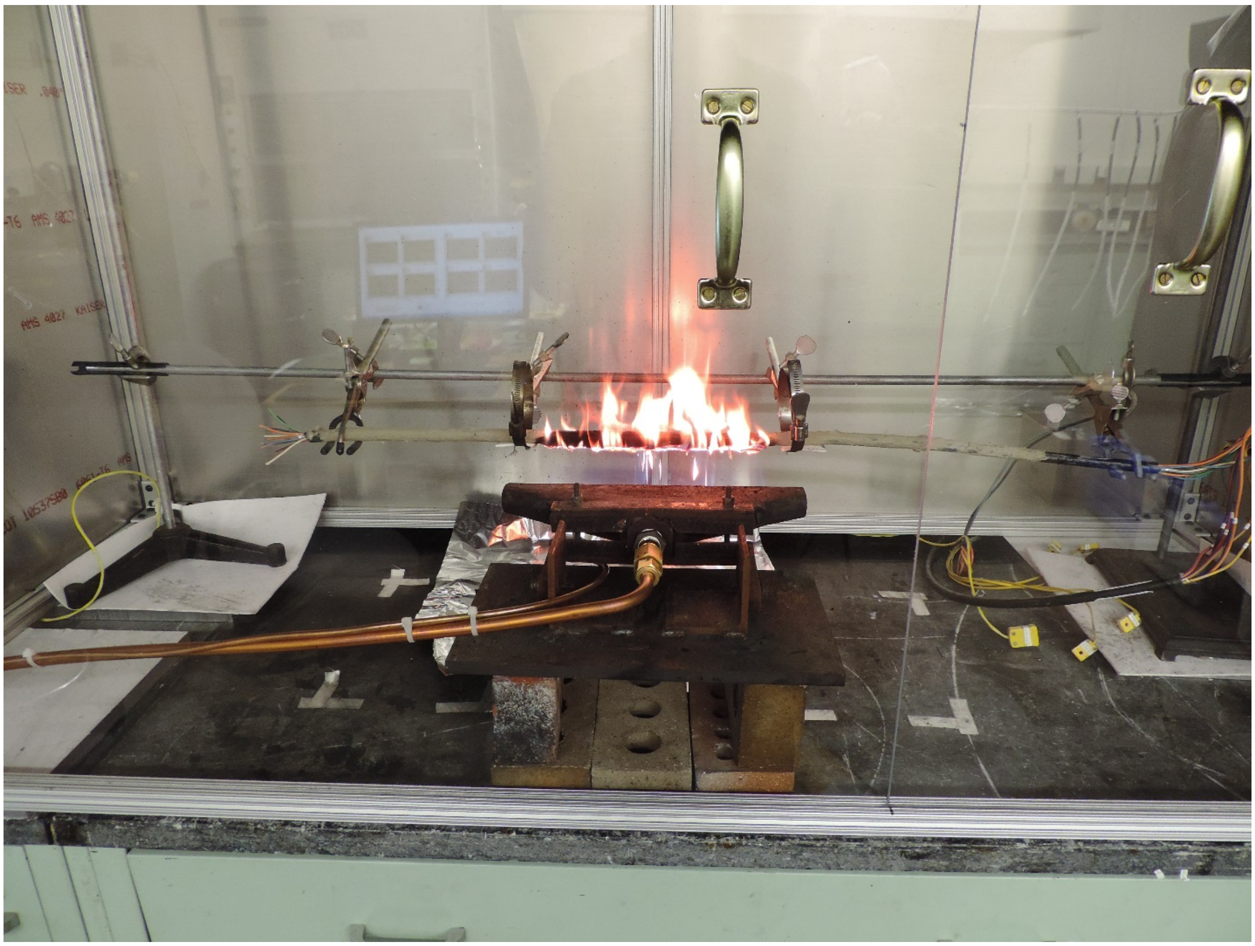

**Figure 7-1. Photograph of a typical circuit integrity experiment.**

In this experiment, a single cable, either coated or uncoated, was immersed in a pre-mixed 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. The propane and air flow rates flowing into the pre-mixed burner were half of what is called for in the standard – 2.5 L/min propane and 40 L/min air at 1 bar and 20 °C, 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 thermocouples were positioned at the location of the cable centerline to ensure that the average flame temperature over 10 minutes was between 700 °C (1292 °F) and 800 °C (1472 °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 thermoplastic cable, and Cable 813 is a 12 conductor thermoset 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 testing. Table 7-1 lists the average coating thicknesses for the two cables and the four different coatings.

The test apparatus could only accommodate one cable segment at a time, and temperature and electrical integrity measurements could not be done within the same cable. Thus, for each test sample, separate experiments were conducted – one for circuit integrity and one for temperature measurement. Experiments involving coated cables were repeated three times; that is, 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 V and the cable was heated until a 3 A circuit breaker tripped.

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

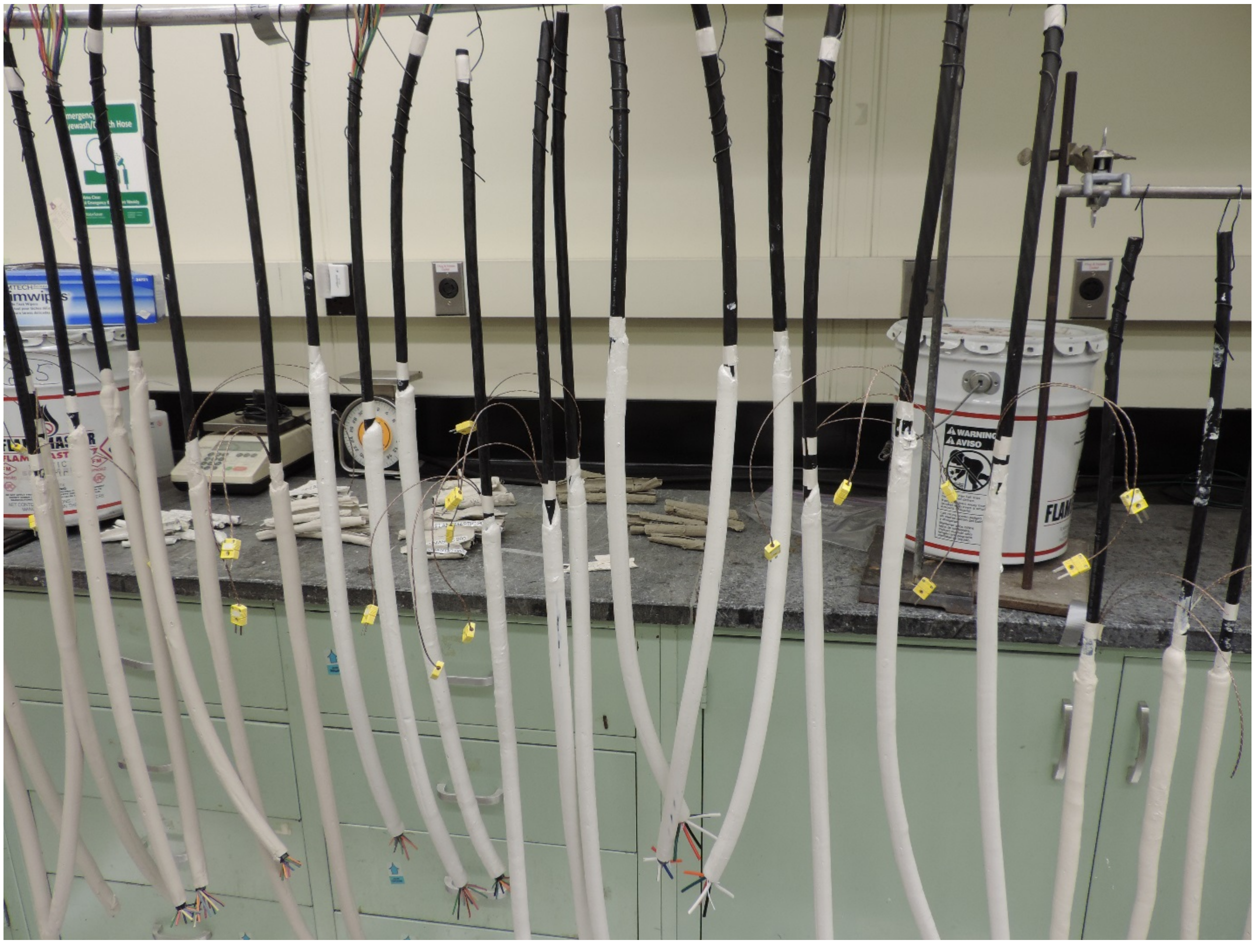


**Figure 7-2. Coated cables in preparation for experiments.**

## 7.2 Results

The results of the experiments are summarized in Table 7-1. 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.

For the nominal coating thickness of 1.6 mm (1/16 in or 62.5 mil), the average delay in failure time was 3.4 min for Cable 813 and 10.1 min for Cable 900.

For the nominal coating thickness of 3.2 mm (1/8 in or 125 mil), the average delay in failure time was 12.8 min for Cable 813 and 23.3 min for Cable 900.

However, 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.

The complete results of the experiments are included in Appendix A.

**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 |

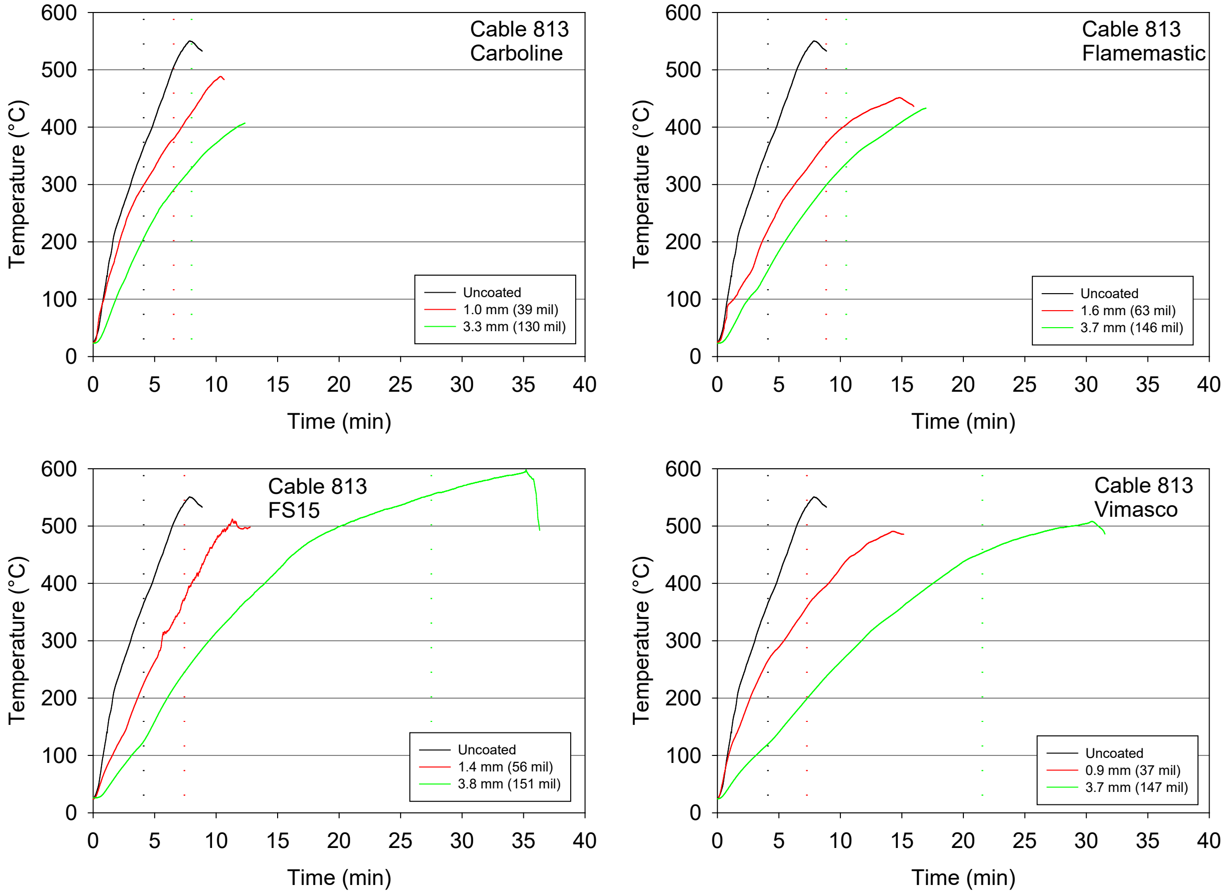


**Figure 7-3. Inner temperature and circuit failure time for Cable 813.**

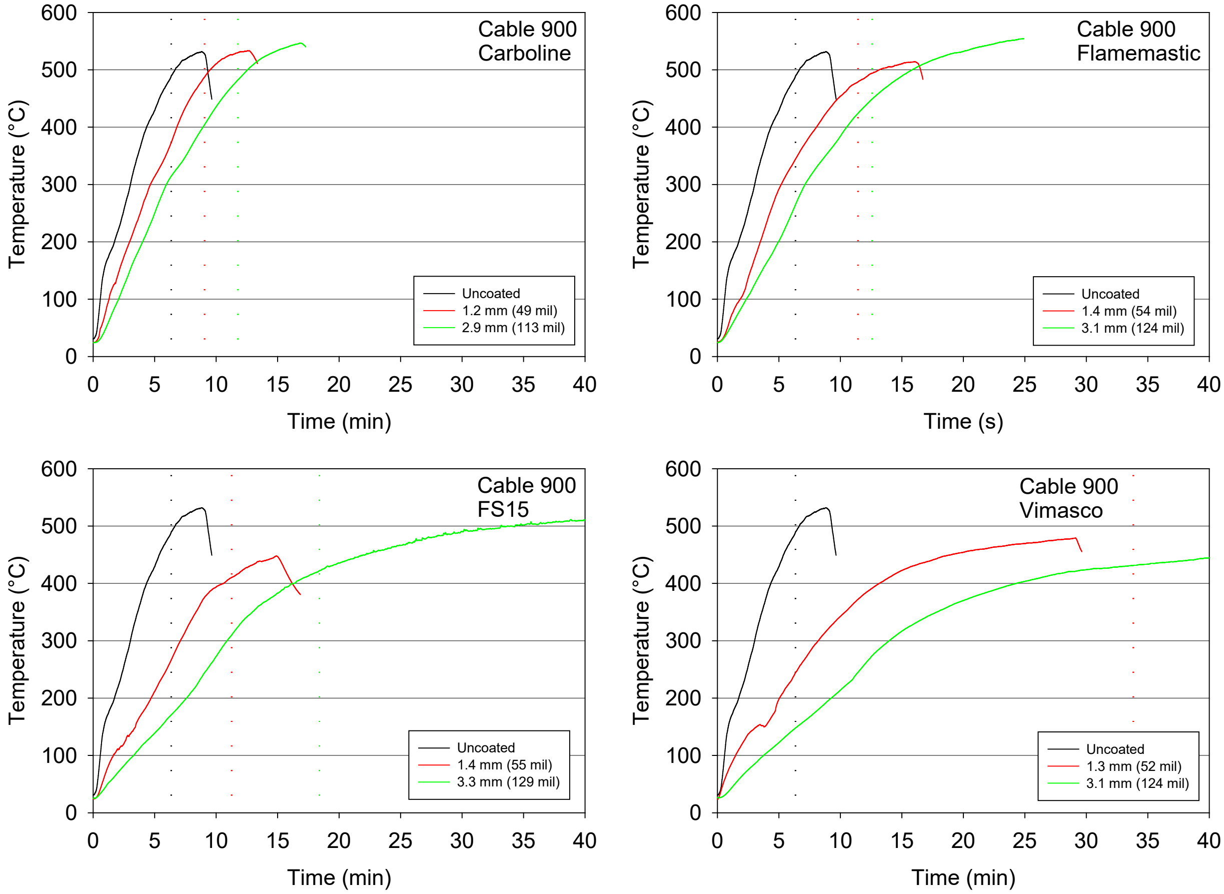


**Figure 7-4. Inner temperature and circuit failure time for Cable 900.**

# 8 FULL-SCALE HORIZONTAL FLAME SPREAD EXPERIMENTS

This chapter 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

The test compartment is shown in Figure 8-1. 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 MW.

Four 30 cm (12 in) wide, 1.8 m (6 ft) long horizontal trays, were positioned as shown in the figure, containing 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. All 8 experiments used Cable 900, a 7 conductor thermoplastic 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 was applied in all trays. The cables in the upper most two trays dropped down from one tray to the other. In each tray, four cables were energized (yellow) and four cables were instrumented with thermocouples (red), as shown in the figure. Given that there were 2 cable configurations and 4 coatings, 8 experiments were conducted.

Cable 900 has a mass of 0.38 kg/m (257 lb per 1000 ft). For Configuration A (see Figure 8-3), the six uncoated cables have a mass of 2.3 kg/m (1540 lb per 1000 ft), and the six coated cables have a mass of approximately 2.6 kg/m (1740 lb per 1000 ft). For Configuration B, the 15 uncoated cables have a mass of 5.7 kg/m (3860 lb per 1000 ft), and the 15 coated cables have a mass of 6.1 kg.m (4090 lb per 1000 ft). The dry thickness of the coatings was at least 1.6 mm (1/16 in), as per manufacturer instructions. Measured samples fell between 1.6 mm 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 heat release rate of the burner was initially 50 kW. After 15 min, it was increased to 100 kW. After 30 min, 200 kW, and after 45 min, 400 kW.

Sheathed thermocouples 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 thermocouples 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, who also manufactured the Type X gypsum board.

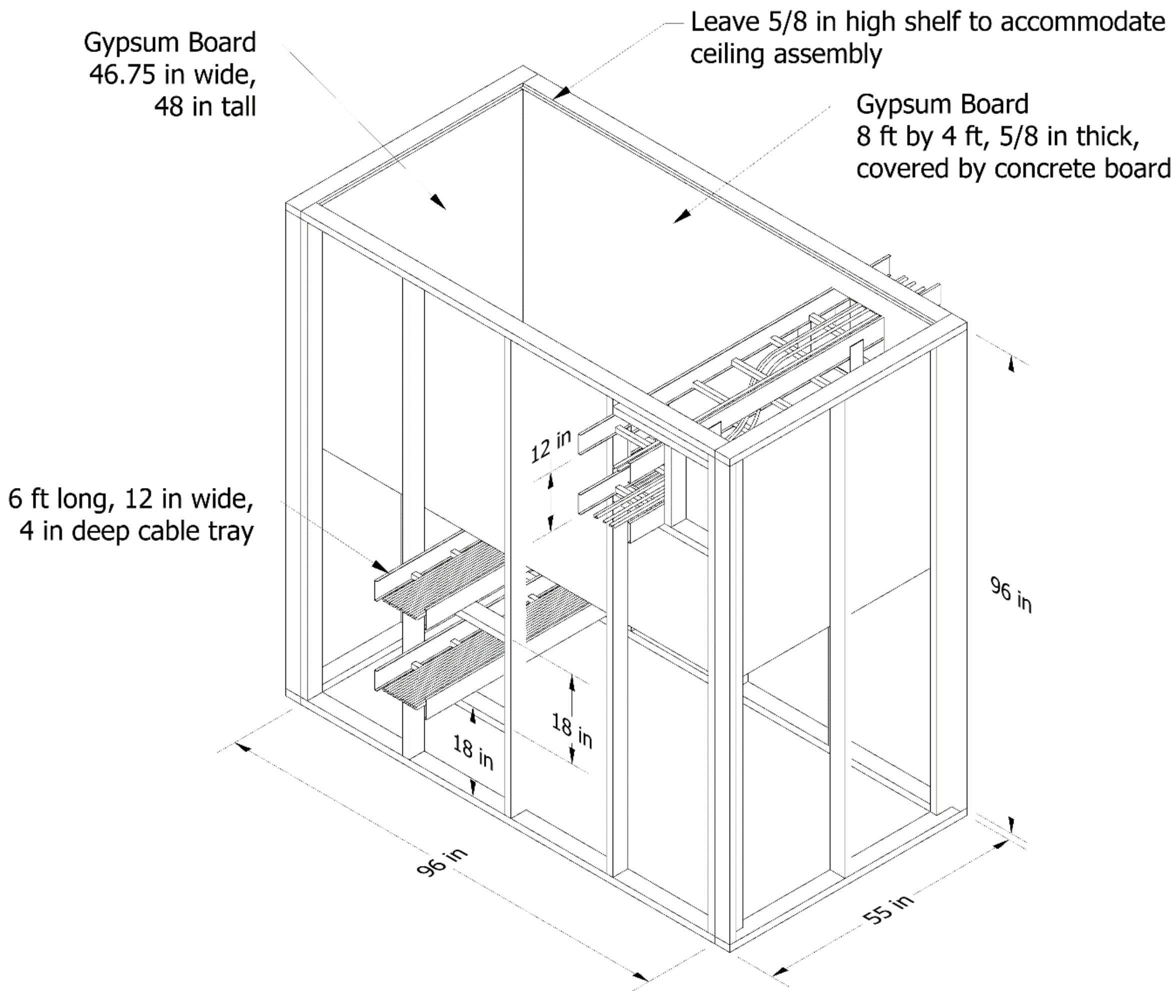


**Figure 8-1. Compartment to be used for the horizontal cable experiments.**

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

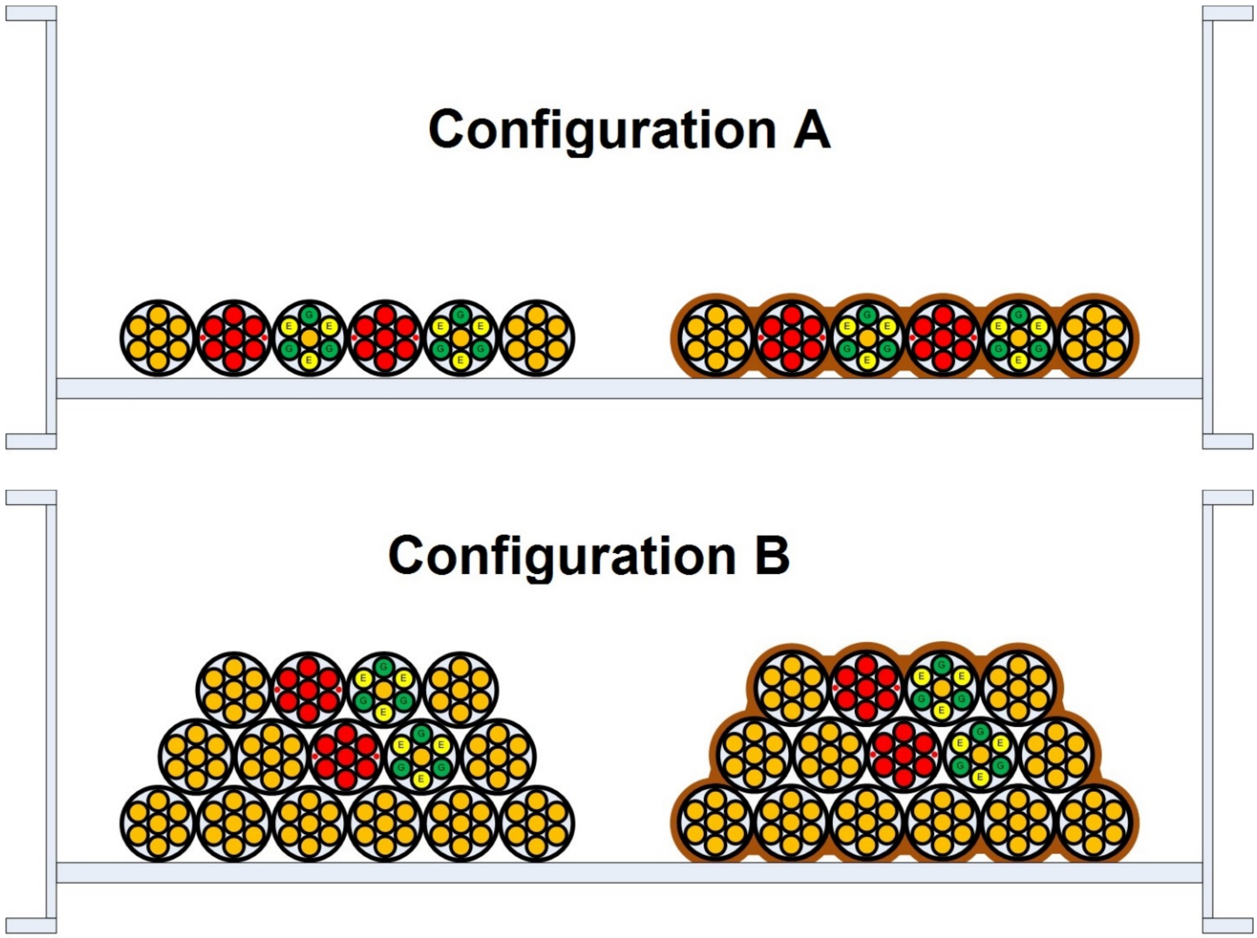


**Figure 8-3. Schematic diagram of cable layouts: A “single row”, B “bundle”.**

## 8.3 Results

Eight experiments were conducted. The results are summarized in Table 8-1 and Figure 8-4 through Figure 8-7. 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 thermocouples 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 (Tests 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 (Tests 5-8), the cables labelled “Uncoated 1” and “Coated 1” were positioned at the top of their respective bundles, and the cables labelled “Uncoated 2” and “Coated 2” were buried within the bundle and were completely 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. Note that the energized cables could not be simultaneously instrumented with thermocouples because the thermocouples would interfere with the electrical current and vice verse. The correspondence between electrical failure time and cable temperature is shown graphically in Figure 8-4 through Figure 8-7, 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 cables labelled “Uncoated 1” and “Coated 1”; the dashed lines indicate “Uncoated 2” and “Coated 2”. Red indicates uncoated cable; green indicates coated cable. In Table 8-1, “Delay 1” indicates the difference in failure between the cables labelled “Coated 1” and “Uncoated 1”. “Delay 2” indicates the difference in failure between “Coated 2” and “Uncoated 2”.

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

| Test Number Coating Configuration | Tray No. | Uncoated 1 | | Uncoated 2 | | Coated 1 | | Coated 2 | | Delay 1 | Delay 2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Time (min) | Temp. (°C) | Time (min) | Temp. (°C) | Time (min) | Temp. (°C) | Time (min) | Temp. (°C) | (min) | (min) |
| Test H-1 Carboline Single row, 6 cables | 1 | 5.7 | 200 | 14.6 | 290 | 24.2 | 330 | 21.4 | 190 | 18.4 | 6.8 |
| | 2 | 15.5 | 235 | 14.4 | 210 | 24.7 | 270 | 23.3 | 190 | 9.2 | 8.9 |
| | 3 | 34.4 | 225 | 34.4 | 215 | 48.4 | 260 | 44.9 | 190 | 13.9 | 10.4 |
| Test H-2 Flamemastic Single row, 6 cables | 1 | 10.0 | 560 | 6.6 | 250 | 17.3 | 270 | 19.8 | 240 | 7.4 | 13.2 |
| | 2 | 13.6 | 220 | 9.9 | 180 | 26.9 | 290 | 27.9 | 260 | 13.3 | 18.0 |
| | 3 | 33.0 | 210 | 34.5 | 210 | 46.6 | 255 | 39.8 | 195 | 13.7 | 5.3 |
| Test H-3 FS15 Single row, 6 cables | 1 | 3.9 | 140 | 7.8 | 280 | 24.4 | 370 | 29.0 | 315 | 20.5 | 21.2 |
| | 2 | 12.7 | 315 | 9.0 | 170 | 43.0 | 560 | 24.7 | 205 | 30.3 | 15.8 |
| | 3 | 33.3 | 220 | 34.6 | 235 | 40.2 | 205 | 39.5 | 200 | 6.8 | 5.0 |
| Test H-4 Vimasco Single row, 6 cables | 1 | 9.0 | 305 | 4.7 | 170 | 19.0 | 400 | 18.1 | 200 | 10.0 | 13.4 |
| | 2 | 5.9 | 110 | 6.0 | 110 | 23.5 | 275 | 21.7 | 175 | 17.6 | 15.8 |
| | 3 | 28.5 | 210 | 30.5 | 220 | 39.6 | 190 | 36.8 | 170 | 11.2 | 6.3 |
| Test H-5 Carboline Bundle, 15 cables | 1 | 14.8 | 520 | 17.9 | 390 | 29.1 | 355 | 45.8 | 360 | 14.3 | 27.9 |
| | 2 | 17.9 | 385 | 25.2 | 280 | 36.8 | 240 | 41.6 | 210 | 18.9 | 16.4 |
| | 3 | 37.3 | 245 | 44.6 | 210 | 60.3 | 330 | 55.5 | 170 | 23.0 | 11.0 |
| Test H-6 Flamemastic Bundle, 15 cables | 1 | 16.5 | 590 | 22.0 | 355 | 24.6 | 400 | 33.6 | 590 | 8.1 | 11.6 |
| | 2 | 24.6 | 625 | 25.1 | 200 | 27.3 | 330 | 39.1 | 250 | 2.7 | 14.0 |
| | 3 | 42.5 | 300 | 45.7 | 215 | 54.4 | 440 | 51.0 | 170 | 12.0 | 5.3 |
| Test H-7 FS15 Bundle, 15 cables | 1 | 12.9 | 490 | 18.6 | 205 | 19.8 | 245 | 34.9 | 620 | 6.9 | 16.4 |
| | 2 | 21.9 | 540 | 24.0 | 225 | 43.9 | 630 | 41.6 | 305 | 22.0 | 17.6 |
| | 3 | 34.0 | 235 | 41.9 | 195 | 50.7 | 270 | 53.8 | 160 | 16.7 | 12.0 |
| Test H-8 Vimasco Bundle, 15 cables | 1 | 10.1 | 550 | 14.8 | 280 | 19.0 | 410 | 28.1 | 165 | 8.8 | 13.4 |
| | 2 | 20.2 | 625 | 23.4 | 275 | 25.6 | 170 | 39.7 | 340 | 5.3 | 16.3 |
| | 3 | 33.4 | 280 | 41.6 | 200 | 44.3 | 235 | 51.2 | 180 | 11.0 | 9.6 |

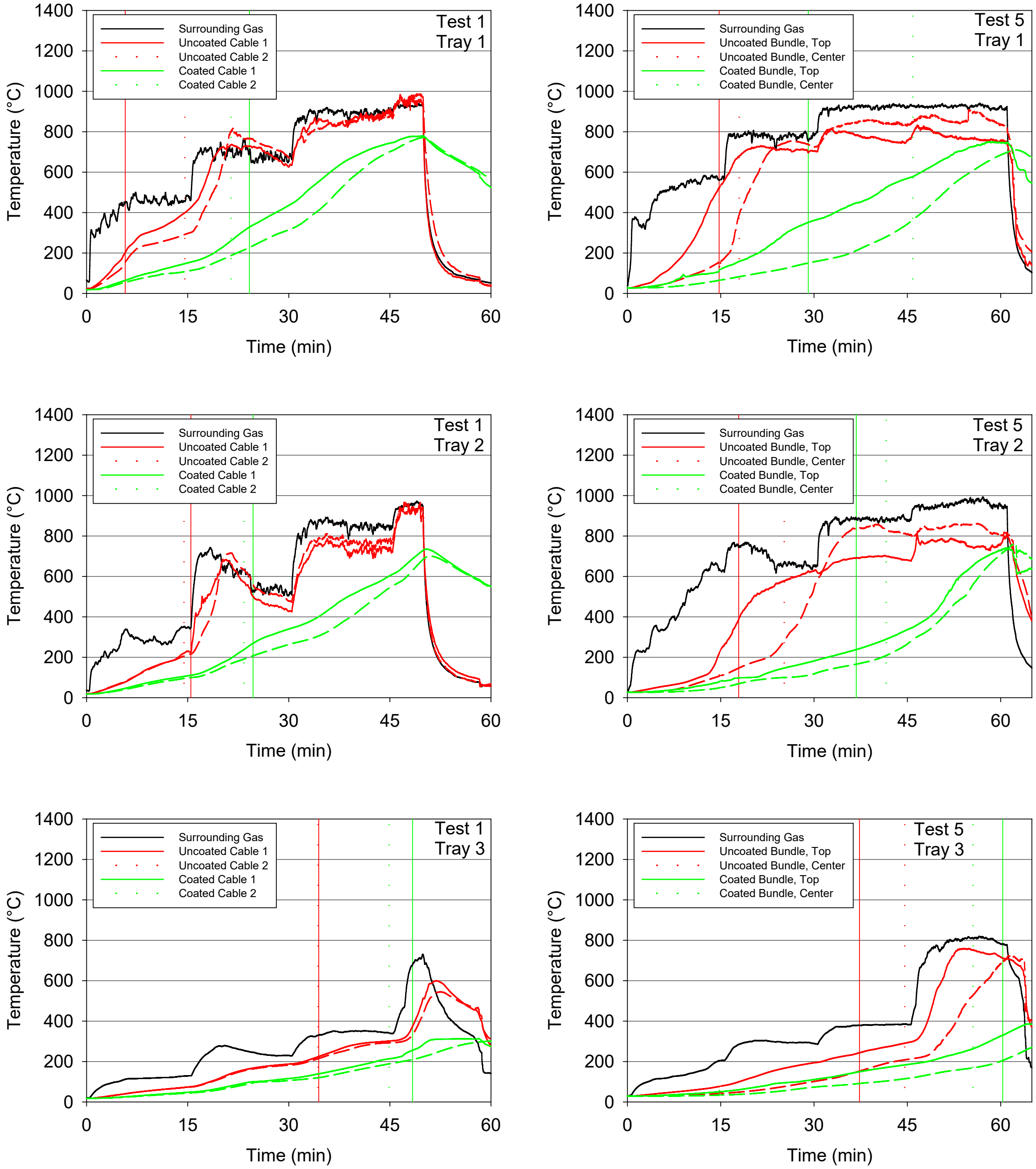


**Figure 8-4. Full-scale compartment temperatures, Carboline.**

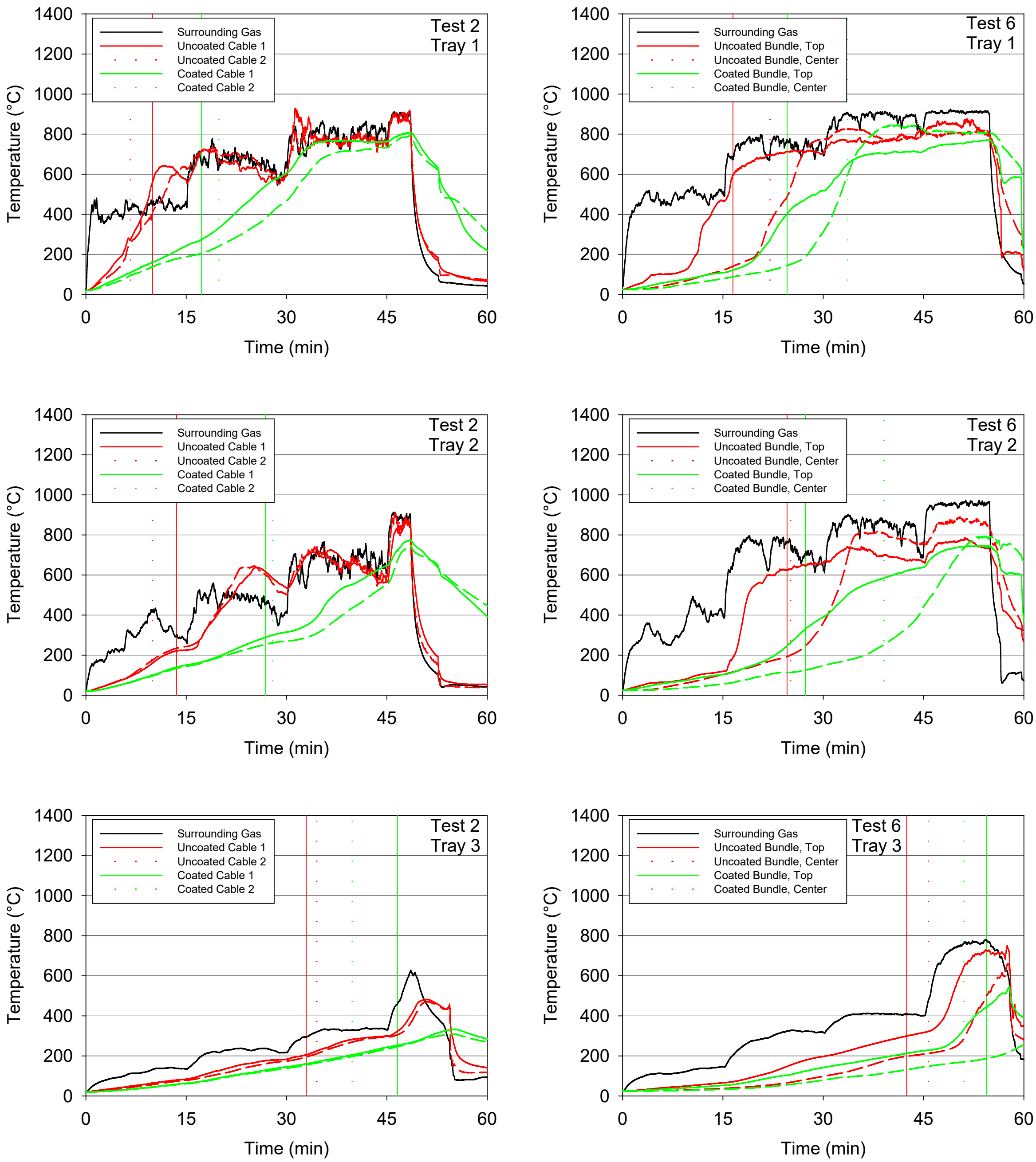


**Figure 8-5. Full-scale compartment temperatures, Flamemastic.**

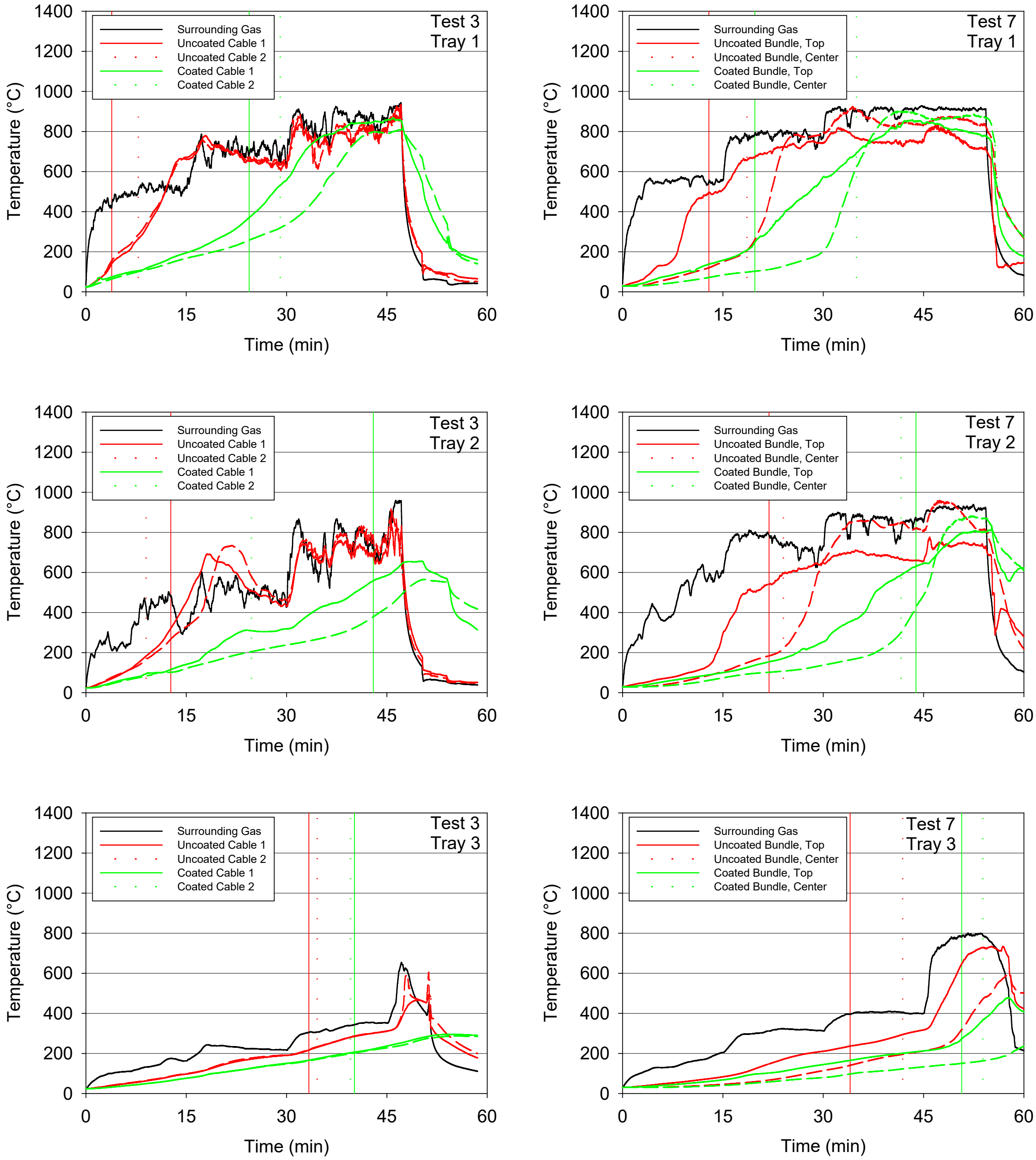


**Figure 8-6. Full-scale compartment temperatures, FS15.**

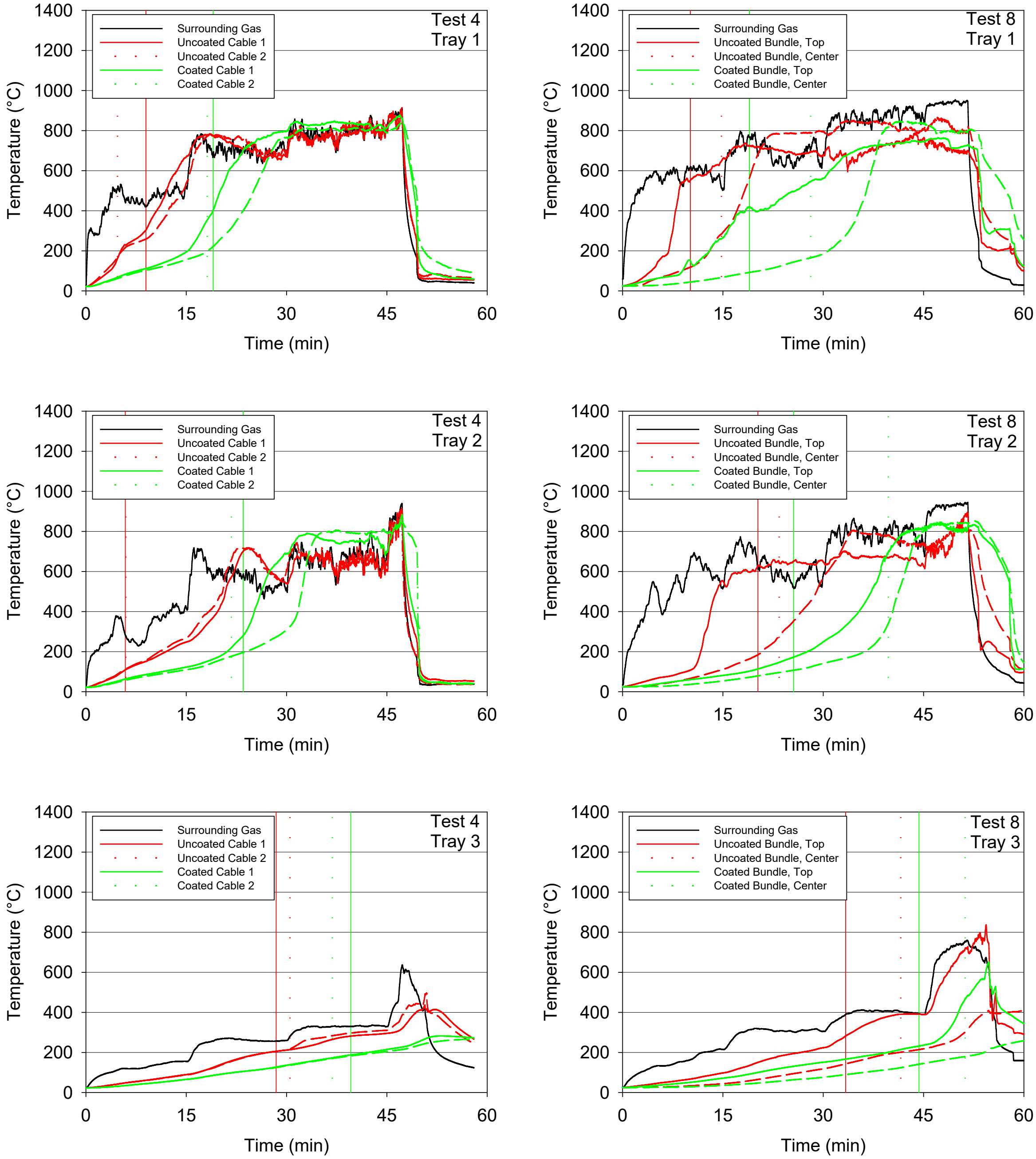


**Figure 8-7. Full-scale compartment temperatures, Vimasco.**

## 8.4 Discussion

The data presented 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 affect of cable location and configuration on the failure times and temperatures. These results are shown in Table 8-2. For example, the average time to failure for all uncoated cables in the single row configuration in Tray 1 was 7.8 min. The average delay time brought about by applying a protective coat for these same cables was 13.9 min. The average delay time for all cables in all trays was 13.3 min.

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. 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 Trays 1 and 2. Two possible reasons for this is that (1) these cables were subjected to a more gradual heating rate, and (2) these cables dropped from the upper tray to the lower tray which were separated by 30 cm (12 in). This drop subjected the cables to a fairly tight bend radius that would tend to draw the individual conductors closer together as the insulation underwent thermal and mechanical degradation.

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

| Tray No. | Cable Position | Uncoated Cables | | Coated Cables | | Delay Time (min) |
|---|---|---|---|---|---|---|
| | | Time (min) | Temp. (°C) | Time (min) | Temp. (°C) | |
| 1 | Single row of 6 | 7.8 | 274 | 21.7 | 289 | 13.9 |
| 2 | Single row of 6 | 10.9 | 194 | 27.0 | 278 | 16.1 |
| 3 | Single row of 6 | 32.9 | 218 | 42.0 | 208 | 9.1 |
| 1 | Bundle of 15, exterior | 13.6 | 538 | 23.1 | 353 | 9.5 |
| 2 | Bundle of 15, exterior | 21.2 | 544 | 33.4 | 343 | 12.2 |
| 3 | Bundle of 15, exterior | 36.8 | 265 | 52.4 | 319 | 15.7 |
| 1 | Bundle of 15, interior | 18.3 | 308 | 35.6 | 434 | 17.3 |
| 2 | Bundle of 15, interior | 24.4 | 245 | 40.5 | 276 | 16.1 |
| 3 | Bundle of 15, interior | 43.4 | 205 | 52.9 | 170 | 9.5 |

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 the previous chapter. For the Carboline coating, the average delay time of all trays and configurations was 14.9 min. For Flamemastic, it was 10.4 min. For FS15, it was 15.9 min. For Vimasco, it was 11.6 min.

# 9 CONCLUSION

Phase 2 of the REBECCA-FIRE program has focused on the burning behavior of protective cable coatings. The sections below summarize the results of the measurements.

## 9.1 Basic Thermal Properties

One of the objectives of the REBECCA-FIRE program has been to develop a calculation method to determine the thermal penetration time into coated cables and thereby predict the delay in electrical failure time of a cable exposed to a fire. This method would be an extension of the THIEF model (McGrattan 2008).

A limited number of calculations have been performed and compared with experimental measurements made on coated cable bundles exposed to a specified heat flux. The results demonstrate that while it is possible to estimate the thermal penetration time for different cables within a bundle; there are a number of reasons why this methodology may not be practical:

1. It is not always possible to characterize a coated cable bundle in terms of a homogenous, cylindrical object amenable to a one-dimensional heat conduction calculation. While it is always 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 some kind of simple spreadsheet calculation method.

2. The results of the thermocouple measurements in the full-scale vertical flame spread experiments suggest that it is not practical to apply coatings with a uniform thickness. Whether the coating is painted, sprayed, or troweled onto the cables, one could never assume a perfectly uniform thickness.

3. The results of the full-scale, horizontal tray circuit integrity experiments (Chapter 8) indicate that the inner cable temperature at which circuit failure occurs depends on the rate of heating and possibly the bend radius at the point of exposure. A simple thermal model like THIEF cannot account for these conditions.

## 9.2 Burning Rate

The burning rate of coated cables was measured at bench scale in the cone calorimeter. In general, the coatings delay the time to ignition, decrease the peak burning rate, and increase the total energy released because the coatings do add to the fuel load. 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.

The full-scale vertical and horizontal tray experiments (Chapters 6 and 8) indicate that even though the coatings might add to the overall combustible mass, they do effectively prevent the spread of fire and restrict it to the point of flame impingement. The amount of additional energy released due to the coatings is negligible.

## 9.3 <u>Ignition Temperature</u>

Coated and uncoated cable segments were placed within a convection oven and heated gradually until ignition was observed, and the temperature was measured with thermocouples 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 not only a function of the material properties, but also 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 in the neighborhood of 300 °C (572 °F), whereas thermoset cable ignited in the neighborhood of 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 (thermogravimetric analysis) and MCC (micro-combustion calorimetry) and the cone calorimeter measurements indicate that the coatings pyrolyze in the neighborhood of 350 °C (662 °F) and do contribute to the volatized fuel vapors, albeit weakly. The coatings are not designed to prevent pyrolysis and ignition, but rather to delay it by slowing the heat penetration through the coating and into the cable.

In short, it cannot be demonstrated that the coatings increase the effective ignition temperature of the cables, but rather delay the time to reach the ignition temperature.

## 9.4 <u>Flame Spread</u>

Vertical flame spread experiments based on the IEEE-1202 (1991) standard 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 where the coatings were applied at a thickness just less than the recommended value, the fire did spread upwards to various extents, but this behavior was not repeated when the coatings were applied as directed.

# 10 REFERENCES


[1] ASTM D6113-03 (2003) *Standard Test Method for Using a Cone Calorimeter to Determine Fire-Test-Response Characteristics of Insulating Materials Contained in Electrical or Optical Fiber Cables*. ASTM International, West Conshohocken, Pennsylvania.

[2] ASTM D7309-13 (2013) *Standard Test Method for Determining Flammability Characteristics of Plastics and Other Solid Materials Using Microscale Combustion Calorimetry*. ASTM International, West Conshohocken, Pennsylvania.

[3] ASTM E1131-08 (2014) *Standard Test Method for Compositional Analysis by Thermogravimetry*. ASTM International, West Conshohocken, Pennsylvania.

[4] ASTM E1269-11 (2011) *Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry*. ASTM International, West Conshohocken, Pennsylvania.

[5] ASTM E1354-09 (2000) *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*. ASTM International, West Conshohocken, Pennsylvania.

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

[7] IEC International Standard 60331-11 (2009) *Tests for electric cables under fire conditions – Circuit integrity – Part 11: Apparatus – Fire alone at a flame temperature of at least 750 °C,* International Electrotechnical Commission, Geneva, Switzerland.

[8] IEEE Standard 384 (2008) *Standard Criteria for Independence of Class 1E Equipment and Circuits*. Institute of Electrical and Electronics Engineers, New York, New York.

[9] IEEE Standard 1202 (1991) *Standard for Flame Testing of Cables for Use in Cable Tray in Industrial and Commercial Occupancies*. Institute of Electrical and Electronics Engineers, New York, New York.

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

[11] Lyon, R.E., N. Safronava, J. Senese, and S.I. Stoliarov (2012) "Thermokinetic model of sample response in nonisothermal analysis," *Thermochimica Acta*, **545**, pp. 82-89.

[12] McGrattan, K. (2008) *Cable Response to Live Fire (CAROLFIRE) Volume 3: Thermally-Induced Electrical Failure (THIEF) Model*, NUREG/CR-6931, Vol. 3, U.S. Nuclear Regulatory Commission, Washington, DC.

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

[14] McGrattan, K. and S. Bareham (2013). *Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE)*, NUREG/CR-7010, Vol. 2, U.S. Nuclear Regulatory Commission, Washington, DC.

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

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

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

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

# 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 Chapter 7 . In these experiments, a single horizontal cable segment was immersed within a 25 cm (10 in) long flame whose temperature at the point of impingement was approximately 750 °C (1382 °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 A 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 indicate “Replicate”. Note that there is no correspondence between replicate thermal and electrical measurements because these measurements were made on separate cables.

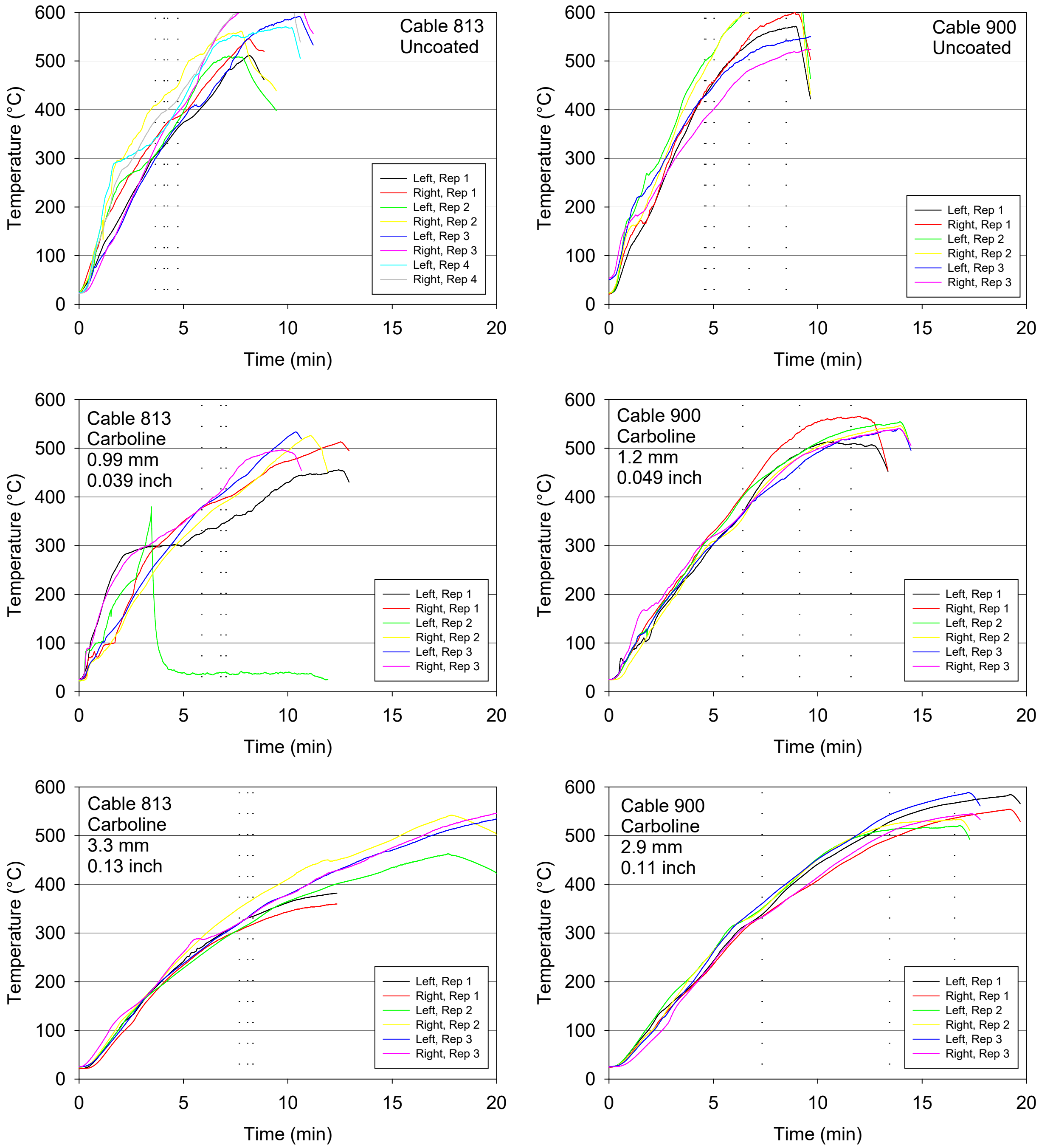


**Figure 10-1. Inner temperature and time to failure for cables coated with Carboline.**

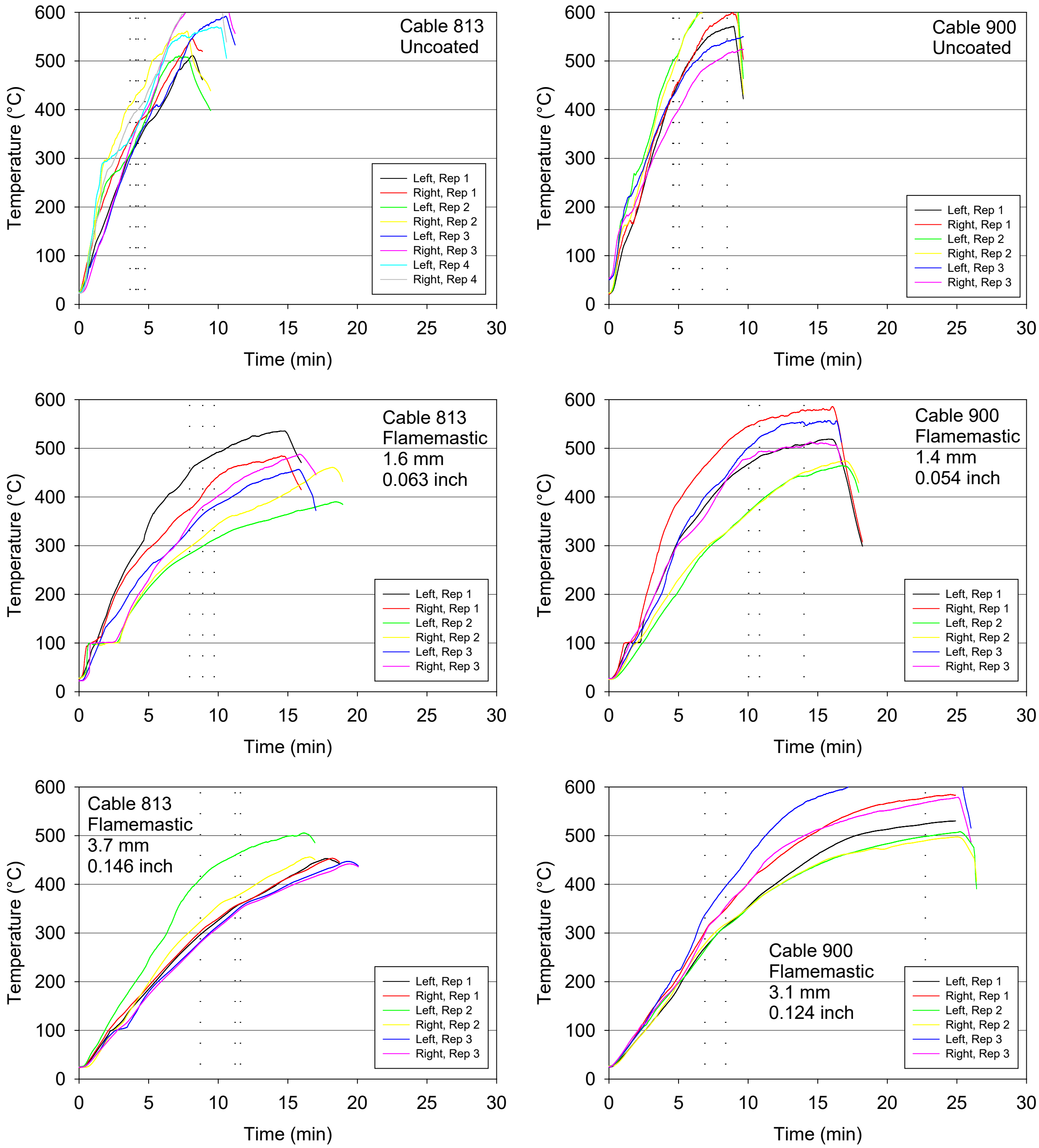


**Figure 10-2. Inner temperature and time to failure for cables coated with Flamemastic.**

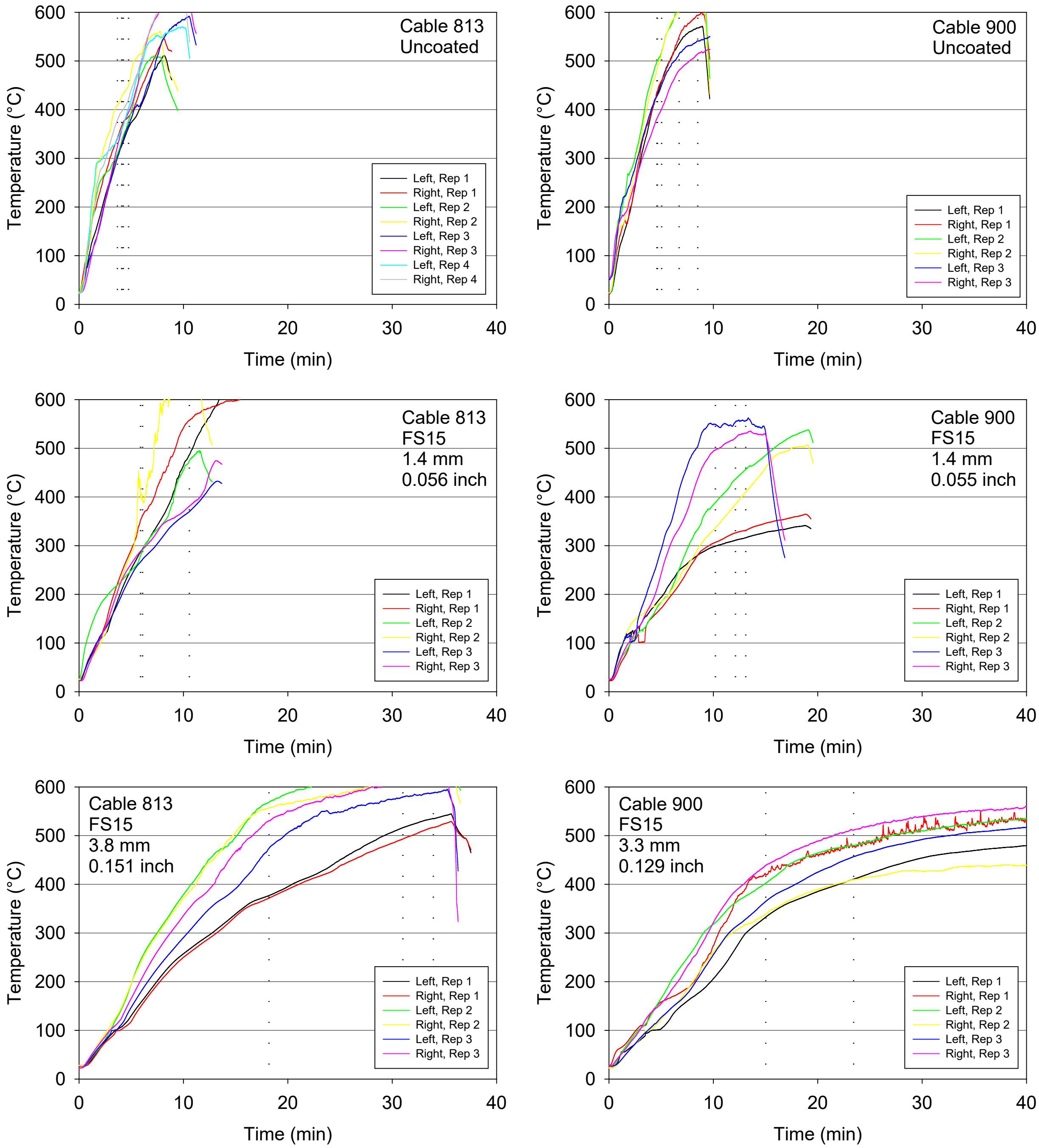


**Figure 10-3. Inner temperature and time to failure for cables coated with FS15.**

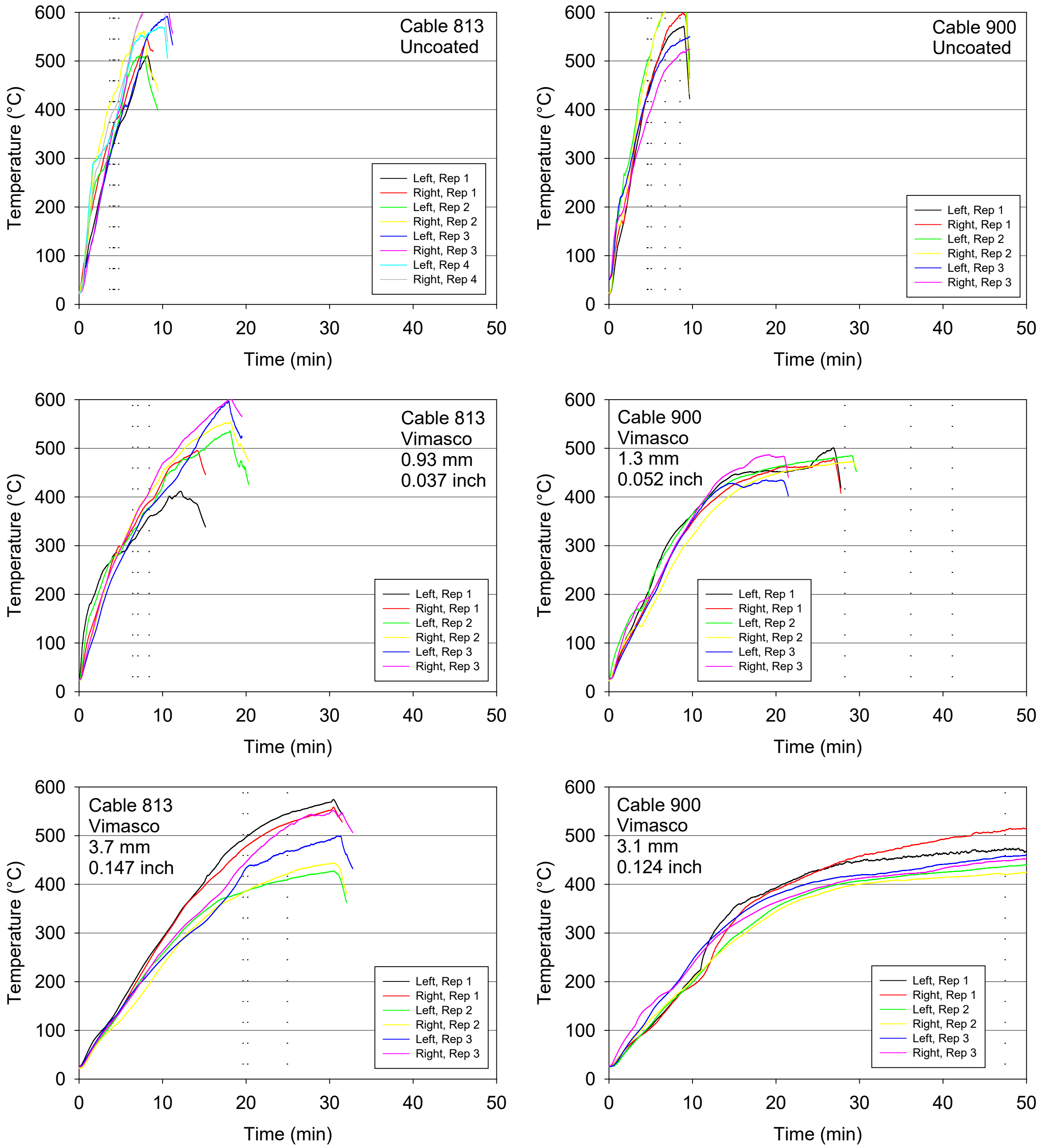


**Figure 10-4. Inner temperature and time to failure for cables coated with Vimasco 3i.**

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

This report contains results of a multi-year experimental program called REBECCA-FIRE (Response Bias of Electrical Cable Coatings at Fire Conditions). Volume 2 of the three volume report focuses on the burning behavior of electrical cables that are protected with a variety of protective coatings. The experiments range from bench to full-scale. Ignition temperatures have been measured using a well-controlled convection oven. Burning rates of coated cables have been measured using a cone calorimeter in which 10 cm (4 in) by 10 cm (4 in) cable segments are exposed to a relatively high heat flux to determine their burning rate, heat of combustion, and other properties. Full-scale horizontal and vertical flame spread experiments have been conducted to determine if the coatings prevent the lateral and upward spread of fire over different types of cables, and to determine the time at which circuit integrity is lost.

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