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RESPONSE BIAS OF ELECTRICAL CABLE COATINGS AT FIRE CONDITIONS

Volume 3
Cable Functionality

Final Report

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Disclaimer

ABSTRACT

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

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

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

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

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

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

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

KEY RESEARCH QUESTIONS

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

RESEARCH OVERVIEW

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

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

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

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

KEY FINDINGS

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

WHY THIS MATTERS

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

HOW TO APPLY RESULTS

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

LEARNING AND ENGAGEMENT OPPORTUNITIES

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

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

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

ACKNOWLEDGMENTS

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

We also acknowledge support from current and former resident inspectors at Brunswick Steam Electric Plant, Michelle Catts and Mark Schwieg, as well as current and former NRC Region II staff members Scott Shaeffer, Jonathan Montgomery, John Dymek, and Jigar Patel all of whom provided information related to plants with fire-retardant cable coatings in use. This information improved the quality of the testing and of this report.

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

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

ABBREVIATIONS AND ACRONYMS

°C	degrees Celsius
°F	degrees Fahrenheit
cm	centimeter(s)
CSPE	chlorosulfonated polyethylene
DNF	did not fail
EPRI	Electric Power Research Institute
FLASH-CAT	Flame Spread over Horizontal Cable Trays (model)
ft	foot/feet
HGL	hot gas layer
HRR	heat release rate
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
in.	inch(es)
IRMS	Insulation Resistance Measurement System
kg	kilogram(s)
km	kilometer(s)
kW	kilowatt(s)
L	liter(s)
lb	pound(s)
m	meter(s)
mi	mile(s)
min	minute(s)
MJ	megajoule(s)
MOV	motor-operated valve
NEI	Nuclear Energy Institute
NIST	National Institute of Standards and Technology
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
PE	polyethylene
PVC	polyvinyl chloride
RES	Office of Nuclear Regulatory Research
RIL	research information letter
s	second(s)
SCDU	Surrogate Circuit Diagnostic Unit
SNL	Sandia National Laboratories
TC	thermocouple
TP	thermoplastic
TS	thermoset
TVA	Tennessee Valley Authority
VAC	volts alternating current
XLPE	crosslinked polyethylene

1. INTRODUCTION

The main objective of Volume 3 is to develop a dataset, by performing fire experimentation, that can be used to assess the impacts of fire-retardant cable coating on electrical cable functionality. This effort focuses on generating empirical data that will be used to support a direct relationship between time delay loss of electrical functionality and fire-retardant cable coating. This volume does not address aging effects. A project to investigate the impact of aging on fire-retardant cable coatings is currently underway. Nor does this volume address guidance for the application of these results. Instead, the guidance will be published in Volume 5, a joint report between the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) and the Electric Power Research Institute (EPRI).

2. TECHNICAL APPROACH

2.1 General Approach

The experiments described in this report represent the first significant follow-up on cable coating performance sponsored by the NRC since the 1970s. These follow-up series of experiments were performed to assess the performance of cable coatings in terms of fire and electrical response characteristics. Volume 2 presents the results pertaining to fire characteristics; this report (Volume 3) presents the results pertaining to electrical response characteristics.

Initial experiments were performed at Sandia National Laboratories (SNL) in an apparatus known as Penlight. This apparatus provides a well-characterized radiant thermal exposure that is uniformly applied to the experiment specimen. These scoping experiments provided general insights on the coating response to severe thermal conditions but were limited by the amount of combustible material and the type of cable specimens available. Section 4 presents details and results from the radiant energy experiment series

Additional experiments were performed at the National Institute of Standards and Technology (NIST). The NIST experiments involved the exposure of coated and uncoated cable samples to common fire conditions (flame, plume, and hot gas layer). Radiant exposure experiments were not performed at NIST. Three series of experiments were performed at NIST to evaluate circuit functionality. Two of the series followed protocols similar to standardized experiments, which exposed cables to flaming fire conditions. The last series followed a protocol that was similar to previous NRC-sponsored circuit functionality experiments (Nowlen 1999). The last series utilized an intermediate-scale mock room, which allowed cables to be exposed to flaming, plume, and hot gas layer types of thermal environments.

Electrical response is monitored using two different electrical integrity measurement systems. The first system, the Insulation Resistance Measurement System (IRMS), measures actual insulation resistance between the conductors of a multiconductor cable and between the conductors and ground. This system was used only during the SNL radiant experimental series. The second system, the Surrogate Circuit Diagnostic Unit (SCDU), simulates a 120-volt alternating current (VAC) control circuit for a motor-operated valve (MOV). Both the SNL and NIST series of experiments used the SCDU system to monitor circuit integrity.

The cable's temperature response was measured under the cable's outer jacket (i.e., subjacket). This technique has been used previously (Nowlen and Wyant 2008b). Prior experiments have shown that the cable insulation temperature is well correlated to electrical failure, and that subjacket thermocouples (TCs) provide a reasonable measure of the cable insulation temperature. Volume 2 of this research information letter (RIL) presents the thermal data from the NIST experiments.

2.2 Circuit Functionality

Two systems were used to measure cable electrical performance during the fire experiments. Both systems utilize electrical sources powered by 120 VAC and have been used in multiple programs to analyze the failure modes and effects of cables subjected to adverse thermal environments (Nowlen and Wyant 2008a) (Nowlen and Brown 2011) (Nowlen, Brown and Oliver, et al. 2012) (Wyan and Nowlen 2002). Sections 2.3.1 and 2.3.2 briefly describe the characteristics of these two diagnostic systems.

2.3 Background

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

After the 1975 Browns Ferry fire, NPP operators and the NRC staff sought to improve fire safety. One possible option was the application of fire-retardant cable coatings. In the latter half of the 1970s, the NRC-sponsored fire safety research program investigated seven fire-retardant coating materials approved by Factory Mutual (Nowlen 1999). These early efforts focused on flammability effects, such as whether the coatings could prevent or delay flame spread along the lengths of cables, delay cable ignition, and prevent or delay tray-to-tray fire spread. The experiments also explored cable electrical failure behaviors using low-voltage (28 VAC) power sources. However, the use of low-voltage sources is now known to be not representative of in-plant performance and generally understates cable damageability; these results are considered suspect.

The 1970s experiments involved gas chromatography and emission spectroscopy to determine outgassing at temperatures below 300 degrees Celsius (°C) (572 degrees Fahrenheit (°F)). Small-scale and full-scale performance experiments were then conducted with the coated cables. Small-scale experiments used the Ohio State University Release Rate Apparatus to measure relative ignition time, smoke release rates, and heat release rates for coated single-conductor and three-conductor light power cable samples. These small-scale experiments used a thermoset (TS) cross-linked polyethylene (XLPE)-insulated cable.

Full-scale experiments were performed at SNL in three phases. The first phase involved the piloted ignition of one horizontal random-fill cable tray using a gas burner apparatus. The second phase involved the piloted ignition of a stack of two random-fill horizontal trays using the same gas burner. The third phase investigated the effect of a spilled hydrocarbon (diesel fuel) pan fire on a two-tray stack similar to that used during the second phase. For the diesel fuel fire, there was no barrier between the two trays.

The results of the small-scale and large-scale experiments showed that all coatings offered some additional protection. However, the coatings showed a wide range of effectiveness in both their ability to retard combustion and to prevent fire propagation from one tray to another. While electrical measurements were made during full-scale experiments, very little discussion and interpretation were provided on the electrical data. Additionally, as noted above, the techniques used are no longer considered reliable. The diesel fire experiments provided a more realistic fire exposure to the assemblies than the propane burner experiments. Delays, on the order of several minutes, were typical for most of the coating products.

As noted above, these early experiments focused on the effectiveness of cable coatings relative to material flammability. Although these experiments provided some unique insights on flame propagation and fire spreading behavior of coated and uncoated cables, only limited insights on the electrical performance of these cables could be gained. The data indicated some relative differences for cables with and without coatings, and there were some differences from coating to coating, but neither is considered a reliable indicator in comparison to current practice. Also, while temperatures were measured during the experiments, the measurements cannot be correlated to the actual cable conditions. Hence, one cannot correlate cable temperature and electrical failure behaviors. Overall, these early experiments provided important insights but did not produce the type of information most relevant to current applications. Currently, performance-based methods use fire modeling tools to predict the temperature response and failure time behavior for cables under fire exposure conditions.

2.3.1 Surrogate Circuit Diagnostic Unit

The SCDU was developed for NUREG/CR-6931, "Cable Response to Live Fire" (CAROLFIRE), issued April 2008, and Appendix C to NUREG/CR-6931, Volume 1, contains an extensive description of the system (Nowlen and Wyant 2008a). The SCDU system includes four separate modules, each providing the ability to simulate one 120 VAC control circuit. The typical experiment configuration simulates an MOV control circuit with a pair of interlocked motor starter contactor units, although other configurations are possible. Figure 2-1 provides a general system schematic representative of each SCDU. As described below, the SCDU modules were used in a more generic and simplistic configuration for several of the experimental series.

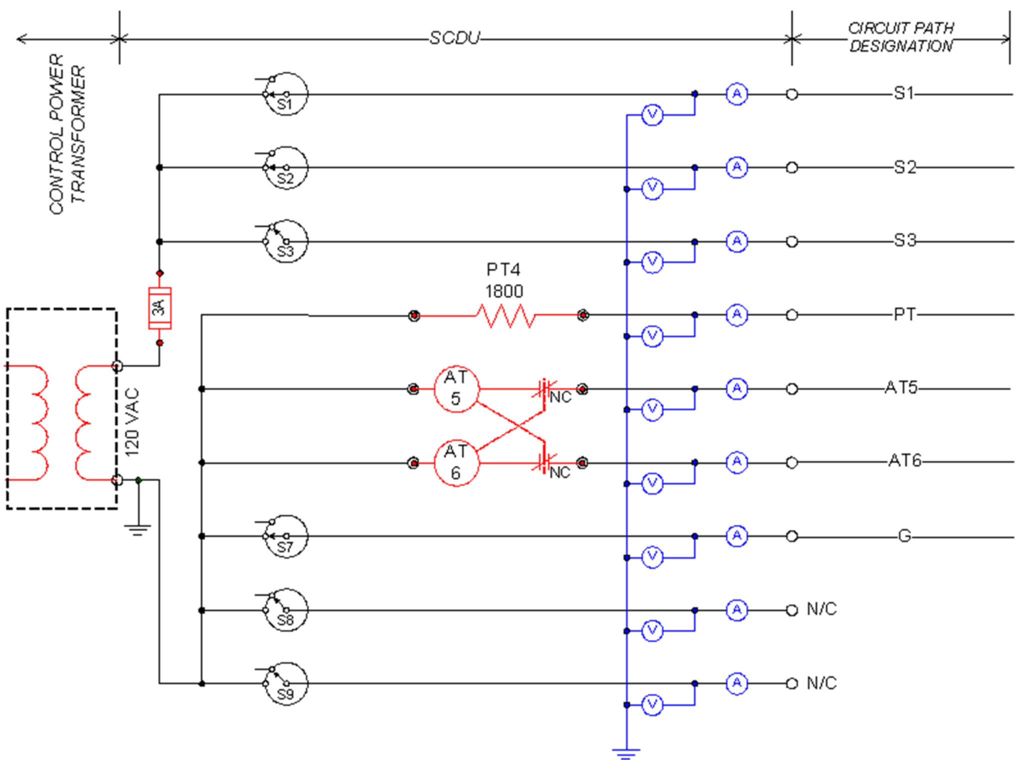

Figure 2-1. Circuit diagram for a generic SCDU including an active electrical interlock on the contactor pair.

Each SCDU allows for the following circuit paths to be used:

- one, two, or three (switch-selectable) energized source circuit paths: “S1” through “S3”
- one passive target path: a 1.8-kilo-Ohm (kΩ) resistor simulating an indicator light, “PT”
- two active target circuit paths: paired motor contactors “AT5” and “AT6”
- one, two, or three (switch-selectable) circuit ground paths: G7 through G9 (only G7 is shown in the figure as connected to the cable, and this path is marked “G”)

The motor starter sets used as active targets are Joslyn-Clark motor starters, the same type used in the original Electric Power Research Institute (EPRI) Fire Experiment Program (EPRI 2002).

For several experiments described in this study, the SCDUs were connected in a simple, first-failure detection configuration, rather than the standard MOV wiring configuration used in CAROLFIRE (Nowlen and Wyant 2008a). The main goal in performance monitoring for this experiment was to determine the time to initial electrical breakdown without concern for the specific failure modes or circuit effects. Hence, the SCDUs were each configured to primarily detect shorting between adjacent conductor pairs within the cable. The configuration can also detect a short between an energized conductor and an external ground (e.g., the cable tray).

The typical wiring configuration between the SCDU and the cable under evaluation was such that the energized “source” conductors (S1, S2, S3) were adjacent to either active target conductors (AT5, AT6) or grounded conductors. Figure 2-2 shows the typical configuration used.

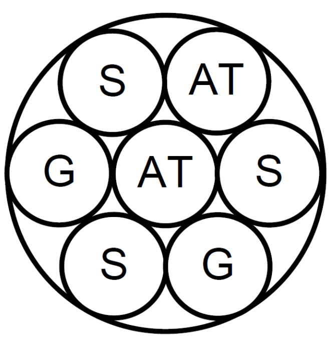

Figure 2-2. Wiring configurations used for experiments performed with the SCDU (S, source; G, ground; AT, active target).

Given this configuration, the voltage and current measurements would detect any conductor-to-conductor short between an energized conductor and either an active target or a grounded conductor. A conductor-to-conductor short to the active target would actuate the device (one of the motor contactors), while shorting to a grounded conductor or grounded raceway would result in a blown-fuse failure. Note that in the analysis of the SCDU experiment data, the only values of interest for determining circuit failure are the source voltage and current (e.g., V1 and A1 for each SCDU module) and the target voltage and current (e.g., V5 and A5 for each SCDU module). Therefore, circuit failure occurs when the voltage of the source conductors (i.e., V1, V2, V3) goes to zero or when the voltage of the active target conductors exceeds approximately 80 volts. Although current measurements can be used to support the identification of the onset of cable failure or used to confirm circuit failure, they are not typically used as a primary indicator of circuit failure.

The SCDU system was modified to allow for monitoring of more circuits during the full-scale horizontal flame spread experiments. Section 7 presents the details.

2.3.2 Insulation Resistance Measurement System

The IRMS was originally developed as a part of the NRC RES collaboration on the 2001 EPRI/NEI Fire Experiment Program (EPRI 2002). NUREG/CR-6776, “Cable Insulation Resistance Measurements Made During Cable Fire Tests,” issued June 2002, includes a detailed description of the IRMS (Wyan and Nowlen 2002). The system was also deployed during CAROLFIRE; NUREG/CR-6931, Volume 1, describes the design, operation, and data analysis associated with the IRMS (Nowlen and Wyant 2008a).

The IRMS uses 120 VAC (60 hertz) line power as the energizing source potential. The system works by energizing one conductor at a time while monitoring for a return signal on each of the other conductors present. Any current flow from the energized conductor is an indication of insulation breakdown, and the insulation resistance values between conductor pairs (conductor-to-conductor (i.e., c-c resistance)) and between conductors and ground (c-g resistance) can be calculated. To determine the loss of circuit functionality, the IRMS threshold value of 1,000 ohms was used. The IRMS was used in only 10 of the current experiments (see section 4 for experiment configurations).

2.4 Thermal Response

Cables not monitored for electrical response were monitored for thermal response using Type K, bare-bead, fiberglass-insulated TCs. Volume 2 of this RIL series presents the thermal response for the NIST experiments.

3. CABLE AND COATING PROPERTIES

This section describes the electrical cables and the coatings used in the functionality experiments.

3.1 Cable Descriptions

Previous cable fire experimental programs (Nowlen and Wyant 2008a) evaluated the response, at fire conditions, of various cable types and constructions commonly in use at NPPs. Those results indicate that thermoset (TS) and thermoplastic (TP) insulated cables behave differently. Additionally, various TS cable types behaved similarly, as did the various TP cable types. For the purposes of this study, the experiments focused on a limited number of cable varieties, as described in Table 3-1, with parameters identified in Table 3-2.

Two of the TP cables used in the NIST experimental series were not evaluated in previous experimental programs. They were acquired to represent the nonqualified class of cables that are most like the types of cables coated in NPPs. Cable 900 is a TP cable provided to the NIST experimental series by a utility. This cable type was sought to represent a cable variety that was produced before the application and use of flame propagation standards, such as the Institute of Electrical and Electronics Engineers (IEEE) Standard 1202, “Standard for Flame Testing of Cables for Use in Cable Tray in Industrial and Commercial Occupancies,” issued 1991 (IEEE 1991), or the flame spread portion of IEEE Standard 383, “Standard for Type Test of Class 1E Electric Cables, Field Splices, and Connections for Nuclear Power Generating Stations,” issued 1974 (IEEE 1974). This cable was manufactured in 1975 and stored in a warehouse until used in this program. Selection of such a cable was intended to verify that cable 900, a cable procured for the NIST experimental series (newly manufactured cable, circa 2015), performed on par with the vintage cable from a flame propagation standpoint. The results from Volume 2 of this RIL series demonstrate that the vintage cable 902 was easier to ignite and propagated flame more rapidly than the newly procured cable 900. These findings indicate that the use of cable 900 to represent preflame spread standard type cables is reasonable.

3.2 Cable Coating Descriptions

This experimental program used four different cable coatings. Three of these coatings were selected based on their availability, their use in existing NPPs, and their performance in past experiments (see Volume 1). It should be noted that some of the coating varieties used in current nuclear facilities contain asbestos. None of the coatings procured for these experiments contained asbestos. One additional cable coating material was procured to provide a comparison to a current generation of cable coating materials available on the market.

Each of the coatings required proper handling and storage. Once received, the 5-gallon containers were stored in a climate-controlled room in accordance with the manufacturer’s recommendations. Each coating had a shelf life of 12 to 18 months after opening, and all samples were prepared within, at most, 1 month of the containers being initially opened. The coatings were either painted, sprayed, or troweled onto the cables depending on the manufacturers’ guidance, thickness requirements, and workability of the coating. Sections 3.2.1 through 3.2.4 describe each material used for this study and the application technique used.

Table 3-1. Manufacturers' descriptions of the cables.[†]

Cable No.	Source[‡]	Manufacturer	Date	Cable Markings
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
807	CAROLFIRE #15	General Cable	2006	GENERAL CABLE® BICC® BRAND SUBSTATION CONTROL CABLE 7/C #12AWG 600V 30 MAY 2006
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
900	Purchased	Lake Cable	2015	#2582 FT. TPT127 LAKE CABLE 12AWG 7C PE/PVC2010 CONTROL CABLE 600V 75º C 2015 "ROHS 11" REACH MADE IN USA 280547
902	Utility Provided	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 or Sandia National Laboratories, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

‡ Note that the CAROLFIRE # refers to the number assigned to that cable during the CAROLFIRE program (Nowlen and Wyant 2008a) and (Nowlen and Wyant 2008b).

Table 3-2. Cable properties for cables used in functionality experiments.

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
802	XLPE	CSPE	TS	7	15.0	2.32	1.16	0.42	0.50	0.30	0.20	0.01
807	PE	PVC	TP	7	14.0	1.54	0.27	0.37	0.59	0.24	0.15	0.01
813	XLPE	CSPE	TS	12	12.7	1.46	1.18	0.25	0.37	0.33	0.29	0.01
900	PE	PVC	TP	7	15.9	1.85	1.07	0.38	0.55	0.27	0.10	0.08
902	PE	PVC	TP	3	10.0	1.32	1.09	0.13	0.42	0.36	0.10	0.12

3.2.1 Carboline Intumastic 285

Carboline Intumastic 285 is a registered product of the Carboline Company. The coating material is described as a water-based mastic that can be applied to impede fire propagation along the length of electrical cables. The wet film thickness is specified at 3.2 millimeters (mm) (1/8 inch (in.)), which will dry to approximately 1.6 mm (1/16 in.). Recommended cure time is 15 days. Once dried, the coating meets code and insurance requirements for both interior and exterior use.

Common application procedures for this product include palming, troweling, and spraying the material onto cables. Given the limited number of samples and the desire to achieve uniform coverage, it was decided that palming the material would provide the most consistent and even coverage. The material required considerable manipulation to achieve a uniform thickness consistent with the manufacturer's recommendations. Typically, the material was initially applied to the cables by the handful and then squeezed out along the length of the cable(s). If the material was spread too thin, it would separate from the cables and stick to the gloves used during application. The material was, in fact, somewhat difficult to apply as a thin and uniform final coating. In the case of the bundles, material gathered in the depressions between adjacent cables, and the material thickness in these areas was somewhat greater than the recommended wet thickness. For the bench-scale circuit integrity experiments, a modified application process was followed to achieve the desired thickness. In this case, the material was diluted per manufacturer's specifications.

When the product fully cured, it was gray, and evidence of cracking along the length of the cable was observed in many of the samples (see Figure 3-1). It is important to note that the cracks never appeared to extend to the depth of the cable jacketing material. In addition, fibers were observed extending out of the coating, as shown in Figure 3-1. The fibers were firmly embedded within the coating and varied in length, ranging from approximately 3.18 to 6.36 mm (1/8 to 1/4 in.).

Figure 3-1. Cracking (left) and fibers (right) in the Carboline Intumastic 285 coating along cables.

3.2.2 Flamemastic F-77

Flamemastic F-77 is a registered product of the Flamemaster Corporation. According to the manufacturer's literature, the coating material is a water-based TP resin, flame-retardant chemical, and inorganic, incombustible-fiber compound. It is further described as a non-intumescent, thixotropic compound with no asbestos. There are two available product variations: one is sprayable, and the other is mastic. The latter was used in this series. The wet-film thickness is specified at 3.2 mm (1/8 in.), which will dry to approximately 1.6 mm (1/16 in.). The recommended cure time is 2 days, but the product is dry to the touch after 4 hours.

Once the Flamemastic fully cured, it was off-white with a matte finish. Unlike the Carboline coating, the Flamemastic did not have small cracks after curing. Although the specifications identified the use of fire-retardant fibers in the compound, these fibers were not observed during the application process or after the product had dried. The coating was flexible and allowed cable bending; however, it would crack if bent excessively. When cracking occurred, it was circumferential at the point of bending and axial along the length of the cable. Care was taken not to bend the cables after application of the coating. Figure 3-2 displays a cable sample with cured Flamemastic coating. The peaks created during the application process were common and did not smooth out over the curing period. It was deemed that the peaks did not affect the quality of the experiment.

Figure 3-2. Fully cured Flamemastic F-77 on a cable sample.

3.2.3 Vimasco 3i

Vimasco 3i, also known as Cable Coating 3i, is a registered trademark product of the Vimasco Corporation. The manufacturer describes the material as a “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.” Vimasco further describes Cable Coating 3i 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” (Vimasco Corporation n.d.).

In terms of flammability, the manufacturer states that the product “passes [the] IEEE-383 flame propagation test” and “will not support combustion in wet or dry state.” The manufacturer also indicates an ASTM E84 “Standard Test Method for Surface Burning Characteristics of Building Material,” flame spread index of 15, and an ASTM E162, “Standard Test Method for Surface Flammability of Materials Using a Radiant Heat Energy Source,” flammability index of 16 (Vimasco Corporation n.d.). These ratings are relatively low (roughly equivalent to an epoxy resin or treated plywood). These values indicate that the material is combustible, will burn to a limited extent, and will produce some limited quantity of heat in the burning process.

As with the other two products, a wet-film thickness of 3.2 mm (1/8 in.) is recommended and will dry to approximately 1.6 mm (1/16 in.). The material begins intumescent expansion at 177°C (350°F) and will expand “600% to 700% after 10-minute exposure to 870°C (1600°F)” (Vimasco Corporation n.d.). Expansion by 600 percent would imply an expanded thickness of 9.5 mm (3/8 in.). Recommended cure time is 2 days, but the product is dry to the touch after 2 hours.

Spraying and brushing are the most common application methods for this coating; however, material thinning is not recommended since it will change the physical properties and would adversely impact performance under thermal exposure conditions. Based on facility constraints and the limited number of samples being prepared, spraying the coating material was not attempted. As with the Flamemastic F-77, attempts to brush the coating onto cables proved unsuccessful because uniform coverage was difficult to achieve. As with the other materials, it was decided that palming would be the most effective method to achieve even coverage and ensure appropriate adhesion to the cables. As delivered, the Vimasco product was the thinnest of the three products and had the consistency of very thick latex paint. During the curing period, when cables were suspended from a drying rack, the product continued to thin as if it were still flowing. As a result, a thin secondary coat was applied to some samples to ensure an even coating and complete coverage. This is an acceptable practice according to the manufacturer’s instructions.

Peaks in the coating were created during application and were generally smoothed during the curing period. When the Vimasco product fully cured on the samples, the coating was very smooth, bright white, and with a glossy finish. Once dried, this coating material was very flexible. Figure 3-3 shows a photo of a cable coated with the Vimasco product.

Figure 3-3. Fully cured Vimasco 3i on a cable sample.

3.2.4 FS15

FS15 is a water-based ablative coating made by Fire Security Systems. Its primary mode of protection is ablation as opposed to thermal insulation. The ablation process involves chemical and physical changes to the material, including evaporation, chemical cracking, and melting. The product can be used in both interior (indoor) or external (outdoor) applications. The manufacturer recommends application by brush, roller, or airless sprayer to a wet thickness of 1.4 mm (1/18 in.); the dry film thickness is 1 mm (1/25 in.). The material can be thinned to a maximum of 3 percent potable water by weight. The material is dry to the touch in 6 hours and fully cured in 14 days at

20°C (68°F) and 65 percent relative humidity. An unopened container of FS15 has a shelf life of 24 months from the date of manufacture. Figure 3-4 shows a photo of a cable coated with the FS15 product.

Figure 3-4. Fully cured FS15 on a sample of cables.

4. RADIANT ENERGY EXPERIMENTS

4.1 Experimental Description

The equipment and physical configurations used for the radiant energy experiments are essentially identical to those for the small-scale experiments performed at SNL to evaluate circuit functionality (Nowlen and Wyant 2008a) (Nowlen and Brown 2011) (Nowlen, Brown and Oliver, et al. 2012). This experimental series was conducted at SNL before the additional work performed at NIST. As these programs were performed by different laboratories, the thermal response from the radiant energy experiments performed at SNL will be documented in this Volume 3 RIL report. A general description of the radiant energy facility and protocol is presented below.

4.1.1 General Description of Penlight

Penlight is a radiant heating apparatus, shown in Figure 4-1, which uses computer-controlled, water-cooled quartz lamps to heat a thin, intermediate Inconel steel shroud. The shroud is painted flat black and acts as a grey-body radiant heating source, re-radiating heat to a sample (cables for these experiments) located within the shroud. The computer-controlled TCs mounted on the inner surface of the shroud were used to monitor the exposure temperature. Penlight creates a radiant heating environment analogous to that seen by an object enveloped in a fire-induced, hot-gas layer or in a fire plume outside the flame zone. Table 4-1 shows the relationship between shroud temperature and shroud heat flux, assuming a constant emissivity of 0.815.

Figure 4-1. Penlight apparatus.

All experiments in this series were conducted on a 30-centimeter (cm) (12 in.) wide ladderback style cable tray suspended through the center of the Penlight shroud. The cable trays and other physical experiment conditions are effectively identical to those used in previous experiments (Nowlen and Wyant 2008a) (Nowlen and Brown 2011) (Nowlen, Brown and Oliver, et al. 2012).

Table 4-1. Relationship between the Penlight shroud temperature and radiant heat flux based on measured emissivity of 0.815.

Temperature (°C)	Heat Flux (kW/m^2)	Temperature (°C)	Heat Flux (kW/m^2)
200	2.32	375	8.16
225	2.85	400	9.49
250	3.46	425	10.98
275	4.17	450	12.64
300	4.99	475	14.48
325	5.92	500	16.51
350	6.97	525	18.75

4.1.2 Penlight Heating Profiles

The experimental exposure profile is defined by the Penlight shroud time-temperature history and was varied in this experimental series. In most of the early experiments (R1–R24, including repeats R1a, R19a and R20a, and R32), Penlight was initially set to a moderate temperature point, given the cable type. For the TP cable samples, the initial temperature was set to 200°C (392°F), while for the TS cable samples, the initial temperature was set to 300°C (572°F). These temperatures are well below the anticipated cable failure thresholds. For the balance of the experiment, the Penlight setpoint was increased by 25°C (77°F) every 5 minutes until either failure or ignition was observed. The cable ignition time varied from experiment to experiment. Once ignition occurred, the power to the Penlight lamps was cut, and a cooldown period began. Figure 4-2 illustrates the step-wise increase profiles. For experiments using these profiles, time = 0 is defined as that time when the first step increase from ambient to either 200°C or 300°C (392°F or 572°F) is input into the Penlight controller. Penlight typically reached the new setpoint within 1 minute.

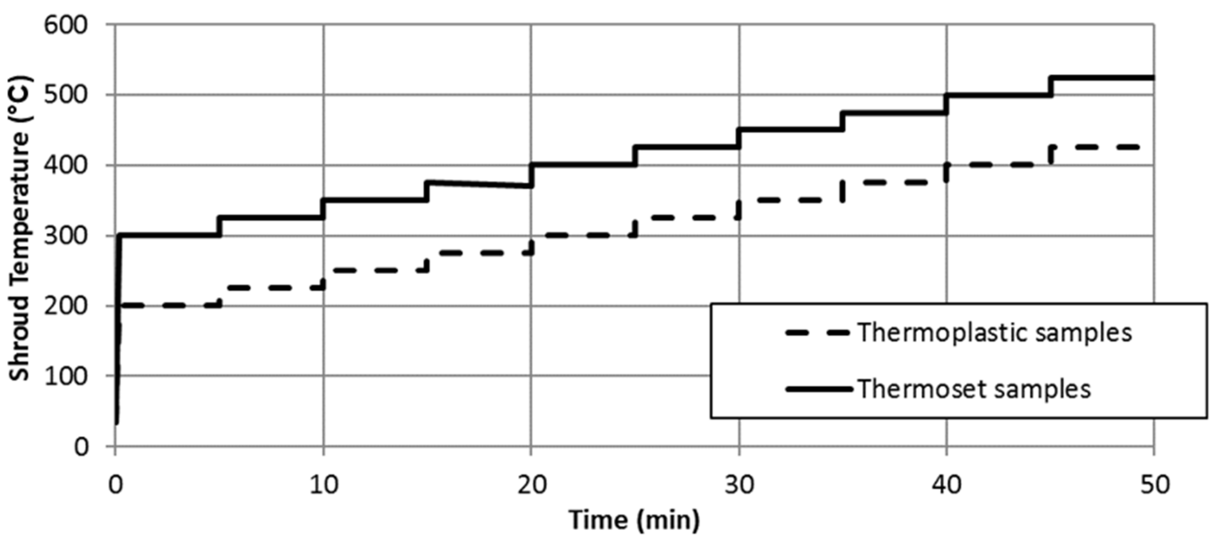

Figure 4-2. Heating profiles using step-wise increases of 25°C (77°F).

The second exposure profile was used in experiments R25–R31, all of which involved single lengths of the TS cable. For these experiments, Penlight was raised to a setpoint temperature and held constant for the duration of the experiment. The setpoint temperatures ranged from 300°C (572°F), which is well below the anticipated damage threshold for the TS cables, to 450°C (842°F), which typically results in rapid ignition of an uncoated cable. Experiments R29, R30, and R31 were intentionally ended before ignition so that the condition of the coatings after heating could be observed.

The final exposure profile was used for all 10-cable bundle experiments (experiments R33–R46). The step-wise profile shown in Figure 4-2 was designed to nominally represent a transient fire development profile; however, the step-wise temperature increases complicated the analysis. For the larger 10-cable bundle experiments, a ramp-and-hold profile was used instead of the step-wise increases. To establish a common starting point, Penlight was initially raised to 35°C (95°F) and held there for 10 minutes. The primary exposure profile then began with a ramp from 35°C (95°F) to 450°C (842°F) at a rate of 45°C (113°F) per minute. Note that 450°C (842°F) is well above the damage threshold for the TS cables. The temperature was then held constant at 450°C (842°F) until failures were observed on two of the three SCDU modules, typically S1 and S2. In all cases, this was after the time of ignition. Figure 4-3 illustrates this heating profile. The intent of the ramp-and-hold profile was not to explicitly represent any particular fire profile, but to generically represent typical fire behavior. Also note that for these experiments, time = 0 is defined as the time when the primary ramp (i.e., from 35°C to 450°C (95°F to 842°F) was initiated. All of the data plots for this experimental set use this same time convention.

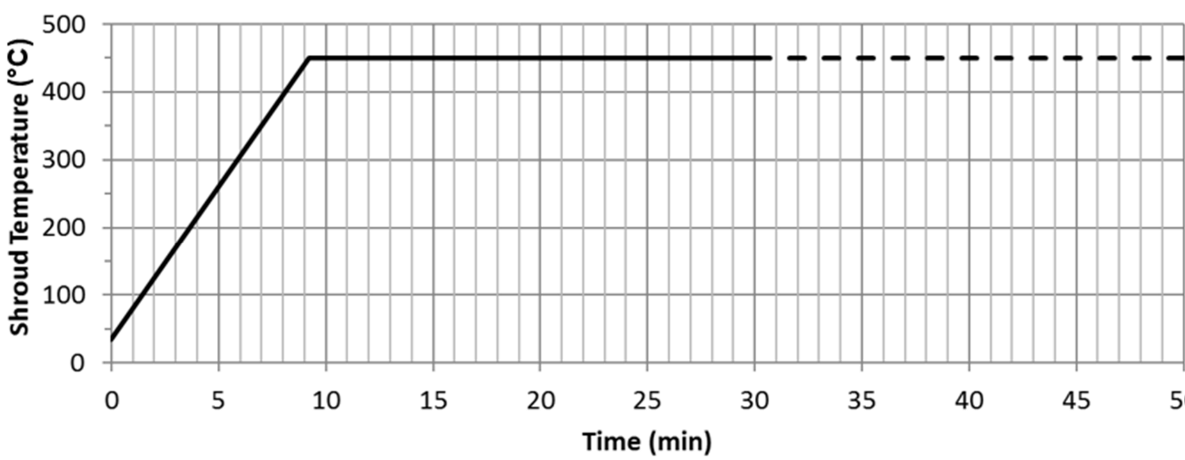

Figure 4-3. Shroud temperature profile used in the final experiments involving the 10-cable bundles.

4.1.3 Experiment Matrix

Table 4-2 and Table 4-3 show the experimental matrices. Table 4-2 defines experiments involving single lengths of cable and seven-cable bundles. These experiments are characterized by the following parameters. An "X" in each column indicates the active choice for each experimental variable:

- Cable type. Either TP-insulated (cable 807) or TS-insulated (cable 802); section 3.1 describes these cables.

- Single cable or bundle. Specifies whether the samples were single lengths of cable or a seven-cable bundle. Note that in some of the single-length experiments, more than one length of cable was present (e.g., both temperature response and an electrical response cable). For these experiments, the cables are coated individually and maintain spatial separation in the tray. The typical practice is to place two cables in symmetric locations on either side of the tray centerline.

- Coating. Indicating an uncoated sample or coating with one of the three products: Vimasco 3i, Flamemastic F-77, or Carboline Intumastic 285.

- Cable electrical performance system. Specifies either IRMS or SCDU for those cases in which an electrical performance monitoring cable was present.

- Starting exposure temperature. Defines the initial setpoint temperature of Penlight. See section 4.1.2 for a description of the step-wise increase profiles. The initial setpoint is either 200°C or 300°C (392°F or 572°F) for the TP and TS samples, respectively.

- Final exposure temperature. Defines the final setpoint temperature of Penlight. For the step-wise increase cases, this differs from the initial temperature. For the single-step increase cases, the initial and final temperatures are the same. The final temperature is also driven by experiment duration. A longer duration experiment ends at a higher temperature, and duration is dependent on time to ignition.

Note that the last three experiments shown in Table 4-2 (R1a, R19a, and R20a) represent experiments that were repeated for various reasons. Experiment R1 was the only experiment in which the Penlight shroud was initially set to 300°C (572°F) and increased by 10°C (50°F) every 5 minutes. Experiment R1a was performed using the modified step-wise profile, using 25°C (77°F) jumps every 5 minutes. Experiments R19a and R20a are repeats of experiments R19 and R20, respectively. Experiment R19 was repeated because a subjacket TC was found to be between the tray rung and the cable, which could affect the data. Experiment R20 was repeated because two TCs were installed in the subjacket, but the subcoat TCs had been omitted.

Table 4-2. Experiment matrix for the single- and seven-cable bundle radiant experiments.

Experiment #	Cable type		Single cable or bundle		Coating				Cable diagnostic system			Starting Exposure Temperature (°C)	Final Exposure Temperature (°C)
	Thermoset	Thermoplastic	Single	Seven-Cable Bundle	No coat	Vimasco	Flamemastic	Carboline	TC	IRMS	SCDU		
R1[1]	X		X		X				X			300	470
R2	X			X	X				X		X	300	450
R3		X	X		X				X			200	525
R4		X		X	X				X		X	200	450
R5	X		X			X			X			300	475
R6	X			X		X			X		X	300	475
R7		X	X			X			X			200	425
R8		X		X		X			X		X	200	450
R9	X		X				X		X			300	500
R10	X			X			X		X		X	300	475
R11		X	X				X		X			200	450
R12		X		X			X		X		X	200	425
R13	X		X					X	X			300	475
R14	X			X				X	X		X	300	500
R15		X	X					X	X			200	450
R16		X		X				X	X		X	200	500
R17	X		X		X				X	X		300	475
R18		X	X		X				X	X		200	425
R19[1]	X		X			X			X	X		300	475
R20[1]		X	X			X			X	X		200	400
R21	X		X				X		X	X		300	475
R22		X	X				X		X	X		200	375
R23	X		X					X	X	X		300	475
R24		X	X					X	X	X		200	450
R25	X		X		X				X		X	450	450
R26	X		X			X			X		X	450	450
R27	X		X				X		X		X	450	450
R28	X		X					X	X		X	450	450
R29	X		X			X	X	X	X			300	300
R30	X		X			X	X	X	X			350	350
R31	X		X			X	X	X	X			400	400
R32[2]	X		X			X	X	X	X			300	525
R1a[1]	X		X		X				X			300	475
R19a[1]	X		X			X			X	X		300	475
R20a[1]		X	X			X			X	X		200	425

1. Experiments R1, R19, and R20 were repeated as experiments R1a, R19a, and R20a, respectively.
2. Experiment 32 was run with the ends of the Penlight shroud open to allow videotaping. All other experiments were run with the ends covered. The open ends change the exposure environment, so this experiment should not be compared to similar experiments run in the closed-end configuration.

Table 4-3 provides the matrix for the final radiant energy experiment set, all involving the 10-cable bundles. The matrix here is much simpler because all experiments in this set used the same cables (i.e., TS type); the same general experiment configuration (the 10-cable bundle); the same SCDU setup; and the same heating profile (section 4.1.2 describes the ramp and hold profile). Hence, this matrix simply distinguishes the experiment article identifiers and the coating. Note that there is one experiment (R37) identified as "uncoated—wire bound," which differs from the others. The purpose of experiment R37 was to evaluate the effect of cable securing methods on the functionality of the circuits. Regarding the last point, the seven-cable bundles had been secured using nylon cable ties placed near each end of the bundle and just outside the exposure zone. These cable ties remained intact through the experiments, but that arrangement left the cable bundle unbound over the roughly 0.9-meter (m) (3-foot) exposure length. During the experiments, separation of the cable bundle had a significant impact on the thermal response. For the 10-cable bundles, additional nylon cable ties were used to secure the cable bundle at roughly 46 cm (18 in.) intervals. The cables were secured in a way similar to that used in the small bundle experiments, with ties just outside the exposure zone; two additional ties were placed along the length of each bundle within the exposure zone. The intent was to focus the results on the coatings and less on the bundle separation behavior. All bundles used the same type of cable tie; the two extra ties were installed between the rungs of the cable tray, about 23 cm (9 in.) outboard from the exposure centerline. Additionally, the coatings were applied over the cable ties (i.e., the ties were installed before the bundles were coated and left in place).

This approach delayed separation of the cable bundle to some extent. However, in all experiments, the nylon cable ties melted before cable ignition or electrical failure times, leading to the separation of the cable bundles during the experiment. Late in the experimental series, the final uncoated bundle was constructed to explore the extent to which melting of the cable ties impacted the behavior of the uncoated bundles. This final experiment article is referred to as the "uncoated—wire bound" configuration. The only difference between this experiment article and the other uncoated bundles is that the two extra nylon cable ties were replaced with steel baling wire, which would not melt. The use of baling wire to secure a cable bundle is not a typical industry practice; this exercise was meant only to explore the effects of the cable ties melting and the interval duration of event times (ignition and failure). Even for this bundle, the cables separated to some degree, but far less than in other experiments.

Table 4-3. Matrix of 10-cable bundle experiments.

Experiment #	Coating Configuration	Notes:
R33	Uncoated #1	TC failure observed
R34	Uncoated #2	TC failures observed
R35	Uncoated #3	SCDU cycling strategy
R36	Uncoated #4	SCDU cycling strategy
R37	Uncoated—wire bound	Used baling wire for cable ties
R38	Vimasco #1	TC failures observed
R39	Vimasco #2	SCDU cycling strategy
R40	Vimasco #3	SCDU cycling strategy
R41	Flamemastic #1	SCDU cycling strategy
R42	Flamemastic #2	SCDU cycling strategy
R43	Flamemastic #3	SCDU cycling strategy
R44	Carboline #1	SCDU cycling strategy
R45	Carboline #2	SCDU cycling strategy

R46	Carboline #3	SCDU cycling strategy

4.2 Experiment Sample Configuration and Coating Application

The first experiment set involved single lengths of cable, each instrumented with four Type K, 32 mm (1.26 in.) bare-bead, fiberglass-insulated TCs. Each cable sample was approximately 1.5 m (5 ft) long with two TCs located at midlength (center) and two located 23 cm (9 in.) off center. For these early experiments, TCs were also placed on the outer surface of the cable jacket material, opposite each subjacket TC, before application of the cable coating. Figure 4-4 shows a sketch of a typical thermal response cable as used in the single- and small-bundle experiments. The brown outer color represents the coating material, and the red dots represent TC positions. Figure 4-5 shows the location of the TCs along the length of the coated sample. Note that the TC spacing allowed both the center and outboard TCs to be centered between the rungs of the cable tray.

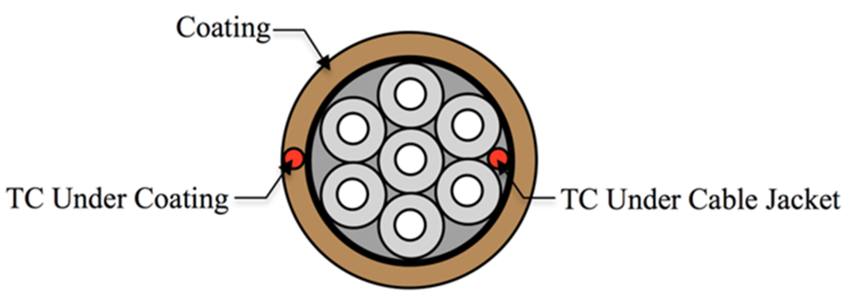

Figure 4-4. Cross-sectional view of a 7/C cable with TC locations.

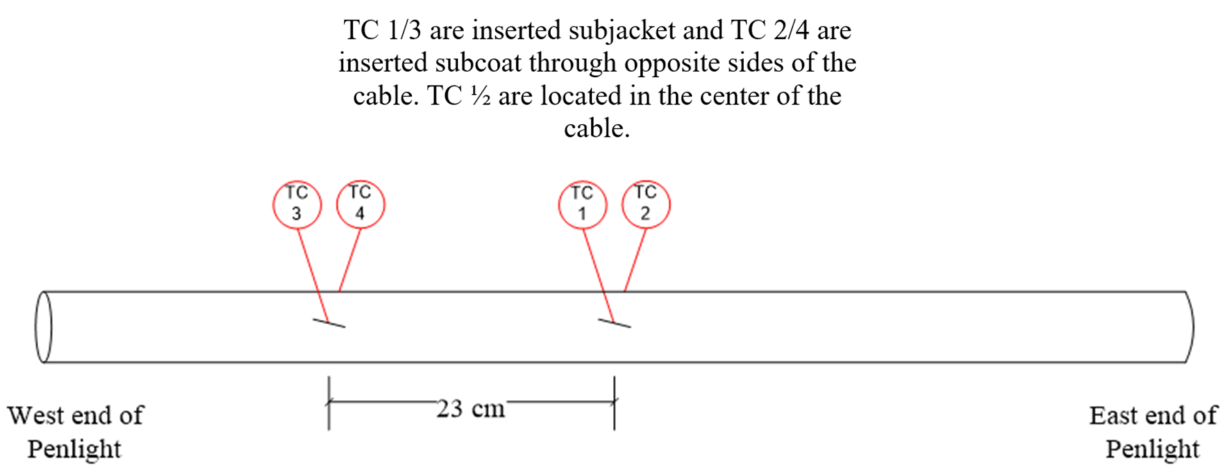

Figure 4-5. Longitudinal view of electrical cable instrumented with TCs.

The TCs placed below the outer cable jacket were installed using a technique in which a small slit was cut in the jacket allowing insertion of the TC bead. This same process was used during the NIST experiments. The bead itself was typically inserted a distance of approximately 5 to 7.5 cm (2 to 3 in.) along the length of the cable, placing it well away from the cut in the outer jacket (placement distance varied depending on the cable type). The slit was then closed and secured with a single wrap of fiberglass electrical tape and the final position of the TC bead marked for reference on the outer jacket (i.e., using a felt-tip marker or a dot of water-based marker).

After being instrumented, the cables were suspended vertically using an A-frame drying rack as shown in Figure 4-6. The heads (or connector end) of the TCs were covered with plastic bags to prevent inadvertent contact with the coating material. The TC lead wires were secured to the cables with fiberglass tape and coated along with the cables.

Given the limited number of samples and the desire to achieve uniform coverage, it was decided that palming the material would provide the most consistent and even coverage for the cable configurations. Troweling was also attempted but did not yield the uniform results achieved with the palming technique.

For the second set of experiments, two individual lengths of cable were used simultaneously; one TS cable was instrumented for thermal response, and one TS cable was instrumented for electrical performance. In these experiments, the two cables were placed in symmetric positions on either side of the cable tray centerline. Figure 4-7 illustrates this dual-cable setup, including the separation distance of 10 cm (4 in.) and the orientation of the TC. Cables connected to the electrical performance monitoring systems were not instrumented with TCs because the installation of a TC on or within a cable could impact the electrical failure behavior.

Figure 4-6. Cable coating drying frame.

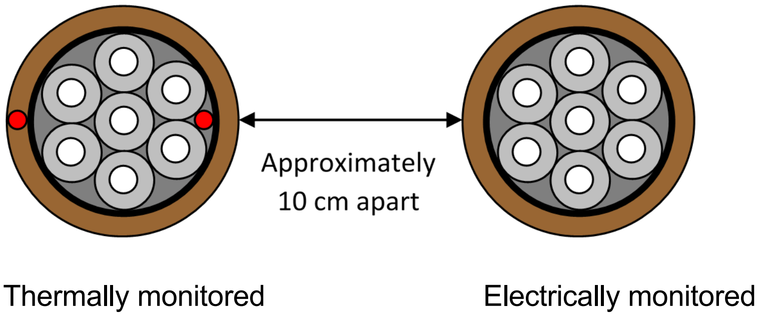

Figure 4-7. Example TC arrangement for temperature monitoring (left) of 7/C cable located near the electrically monitored (right) cable in tray.

The last two experiment sets used 7-cable and 10-cable bundles. The cables were coated in a horizontal configuration within the tray. In this configuration, the material achieved adequate coverage with a single coating, although some sagging to the underside of the bundle was noted after curing overnight. Hence, the underside of the cables likely had a greater coating thickness than the upper side, and the underside may have thus exceeded the nominal desired thickness. This is consistent with field applications. No attempts were made to remove excess material from such locations, but the coverage on the top and sides of the bundles was verified, and the samples were inspected for potential openings or gaps in the coating. One effect noted was excessive coverage in the areas adjacent to the rungs of the cable tray where the cable bundles rested. In these locations, extra material was brushed on to ensure full coverage and no gaps. These locations were not considered critical to the experiment samples because the locations were away from the tray central point where the most severe exposure occurs. During experiments, it was noted that some of this excess material would soften and drip from the trays before ignition

The seven-cable bundle consisted of similar cables, with one cable in the center of the bundle surrounded by the other six. Cables were bound together at the bundle ends (outside the exposure area) using nylon cable ties. Some cables in the bundle were instrumented with TCs, as described previously, while others were monitored for electrical performance. The thermal response cables were paired with a symmetrically located electrical response cable, such that correlations could be made between electrical failure and thermal exposure, as shown in Figure 4-8. Cables E1, E2, and E3 are the electrical performance cables that are mirrored by thermal response cables A, B, and D, respectively. The central cable (cable C) was also monitored for thermal response. As noted above, the bundles were coated in a cable tray, and Figure 4-9 shows some of the seven-cable bundles curing within their respective trays.

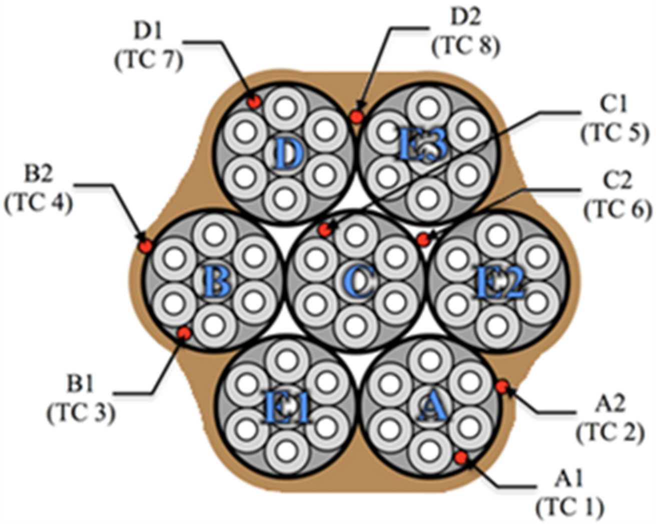

Figure 4-8. Arrangement of thermal response and electrical performance cables in the seven-cable bundle.

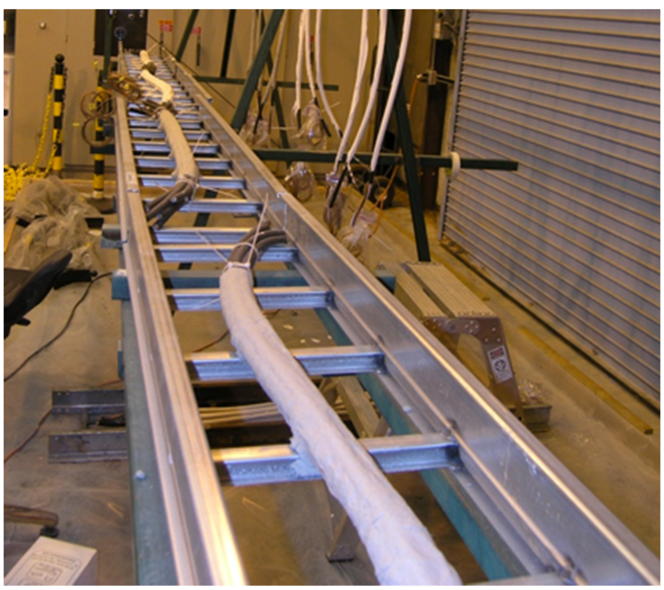

Figure 4-9. The curing of bundled and single lengths of cables.

The last experimental set involved the 10-cable bundles. These bundles were similar in configuration to the small bundles, but three additional thermal response cables were added. Figure 4-10 shows the physical arrangement. The thermal response cables were identified as cables A–G, and the three electrical performance cables were identified as S1, S2, and S3. The instrumentation, construction, and coating application techniques were similar to those used for the seven-cable bundles. However, the 10-cable bundles were unique in three ways. First, the arrangement of cables was slightly different with the three electrical cables located along one side of the bundle. Second, the thermal response cables had only a single, centrally located TC installed below the cable jacket and oriented towards the outside of the bundle (no TCs were installed on the cable jacket). Third, two additional cable ties were located approximately 30.5 cm (12 in.) outboard to each side of the central location (between tray rungs); these ties remained in place for the duration of the experiment. As noted above, the seven-cable bundles used cable ties only at the remote ends of the bundles, and separation of the cable bundles was seen to affect the thermal response.

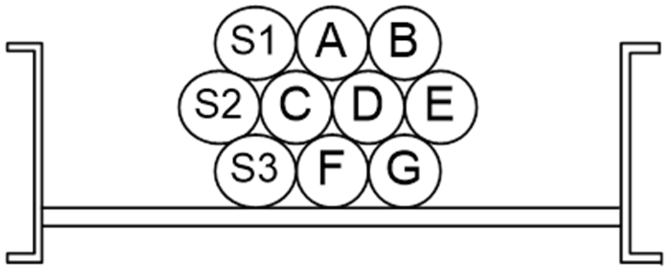

Figure 4-10. Illustration of 10-cable bundle (coating not shown; not to scale).

All 10-cable bundles were constructed using the TS cable only. No experiments were performed using the TP cables in this configuration. The thermal-response results, up to the failure temperature, for the TS cables should extrapolate well to a similar bundle of TP cables. This is because TS cables do not experience significant degradation at temperatures below 300°C (572°F), which is generally above the failure threshold of TP cables. Further, the TP cables tend to show little degradation until their insulation and jacket materials actually melt, which corresponds with the point of electrical failure. The two cables are also similar in mass and physical size. Hence, the pre-degradation thermal responses to the same exposure environment would be very similar through the point of TP cable failure. Eliminating the TP cables from this experiment configuration allowed more repetition of the TS bundle configurations (i.e., three or more repeats for each configuration). While this was a reasonable assumption, the results indicated that the expansion of the TS cables impacted the cable coating surface continuity. During experiments, as the coated cable assembly was heated and expanded, cracks in the coating developed. In several instances, these cracks were sufficient to cause the coating material to fall away from the assembly in large pieces. When these breaches occurred, the cables were better exposed to the thermal exposure, resulting in better heat transfer to the cable. This phenomenon was less apparent in the experiments involving TP cables.

4.3 Experimental Results

Table 4-4 presents the results of the radiant energy experiments for the single cable and seven-cable bundle experiments. Table 4-5 shows the results for the 10-cable bundle experiments.

Table 4-4. Single and seven-cable bundle experiment results.

Cable Type	Cable ID	Exp #s	Coating Material	Coating Thickness (inches)	Cable Config.	Temperature Setpoints (°C)		Electrical Failure	Comments
						Initial	Final	Time (min.)	
Thermoplastic	807	R18	None	0.00	Single	200	425	32.08	IRMS
		R20a	Vimasco	0.09	Single	200	425	27.37	IRMS, Penlight shut off after cable elec. damage.
		R22	Flamemastic	0.06	Single	200	375	31.58	IRMS
		R24	Carboline	0.15	Single	200	450	31.32	IRMS
		R4	No Coat	0.00	7-Bundle	200	450	32.02	
		R8	Vimasco	0.15	7-Bundle	200	450	39.33	
		R12	Flamemastic	0.32	7-Bundle	200	425	42.65	
		R16	Carboline	0.44	7-Bundle	200	500	50.00	
Thermoset	802	R17	No Coat	0.00	Single	300	475	38.00	IRMS
		R19a	Vimasco	0.13	Single	300	475	39.15	IRMS
		R21	Flamemastic	0.10	Single	300	475	39.78	IRMS
		R23	Carboline	0.12	Single	300	475	36.28	IRMS
		R25	No Coat	0.00	Single	450		11.63	
		R26	Vimasco	0.08	Single	450		14.27	
		R27	Flamemastic	0.11	Single	450		15.12	
		R28	Carboline	0.17	Single	450		18.97	
		R2	No Coat	0.00	7-Bundle	300	450	34.72	
		R6	Vimasco	0.27	7-Bundle	300	475	40.38	
		R10	Flamemastic	0.32	7-Bundle	300	475	42.08	
		R14	Carboline	0.19	7-Bundle	300	500	46.22	

Note: Ignition temperature for bundled experiments is the average of subjacket temperatures of peripheral cables.

Table 4-5. Results for 10-cable bundle experiments.

Cable Type	Cable ID	Experiment #	Coating Material	Failure Time (minutes)				Δt ‡ (minutes)	Comments
				SCDU 1	SCDU 2	SCDU3	Average		
Thermoset	802	33	None	29.9	29.2	DNF	**31.4**	- - -	
		34	None	29.3	29.8	34.2			
		35	None	30.3	29.7	33.8			
		36	None	32.9	30.2	36.4			
		37	None	35.2	36.6	38.3	**36.7**	5.3	Wire bound
		39	Vimasco	47.8	47.1	50.3	**46.6**	15.2	
		40	Vimasco	43.5	44.3	DNF			
		41	Flamemastic	42.5	41.9	DNF	**43.2**	11.8	
		42	Flamemastic	41.5	42.9	47.1			
		43	Flamemastic	39.7	41.7	48.7			
		44	Carboline	69.5	70.5	DNF	**66.2**	34.8	
		45	Carboline	59.0	62.0	76.2			
		46	Carboline	60.1	66.0	DNF			

5. BENCH-SCALE CIRCUIT INTEGRITY EXPERIMENTS

This section includes the results of a modified version of International Electrotechnical Commission (IEC) 60331, "Experiments for electric cables under fire conditions—circuit integrity," issued 2009 (IEC 2009) (IEC 2009).

5.1 Experimental Description

Volume 2 presents a complete description of the experiments. The bench-scale circuit integrity experiments followed the general protocol specified in IEC 60331, Parts 11 and 21 (IEC 2009) (IEC 2009). The protocol calls for a single cable in a horizontal orientation subjected to a premixed flame with temperatures of at least 750°C (1,382°F). Instead of using the continuity circuit presented in the protocol, the experiments performed here differ, with the SCDU system being used to monitor circuit functionality. Section 2.3 describes the SCDU.

Cable temperature-response measurements were performed in separate, but identical, experiments to ensure that the functional integrity of the cable was maintained. Each configuration was used in replicates of three. Thus, a single experiment configuration consisted of three circuit integrity experiments and three thermal response experiments, for a total of six experiments per configuration. An exception to the number of replicates was the baseline experiments; they were performed with uncoated cables. For the baseline experiments, six replicates were performed for each cable type. Cable coating thickness was a variable that was evaluated in these experiment series. The manufacturers' specified minimum thickness was typically 0.16 cm (1/16 in.) dry; twice the recommended coating thickness was used. Varying the thickness under these controlled conditions allows for a direct evaluation of the effect of coating thickness on the time to circuit failure. Table 5-1 presents the experiment matrix for the bench-scale circuit integrity experiments.

Table 5-1. Bench-scale circuit integrity experiment matrix.

Experiment Configuration	Cable Number	Coating	Coating Thickness (inches)	Replicates
BSCI-1	900	None	N/A	6
BSCI-2	900	Carboline	1/16	3
BSCI-3	900	Carboline	1/8	3
BSCI-4	900	Flamemastic	1/16	3
BSCI-5	900	Flamemastic	1/8	3
BSCI-6	900	FS15	1/16	3
BSCI-7	900	FS15	1/8	3
BSCI-8	900	Vimasco	1/16	3
BSCI-9	900	Vimasco	1/8	3
BSCI-10	813	None	N/A	6
BSCI-11	813	Carboline	1/16	3
BSCI-12	813	Carboline	1/8	3
BSCI-13	813	Flamemastic	1/16	3
BSCI-14	813	Flamemastic	1/8	3
BSCI-15	813	FS15	1/16	3
BSCI-16	813	FS15	1/8	3
BSCI-17	813	Vimasco	1/16	3
BSCI-18	813	Vimasco	1/8	3

For the bench-scale circuit integrity experiments, only one SCDU circuit was required to evaluate one cable per experiment. The multiconductor cable was connected to the SCDU, such that adjacent conductors alternated between either a source conductor and grounded (or target conductor), and such that the maximum voltage potential between adjacent conductors was present. Figure 2-2 presents this configuration.

The experiments were run until the circuit protective device (fuse) cleared or the 90-minute experiment duration elapsed, whichever occurred first. Appendix B presents the voltage and current profiles from these experiments. Section 5.2 summarizes the results.

5.2 Experimental Results

Following the IEC 60331 protocol, 60 bench-scale circuit integrity experiments were performed with an additional 60 experiments monitoring cable thermal response. Table 5-2 presents the results.

Figure 5-1 and Figure 5-2 graphically present the time-to-failure results from the bench-scale circuit integrity experiments. As expected, the added thickness above the vendor's recommended minimum resulted in an additional delay in time to failure. It is also important to note that a direct comparison between the TP and TS data is not warranted as cable designs differed and influenced the heat transfer.

An interesting observation from these experiments is that one of these coatings is identified in the manufacturer's literature to have provided 90 minutes of circuit integrity. However, in the experiments discussed here, the longest duration was less than 34 minutes, with an arithmetic mean of all experiments with this coating of approximately 16 minutes. Upon further review of the standard, the lack of specificity regarding the cable design may be attributed to these differences between reported and observed performance. For example, a cable that performs well without a coating may have been used. Thus, the addition of the coating, while increasing the delay, may not have added substantial benefit. As such, users are cautioned against using circuit integrity ratings derived from cable types that differ from those planned for use in a regulatory context. It is important to note that the standards body does not provide guidance on the cable design and coating application specifics, therefore caution should be taken to ensure that ratings meet the end user's needs.

Table 5-2. Bench-scale circuit integrity experiment results.

Cable Type	Cable ID	Coating Material	Coating Thickness (mm)	Coating Thickness (mil)	Failure Time (minutes) Rep 1	Rep 2	Rep 3
Thermoplastic	900	None	0.0	0	4.57	6.70	5.03
					4.63	8.49	8.57
		Carboline Intumastic 285	1.2	49	11.59	6.4	9.12
		FS15	1.4	55	13.00	10.16	10.57
		Flamemastic 77	1.4	54	9.89	13.56	10.77
		Vimasco 3i	1.3	52	36.00	28.20	37.20
		Carboline Intumastic 285	2.9	113	5.47	16.49	13.28
		FS15	3.3	129	22.25	17.4	15.5
		Flamemastic 77	3.1	124	8.21	22.7	6.8
		Vimasco 3i	3.1	124	DNF	DNF	47.42
Thermoset	813	None	0.0	0	3.65	4.24	4.09
					4.06	4.72	3.79
		Carboline Intumastic 285	1.0	39	5.84	6.76	7.00
		FS15	1.4	56	10.34	6.04	5.82
		Flamemastic 77	1.6	63	7.93	8.86	9.70
		Vimasco 3i	0.9	37	6.40	7.02	8.37
		Carboline Intumastic 285	3.3	130	8.02	7.65	8.30
		FS15	3.8	151	18.14	30.4	33.9
		Flamemastic 77	3.7	146	11.15	8.69	11.54
		Vimasco 3i	3.7	147	24.86	20.14	19.59

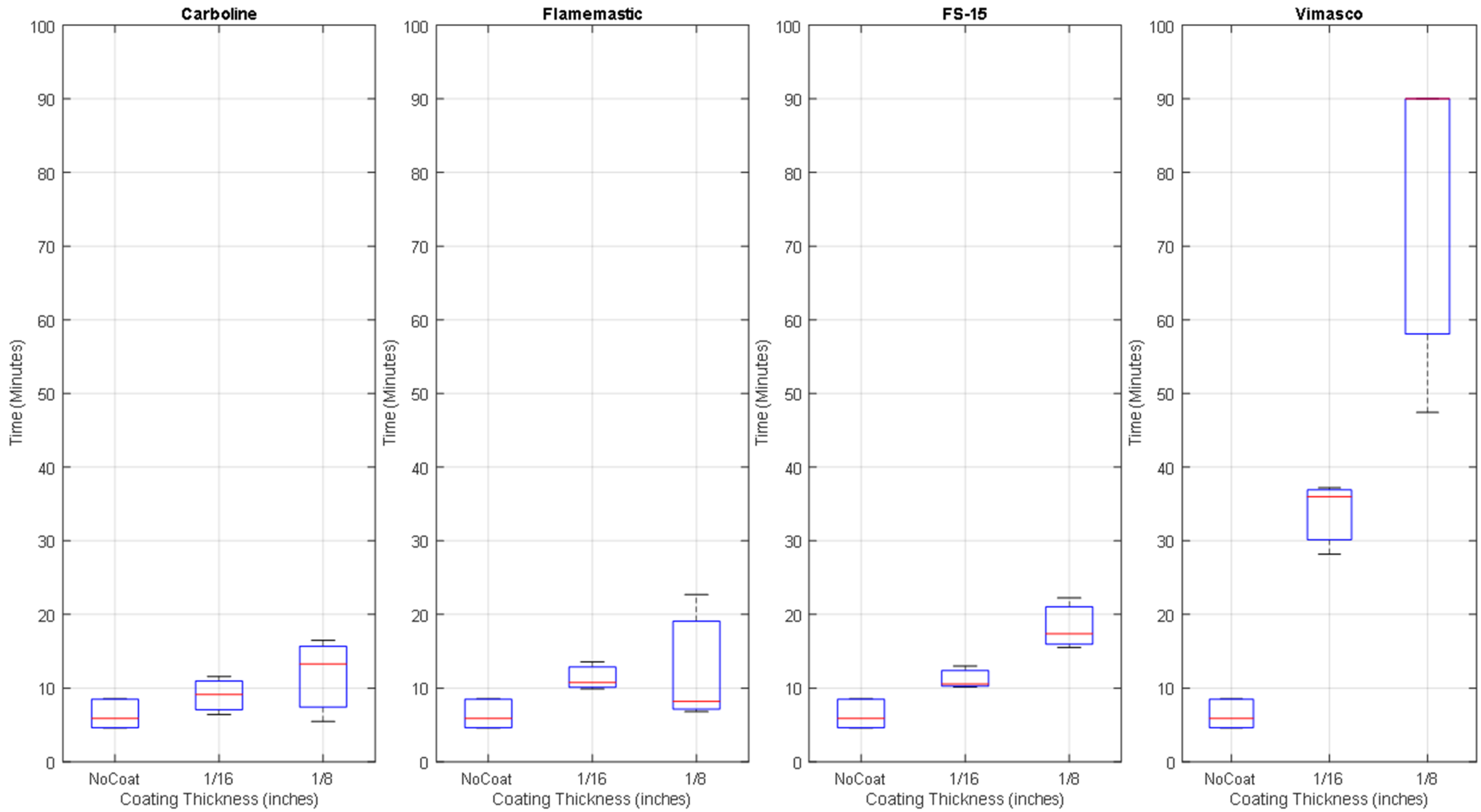

Figure 5-1. Time-to-failure box plots of IEC 60331 for TP-insulated cable 900 coating material and coating thickness.

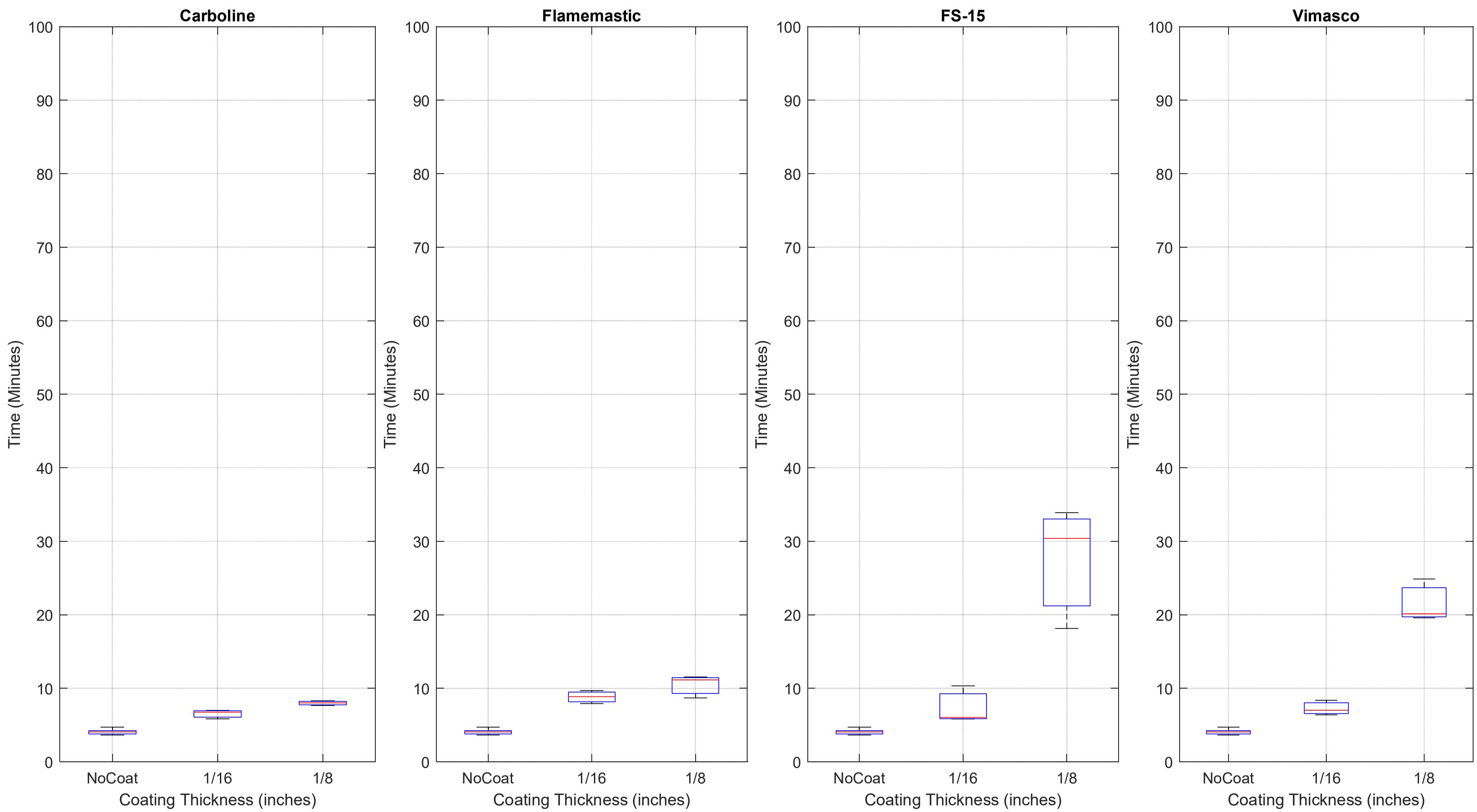

Figure 5-2. Time-to-failure box plots of IEC 60331 for TS-insulated cable 813 coating material and coating thickness.

6. FULL-SCALE CIRCUIT INTEGRITY EXPERIMENTS

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

6.1 Experiment Description

Volume 2 presents a complete description of the experiments. The experimental setup consisted of a vertically oriented cable tray, loaded with cables (bare or coated) and exposed to a specified thermal insult until circuit failure. Exposure lasted until circuit failure was observed or until the experiment duration of 60 or 90 minutes was reached. The vertical flame spread experiments were divided into experiment Series I and II. Cable functionality was evaluated only during Series II. Table 6-1 shows the experiment matrix for Series II. Figure 6-1 shows the vertical flame spread apparatus. The thermal performance results are presented in Volume 2.

Table 6-1. Vertical flame spread experiment matrix (Series II).

Experiment Number	Cable Number	Coating
II-1	900	None
II-2	900	FS15
II-3	900	Flamemastic 77
II-4	900	Vimasco 3i
II-5	900	Carboline Intumastic 285
II-6	813	None
II-7	902	None
II-8	902	FS15
II-9	902	Flamemastic 77
II-10	902	Vimasco 3i
II-11	902	Carboline Intumastic 285
II-12	900	None
II-13	900	Vimasco 3i
II-14	900	Flamemastic 77
II-15	900	Vimasco 3i
II-16	813	FS15
II-17	813	Vimasco 3i
II-18	813	None
II-19	813	Carboline Intumastic 285
II-20	813	Flamemastic 77

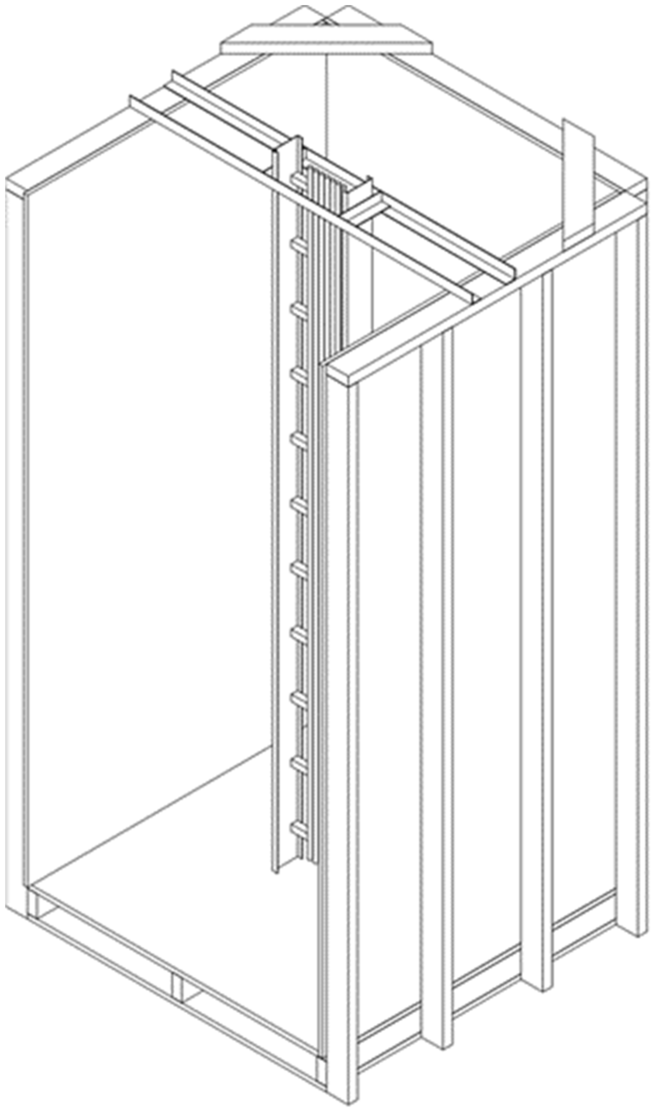

Figure 6-1. Drawing of the vertical flame experiment apparatus.

The Surrogate Circuit Diagnostic Unit (SCDU), developed at SNL, was used to monitor the electrical performance of the cables for the Series II experiments (refer to section 2.3 for a description of the SCDU). Each cable tray experiment assembly included four cables connected to the SCDU to monitor electrical functionality. The cables monitored for functionality were longer than the other cable, typically by 1 m. The extra length ensured that the connections to the SCDU system would not be damaged. The longer lengths are shown to the left in Figure 6-2. The experiment cable was connected to the SCDU using twist-on wire connectors, as shown in Figure 6-3. For several cases, where limited inventory of a cable product was available, the connection point was within 0.6 m of the thermal exposure source (burner). In those instances, the connection point between the SCDU and cable was covered by Kaowool thermal insulation, as shown in Figure 6-3.

Cables monitored for thermal response were located adjacent to the cables monitored for electrical response. Thus, electrically monitored cables were independent of thermally monitored cables. Volume 2 of this RIL series presents the details of the cable thermal response for these experiments.

Figure 6-2. Cable tray assembly following application of coating, showing longer cable leads at left for connection to SCDU.

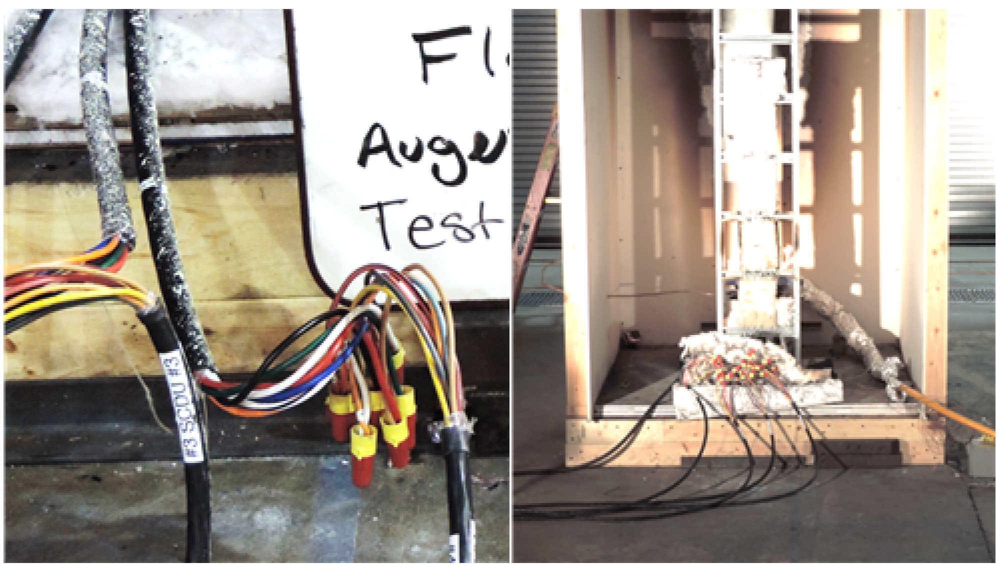

Figure 6-3. (Left) Connection between SCDU (lower) and cable (upper) using wing-nut connectors; (Right) SCDU connections to cable showing use of Kaowool insulation for thermal protection of connection point.

The SCDU and accompanying data acquisition system were located outside the footprint of the calorimetry hood. Connection leads exited the left side of the SCDU and were approximately 25 ft in length. A fifth cable connected the SCDU ground to the cable tray using a self-tapping metal screw. This ensured that the cable tray and circuit grounds were common. Figure 6-4 shows the configuration of the SCDU data acquisition and experiment assembly.

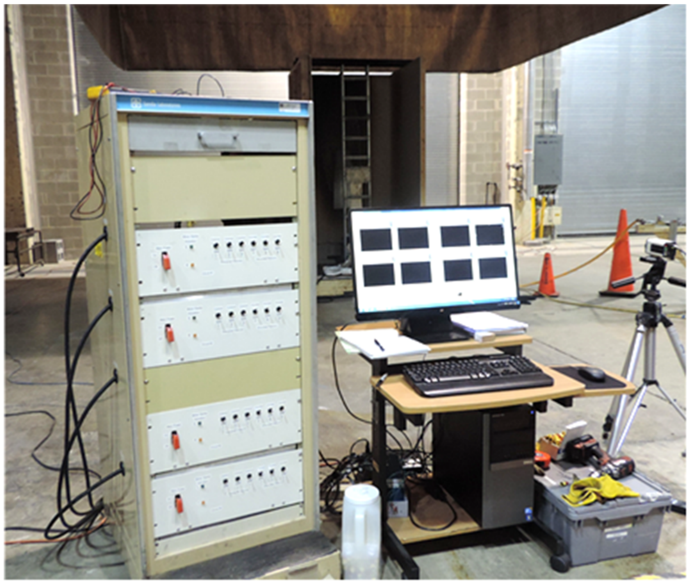

Figure 6-4. Experiment configuration: SCDU (left); data acquisition (right); experiment assembly (background).

6.2 Experiment Results

In Series II, 20 experiments were performed. In each experiment, four cables were monitored for electrical performance. Table 6-2 presents the results from the Series II experiments. In several instances, the cable under experiment did not fail (DNF) electrically. Those instances are identified as “DNF.”

Figure 6-5 presents the time-to-failure results from the vertical flame spread experiments. For the TP cables, all coatings provide delay in the time to damage. However, for the TS cables, the results do not indicate a clear delay time to failure for coated cables. In the case involving TP cables (cables 900 and 902), the earliest coated cable failure occurred beyond the 95 percent failure of the uncoated cable dataset. In the TS case, all coatings experienced at least some failures before the uncoated 95 percent failure. Therefore, for a single layer of cables, the vertical flame spread experiments indicate that the presence of cable coating causes a delay in failure for TP-insulated cables, but not for TS-insulated cables.

Table 6-2. Series II results by cable type.

Cable Type	Cable ID	Experiment #	Coating Material	Failure Time (minutes)				Comments
				SCDU 1	SCDU 2	SCDU 3	SCDU 4	
Thermoplastic	900	II-1	None	5.50	4.00	6.37	15.29	
		II-12	None	0.84	3.01	1.45	1.16	
		II-5	Carboline Intumastic 285	12.36	11.78	13.56	13.49	
		II-3	Flamemastic 77	8.17	8.30	8.29	8.44	
		II-14	Flamemastic 77	8.67	8.12	7.80	8.37	
		II-2	FS15	DNF	DNF	34.64	21.96	Experiment terminated at 90 minutes
		II-4	Vimasco 3i	17.17	17.19	20.12	25.94	
		II-13	Vimasco 3i	10.21	11.61	9.32	17.88	
		II-15	Vimasco 3i	12.90	11.85	8.30	16.39	
	902	II-7	None	1.99	1.05	1.60	1.14	
		II-8	FS15	4.89	6.53	9.28	10.56	
		II-9	Flamemastic 77	9.09	6.69	7.40	6.60	
		II-10	Vimasco 3i	7.58	6.08	4.87	2.91	
		II-11	Carboline Intumastic 285	21.02	20.43	22.64	DNF	Experiment terminated at 60 minutes
Thermoset	813	II-6	None	28.53	30.12	24.43	63.57	SCDU 4 cable agitated at 1 h
		II-16	FS15	48.48	DNF	DNF	DNF	Experiment terminated at 90 minutes
		II-17	Vimasco 3i	11.45	22.60	23.73	40.00	
		II-18	None	7.78	14.05	13.20	DNF	Experiment terminated at 60 minutes
		II-19	Carboline Intumastic 285	DNF	DNF	56.26	19.23	Experiment terminated at 30 minutes
		II-20	Flamemastic 77	10.71	18.33	19.08	14.07	

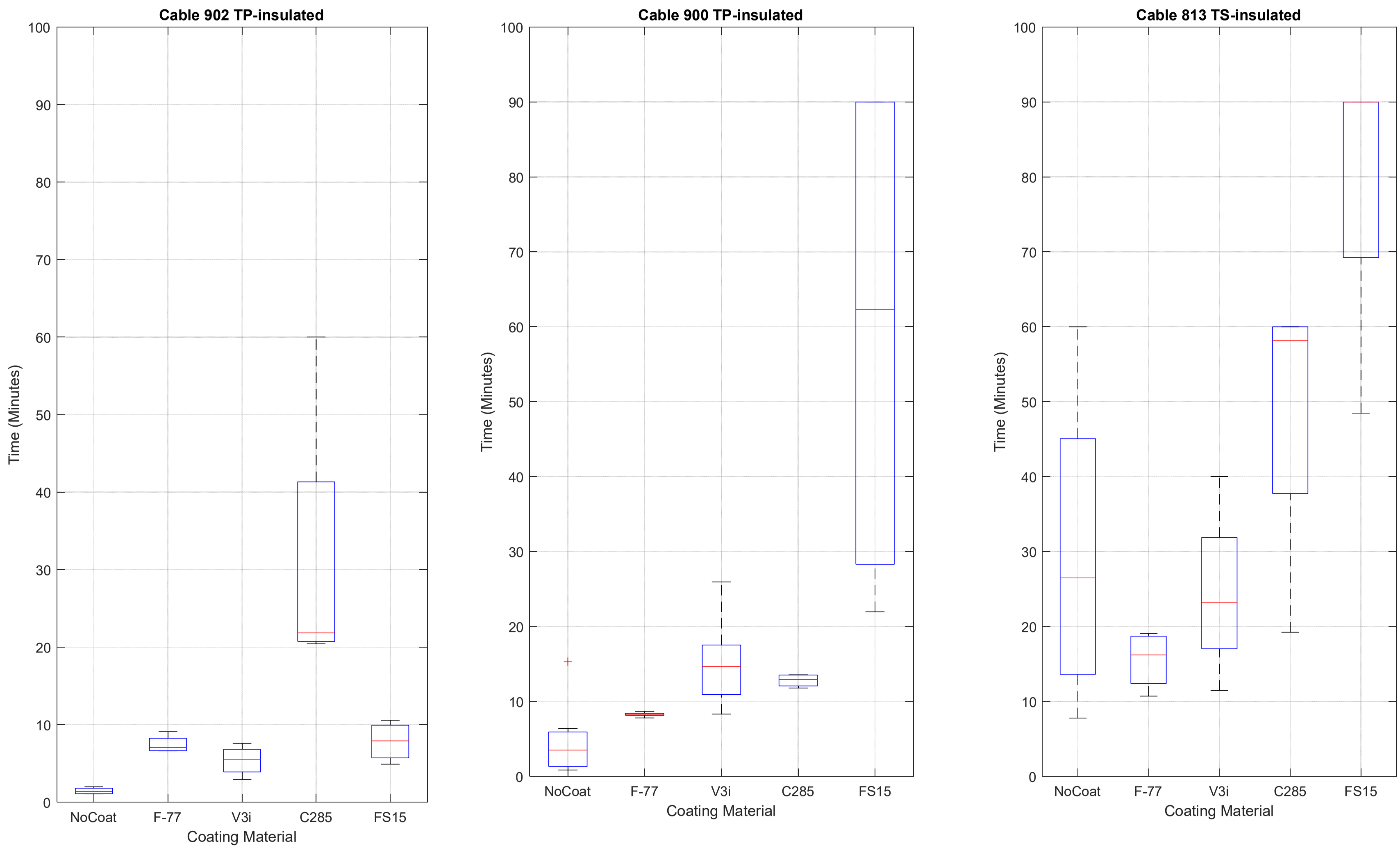

Figure 6-5. Time-to-failure box plots of IEEE Standard 1202 experiments.

7. FULL-SCALE HORIZONTAL FLAME SPREAD EXPERIMENTS

In these experiments, horizontal cable trays containing coated and uncoated cables are exposed to a variety of thermal exposure conditions. The experiments serve two purposes. First, the SCDU will be used to evaluate circuit functionality and determine the effect of delayed electrical cable failure based on various coatings. Secondly, the experiments provide specific input parameters for performing fire model calculations using the Flame Spread over Horizontal Cable Trays (FLASH-CAT) model; parameters such as the heat release rate per unit area of tray, the lateral spread rate, and the vertical spread rate are all used within the FLASH-CAT model. The FLASH-CAT model currently imposes a non-zero lateral and vertical spread rate for both TS and TP cables. Volume 2 of this RIL series presents the thermal results and a complete description of the experiment setup. A general description of the experiment follows.

7.1 Experiment Description

The experiment approach uses an apparatus shown in Figure 7-1. This apparatus is similar to the approach taken in previous experimental circuit functionality programs [2]. This arrangement will allow direct flame impingement on the lowest tray, typical plume temperatures on the middle tray, and a gradual heating on the upper trays. Four 0.3 m (12 in.) wide and 1.8 m (6 ft) long, open ladderback trays are positioned horizontally such that they extend across the apparatus, as shown in Figure 7-1. The cable trays, containing equal numbers of uncoated and coated cables, are monitored for circuit functionality using a modified version of the SCDU system; this modified system expands the number of cables that can be monitored in a single experiment.

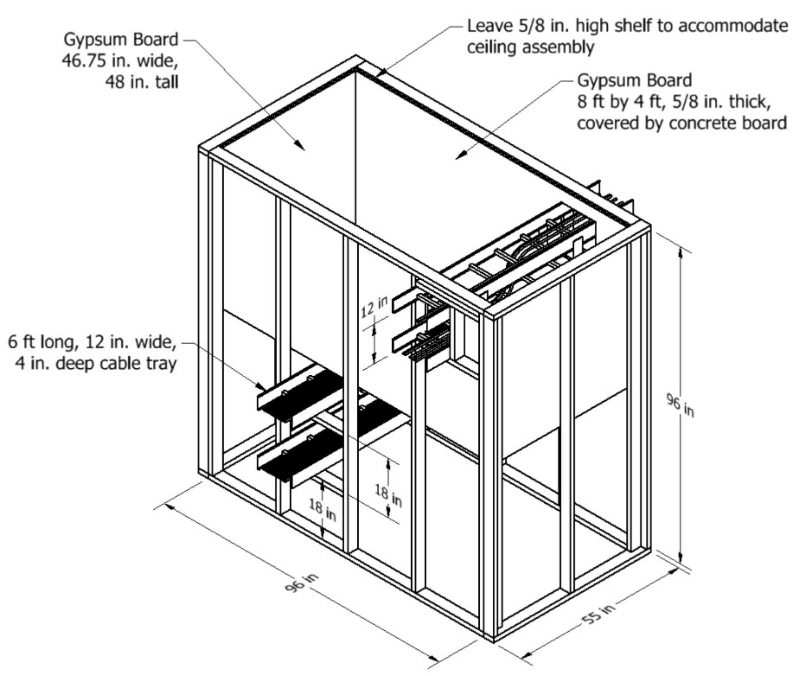

Figure 7-1. Schematic diagram of the full-scale horizontal flame spread experiment.

The SCDU was used in a modified configuration to allow an expanded number of circuits to be monitored during a single experiment. Typically, a single SCDU is connected to a single cable. That configuration allows for identifying specific failure modes however, the number of cables being monitored is limited to four. To expand the number of cables monitored, the SCDU was modified to separately fuse each of the three source conductors. The connections to the field cable were configured to a source-ground configuration as shown in Figure 7-2. That is, energized conductors are adjacent to grounded conductors. Under this configuration, 12 cables could be monitored in a single experiment. Each cable has a dedicated fused source path and ground path. When an energized conductor shorts to an adjacent grounded conductor or externally grounded cable raceway due to fire damage, the fuse clears and indicates the cable failure. In this modified configuration, spurious operations induced by hot shorts are not possible, as the active targets were not included in the experiment.

Figure 7-2. Illustration of modified SCDU cable connection ("E" energized conductor; "G" grounded conductor).

The heat release rate of the burner followed a step-wise profile as shown in Figure 7-3. The step increases doubled the previous rate and occurred every 15 minutes, namely at 50 kilowatts (kW), 100 kW, 200 kW, and 400 kW. The experiment was terminated when all electrical circuits had failed, and ignition of the upper tray (hot gas layer) occurred. This experiment configuration and these cable locations provide a range of thermal exposure conditions within a single experiment, while also allowing for direct comparisons between uncoated and coated cable electrical performance. This thermal exposure approach gradually raised the temperature in the enclosed space to temperatures that would cause ignition of the cables in all three locations.

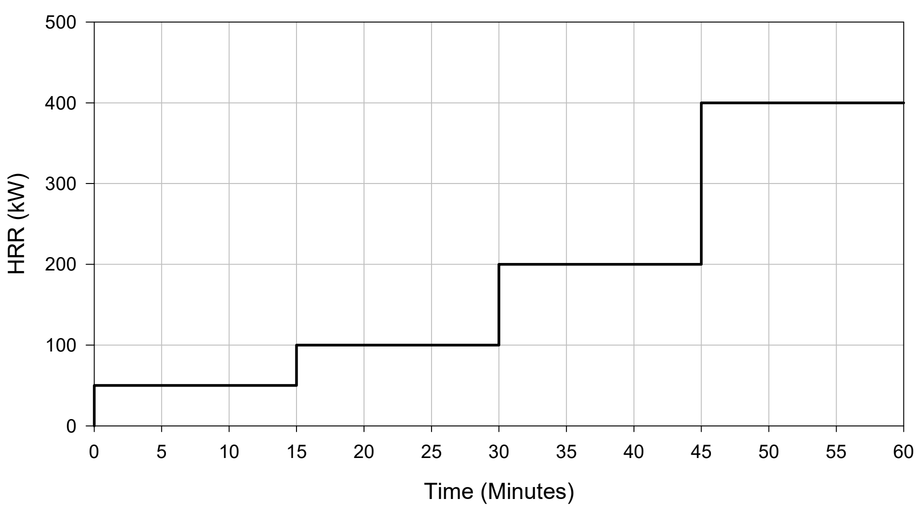

Figure 7-3. Thermal exposure profile for full-scale horizontal flame spread experiments.

For these experiments, the trays contain an equal number of uncoated and coated cables. The cables are arranged in the trays in two different configurations (see Figure 7-4). A single layer of cables was used in configuration A. In configuration B, three layers of cable were installed in a pyramid-like configuration. This configuration was selected as an alternative to a fully loaded cable tray; the goal was to minimize cost and reduce the weight of the overall assemblies to ease removal and installation of tray assemblies in the experiment enclosure. In each case, the four trays contained the same configuration of cables and type of coating. Four of the cables were instrumented to determine electrical failure (yellow), and four were instrumented with TCs. In addition to this variation, the tandem tray in the upper location included a cable drop, as shown above in Figure 7-1.

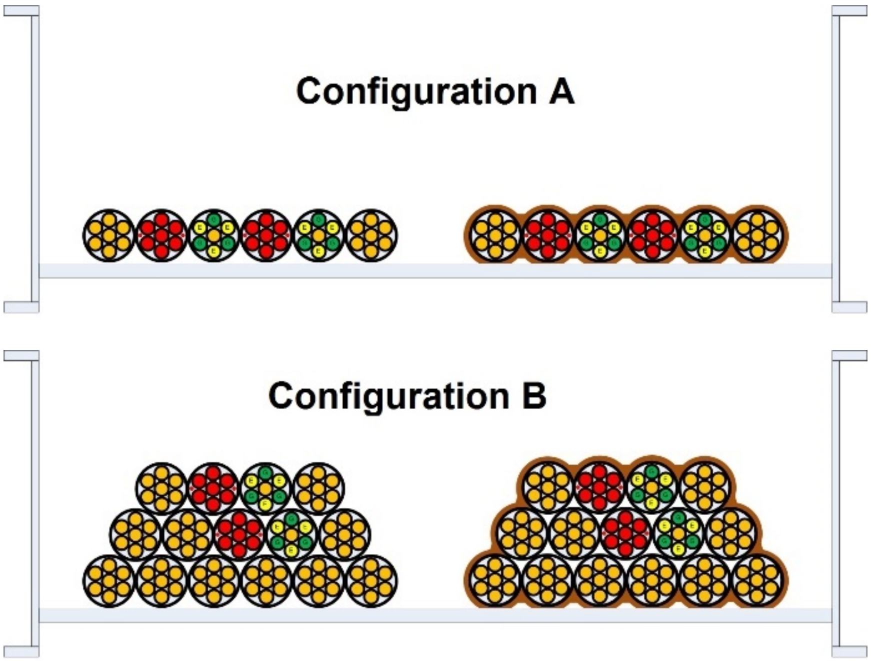

Figure 7-4. Illustration of cable tray loading configurations (not to scale). Red indicates a cable monitored for thermal response. Yellow/green indicates a cable monitored for electrical response. All other cables are unmonitored dummy cables.

Based on this experimental variation, Table 7-1 presents the matrix for the horizontal experiments.

Table 7-1. Horizontal experiment matrix.

Experiment #	Cable Number	Coating	Configuration
H-1	900	Carboline	A
H-2	900	Flamemastic	
H-3	900	FS15	
H-4	900	Vimasco	
H-5	900	Carboline	B
H-6	900	Flamemastic	
H-7	900	FS15	
H-8	900	Vimasco	

7.2 Experimental Results

The full-scale series consisted of eight experiments. In each experiment, 12 cables were monitored for electrical functionality. Table 7-2 presents the results from the full-scale series. In all instances, the cables under experiment failed electrically. Box plots showing results for single layer are shown in Figure 7-5 and multi-layer shown in Figure 7-6.

Table 7-2. Full-scale circuit integrity experiment results.

Cable Type	Experiment #	Coating Material	Exposure Location	Config.	Failure Time (minutes)			
					Uncoated 1	Uncoated 2	Coated 1	Coated 2
Thermoplastic (#900)	H-1	Carboline	Low—Flame	A	5.74	14.55	24.16	21.39
			Middle—Plume		15.47	14.43	24.70	23.32
			High—HGL		34.44	34.42	48.36	44.86
	H-2	Flamemastic	Low—Flame		9.95	6.62	17.30	19.84
			Middle—Plume		13.56	9.93	26.86	27.91
			High—HGL		32.95	34.48	46.6	39.8
	H-3	FS15	Low—Flame		3.870	7.81	24.41	29.03
			Middle—Plume		12.70	8.97	42.98	24.73
			High—HGL		33.34	34.55	40.16	39.52
	H-4	Vimasco	Low—Flame		8.98	4.70	19.02	18.11
			Middle—Plume		5.90	5.95	23.52	21.72
			High—HGL		28.45	30.48	39.61	36.81
	H-5	Carboline	Low—Flame	B	14.75	17.93	29.07	45.83
			Middle—Plume		17.89	25.17	36.79	41.55
			High—HGL		37.30	44.55	60.33	55.51
	H-6	Flamemastic	Low—Flame		16.50	22.01	24.61	33.61
			Middle—Plume		24.59	25.08	27.33	39.05
			High—HGL		42.49	45.69	54.44	50.97
	H-7	FS15	Low—Flame		12.91	18.56	19.78	34.94
			Middle—Plume		21.9	24.02	43.86	41.60
			High—HGL		34.03	41.85	50.7	53.82
	H-8	Vimasco	Low—Flame		10.13	14.75	18.97	28.10
			Middle—Plume		20.24	23.38	25.56	39.70
			High—HGL		33.35	41.56	44.32	51.18

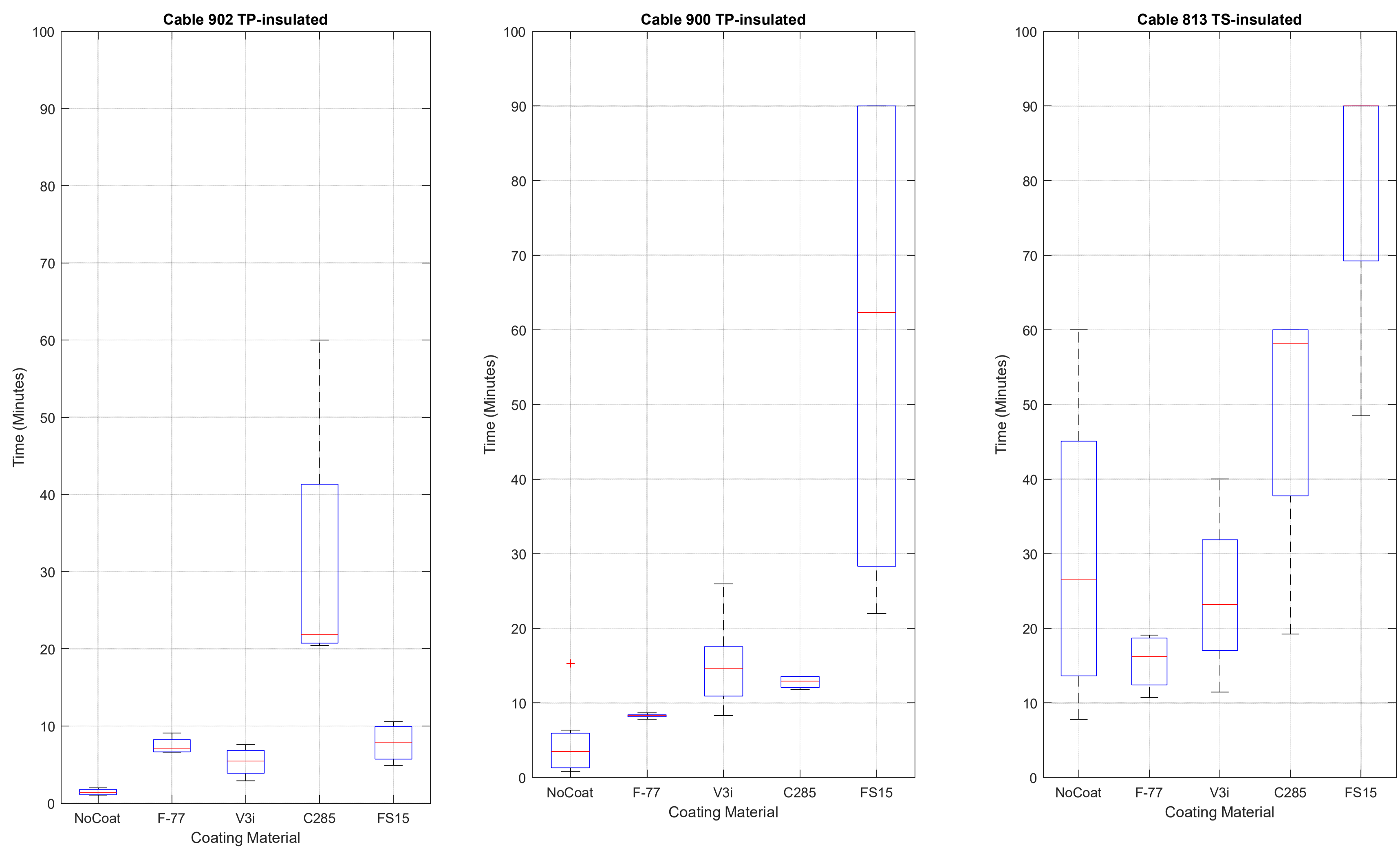

Figure 7-5. Results single-layer nonqualified (cable 900).

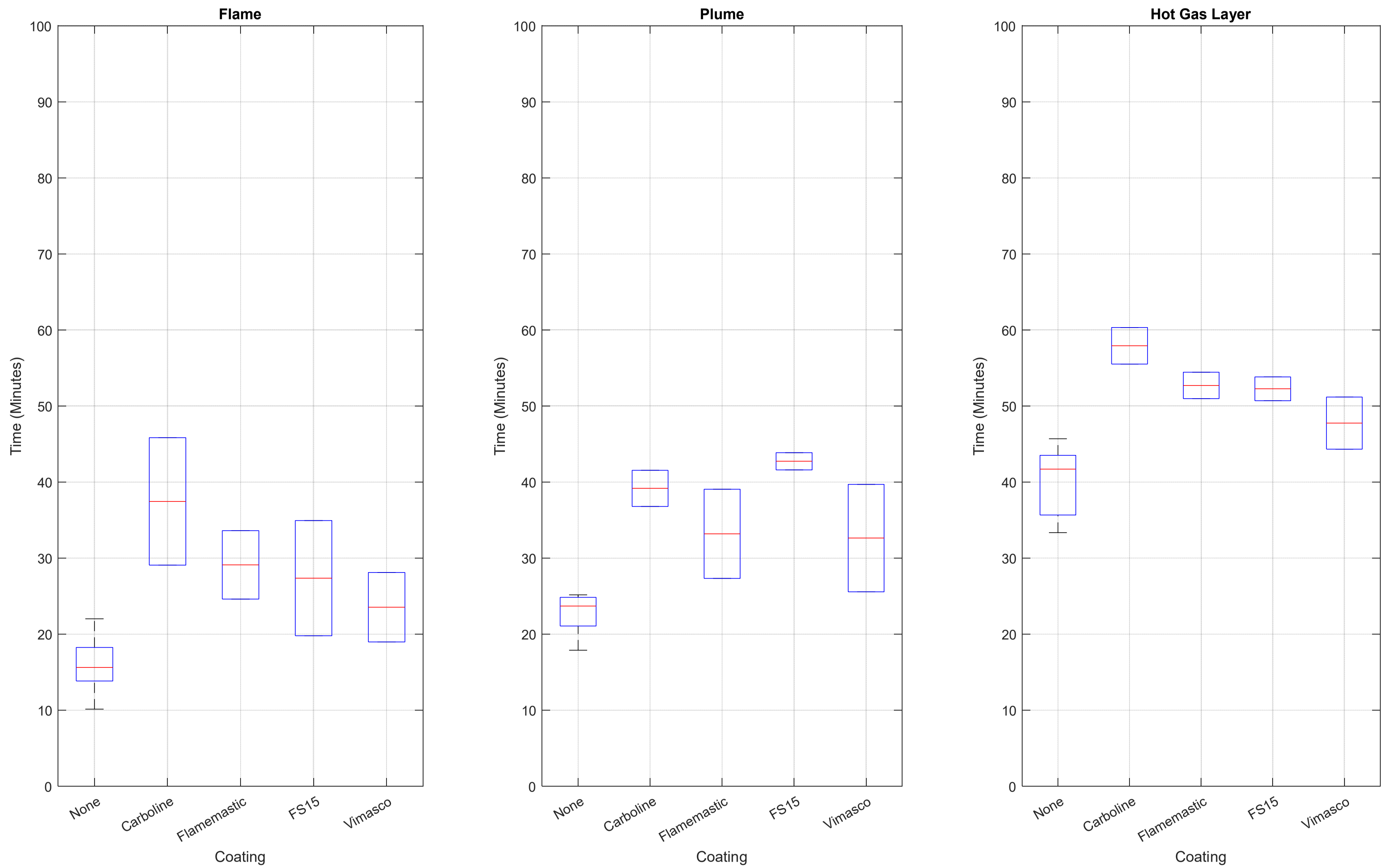

Figure 7-6. Results multilayer nonqualified (cable 900).

8. OBSERVATIONS

This phase of the program focuses on the functionality of energized electrical cables treated with fire-retardant cable coatings. “Time to damage” is commonly defined as the instance when electrical functionality is lost. The objective of this phase was to gather data that would support the subsequent evaluation of the effect of cable coatings on the time to damage. The data will be used to confirm and improve the development of existing guidance NUREG/CR-6850 (EPRI 1011989), “EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities,” Appendix Q, issued September 2005 (EPRI/NRC-RES 2005). This work will conclude during Phase 3, after the aging evaluation is completed in Phase 2.

The objectives of this project were achieved by including an assortment of fire-retardant coatings commonly used in commercial nuclear facilities and exposing them to thermally damaging fire conditions. Fire-retardant coatings were applied to several types of insulated electrical cables according to the fire-retardant coating manufacturers’ specifications. The coated and noncoated (bare) electrical cables were then exposed to a range of thermally damaging fire conditions. Circuit functionality was monitored to determine when conductor-to-conductor shorts or conductor shorts to ground occurred. General insights from the individual series of experiments include the following:

- Delay in time to damage
    - Nonqualified electrical cables coated with a fire-retardant cable coating demonstrate a delay in time to damage, regardless of coating type.
    - Qualified electrical cables coated with a fire-retardant cable coating demonstrated mixed results. Bench-scale experiments demonstrated a delay, while full-scale vertical flame spread experiments did not demonstrate a delay.
- Coating thickness
    - Regardless of cable type, additional cable coating thickness beyond the manufacturer’s specified minimum thickness provides additional delay in time to damage.
- Cable construction
    - Cable construction attributes such as conductor size, insulation thickness, conductor count, etc., will impact the performance of a cable under fire conditions regardless of coating type. The objectives of the experiments were not to identify which attributes affect performance, nor did the experiments do so. However, it is important to note that the primary qualified and nonqualified cables experimented within this program are of different construction, and a comparison of these cables’ performance is not warranted.

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Appendix A
Thermocouple Interference Issues with Surrogate Circuit Diagnostic Unit

Potential interference issues between the electrical performance monitoring systems and the thermocouples (TCs) exist when used in the same experiment. This has been observed as a minor issue in past experiments but became more significant during the radiant energy experiments, especially in the final series of the radiant energy 10-cable bundle experiments.

In past experiments, TC disturbances have been observed concurrent with shorting on the electrical performance systems. This is generally attributed to electromagnetic effects associated with current flow in the shorting cables that interfere with nearby TCs. In the current experiment series, a pronounced and pervasive effect was noted during the final set of radiant energy 10-cable bundle experiments. It appears that this particular experiment configuration, which placed three electrical performance cables together on one side of the bundle, resulted in a much more pronounced effect than had been observed in any previous experiments. A full explanation for the effect has not been pursued, but the impact on the experiment data should be noted.

Specifically, given three Surrogate Circuit Diagnostic Unit (SCDU) modules energized, as the experiment cables are heated beyond approximately 300 degrees Celsius (°C) (572 degrees Fahrenheit (°F)), a pronounced interference effect manifested on the TCs. The TCs would suddenly indicate very low temperatures compared to actual temperatures, typically giving readings close to ambient when the cables were in fact at 300°C (572°F) or greater. Initially, this was thought to be a possible problem with the TC extension leads or potential formation of false junctions in either the lead cable or the TCs themselves. Replacement of the extension leads for the second experiment in the set (experiment R34, uncoated #2) made no difference at all, and the formation of false junctions in multiple TCs concurrently is highly unlikely. In the third experiment performed in this series (experiment R38, Vimasco #1), the undeniable correlation between the SCDU and the TC faults was identified. As soon as the SCDU modules were powered down, the TC readings returned to normal, and if powered back up, the TCs again read false low values.

This effect has not been explored in detail, but the experience during experiment R38 pointed to a simple strategy to mitigate the effect. For the remainder of the experiments, the SCDU system was left deenergized until well into the exposure and was then cycled on/off to optimize the gathering of both temperature and electrical data. As the cable temperatures approached damaging levels (e.g., around 370°C (698°F) for this cable), the SCDU modules were cycled on for short times (roughly 30 seconds per cycle) and then turned off. Cycles were repeated at 1- to 2-minute intervals. Once ignition of the cables was observed, which was consistently before electrical failure, the SCDU cycles were altered so that more time on than off was spent with the SCDU. Typically, the SCDU would be cycled on for 1 to 2 minutes at a time and then cycled off for 30 seconds; this was repeated until electrical failures were observed, and the modules were turned off and left off.

In the end, the interference problems compromised, to some degree, the first three 10-cable bundle experiments performed. In particular, the temperature data for experiments R33, R34, and R38 (uncoated #1 and #2 and Vimasco #1) were compromised during the later stages of each experiment. The early temperature data are correct and have been used, but the interference problem compromised the temperature data once cable temperatures exceeded roughly 300°C (572°F). The remainder of the experiments used the SCDU cycling strategy and will show gaps in the temperature data during later stages of the experiment. However, these experiments provide essentially intact pre-ignition temperature data and periodic post-ignition temperature data.

The data from all experiments are reported and have been included in the analysis because the effect is obvious and can easily be accounted for. Furthermore, before cable ignition, the temperature data provide insights and value. Beyond the point of ignition, temperature data become unreliable because the measurement bead may pop out from under the cable jacket; measurements from a dislodged bead mean that the measurements are uncertain. Finally, the SCDU electrical performance data are not of any interest until the time that cable degradation becomes significant and when shorting occurs. As demonstrated in prior experiments, cable electrical performance tends to remain nominal (good) until a threshold is reached; past this threshold, electrical degradation progresses quickly to full shorting (typically about 1 to 2 minutes or fewer). Hence, the SCDU cycling strategy preserves both the pre-ignition temperature data and the post-ignition cable shorting data. Note also that the data plots presented in the appendices have not been cropped to artificially remove anomalous values but are instead shown as intact data streams. The summary plots presented in the body of the report have generally omitted compromised temperature data.

Appendix B
Voltage and Current Profiles

This section presents the voltage and current profiles from the surrogate circuit diagnostic units (SCDUs) used to monitor circuit integrity. These data were used to identify the time of functional failure. Functional failure occurs by either (1) a fuse clear or (2) a hot-short-induced spurious operation of the motor starter contactor. The former is identified from the plots below when the source voltage on conductor 1, 2, and 3 drops to 0 volts from its nominal value of ~125 volts alternating current (VAC). The latter is identified from the plots below, when the voltage on conductors 5 or 6 exceed a nominal 80-volt threshold with corresponding hold-in current. The earliest functional failure is used to determine the time when circuit functionality is lost. In several cases, the circuits did not fail. These cases are identified in the main body of the report.

B.1 Bench-Scale Horizontal Circuit Integrity Experiment Results

The failure times reported in section 5 of this report were obtained from the data collected from the SCDU. The data from the SCDU are plotted below. Voltages are identified as V1 through V8. Currents are identified as A1 through A8.

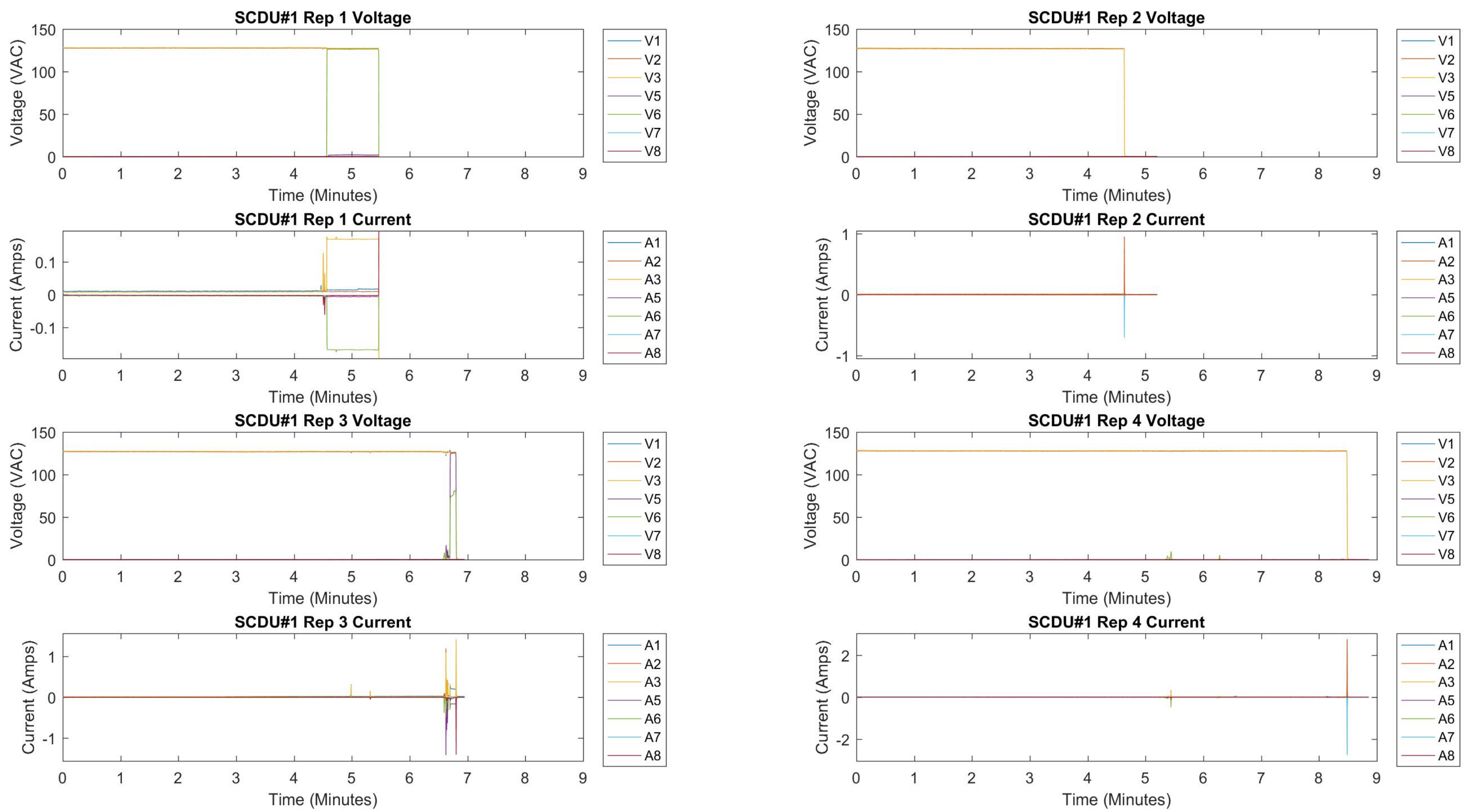


Figure B-1. Experiment configuration BSCI-1—bare cable—cable 900—thermoplastic—replicates 1 to 4.

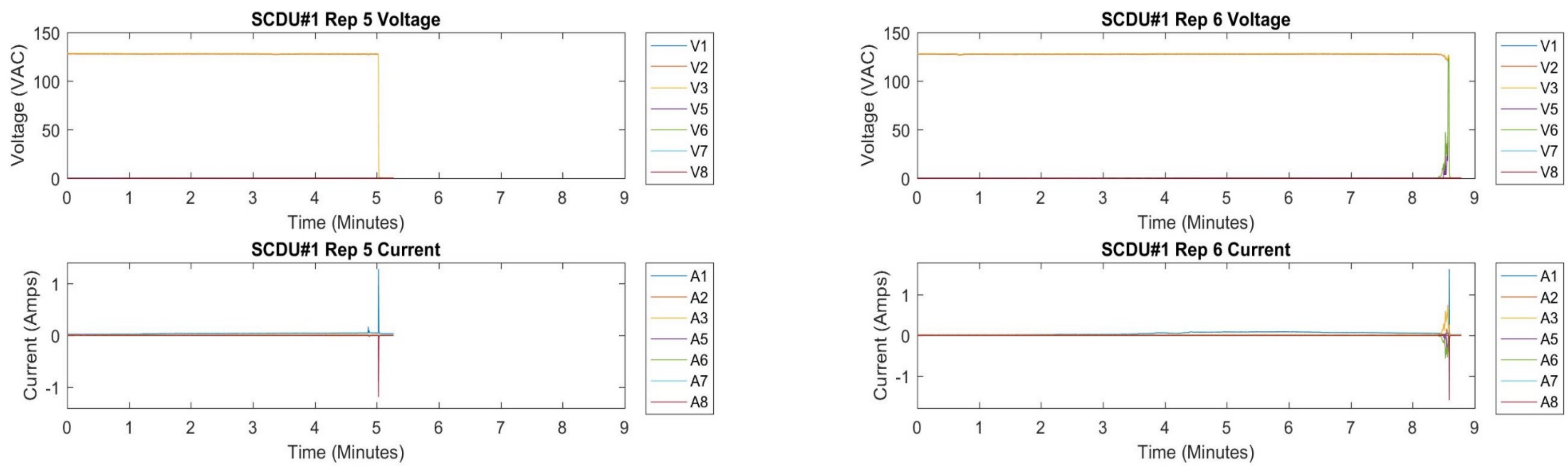


Figure B-2. Experiment configuration BSCI-1—bare cable—cable 900—thermoplastic—replicates 5 to 6.

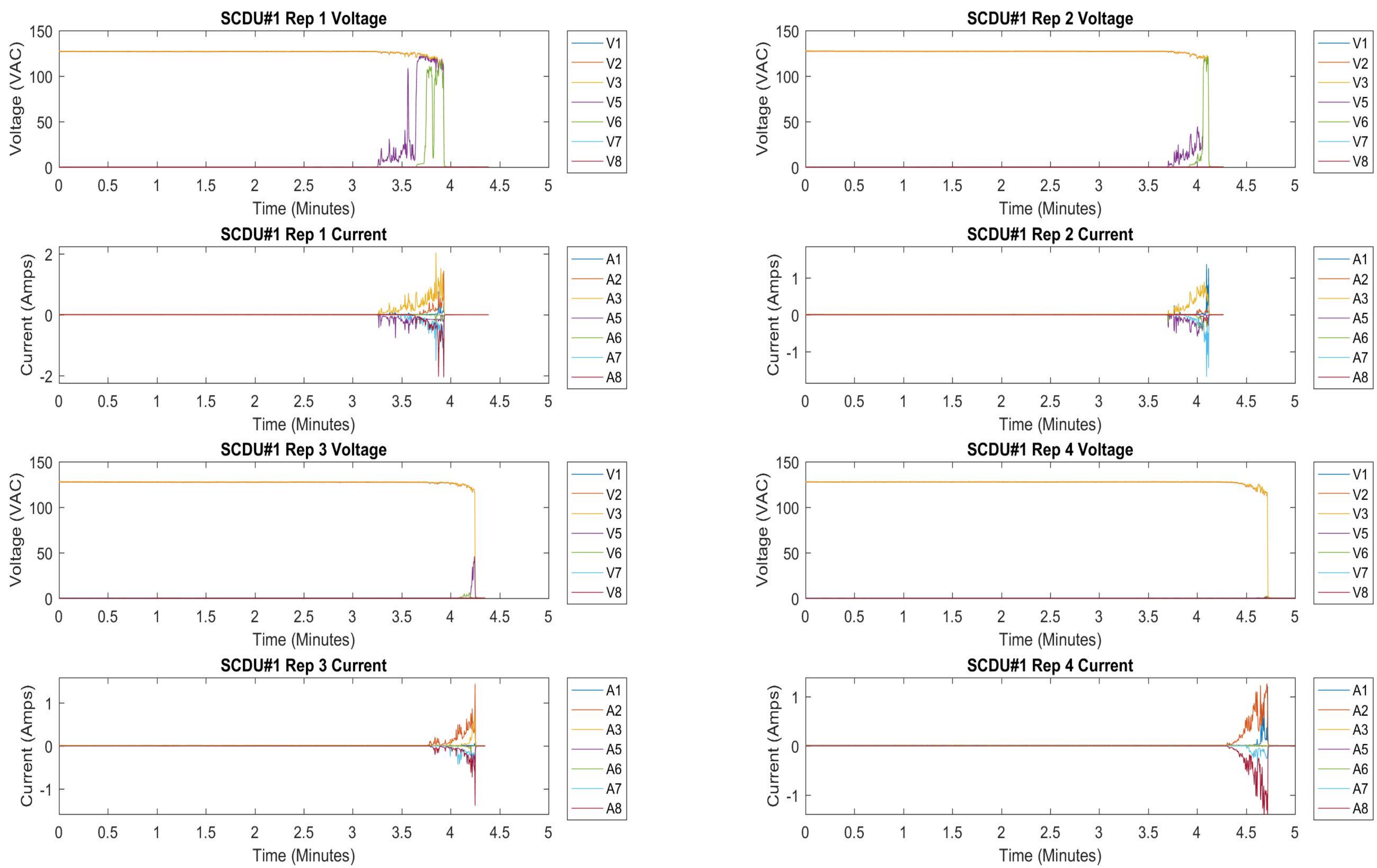


Figure B-3. Experiment configuration BSCI-10—bare cable—cable 813—thermoset—replicates 1 to 4.

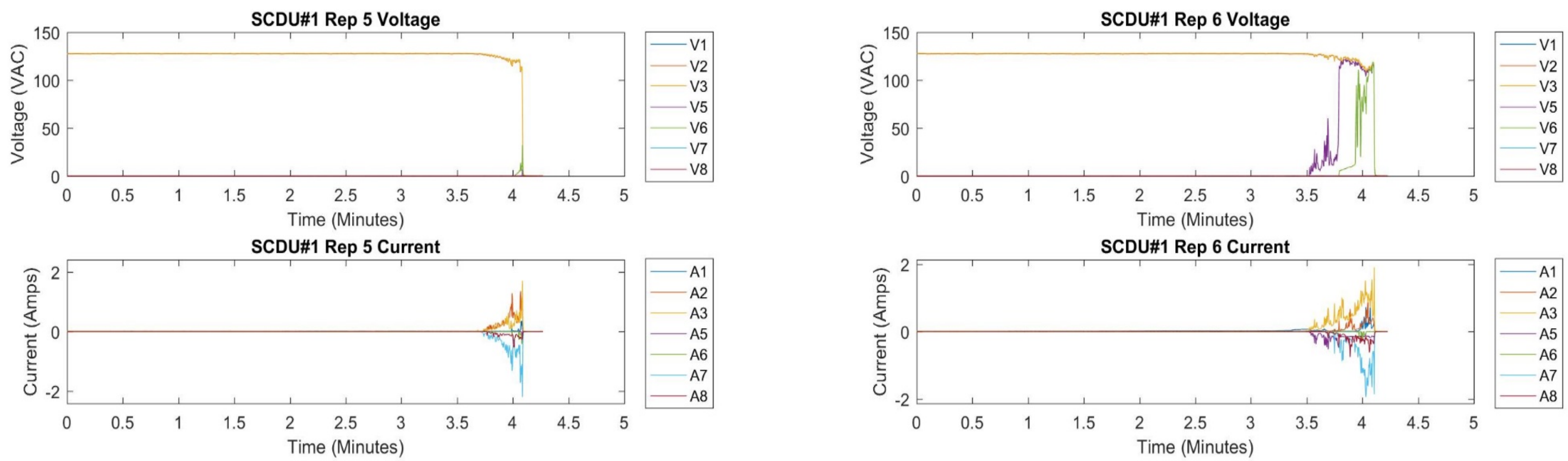


Figure B-4. Experiment configuration BSCI-10—bare cable—cable 813—thermoset—replicates 5 to 6.

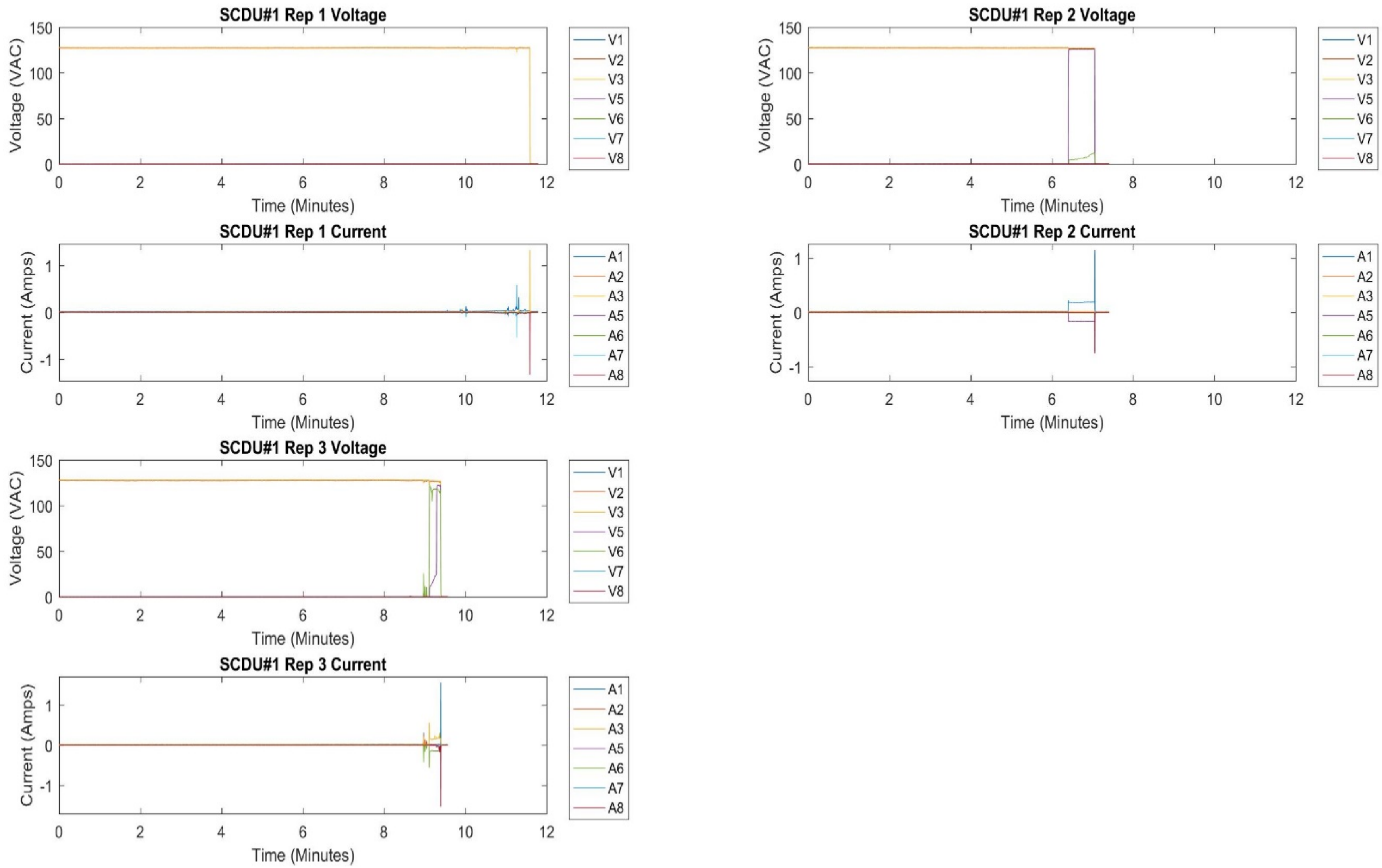


Figure B-5. Experiment configuration 2—Carboline Intumastic 285 coated—1/16th inch thickness—cable 900—thermoplastic.

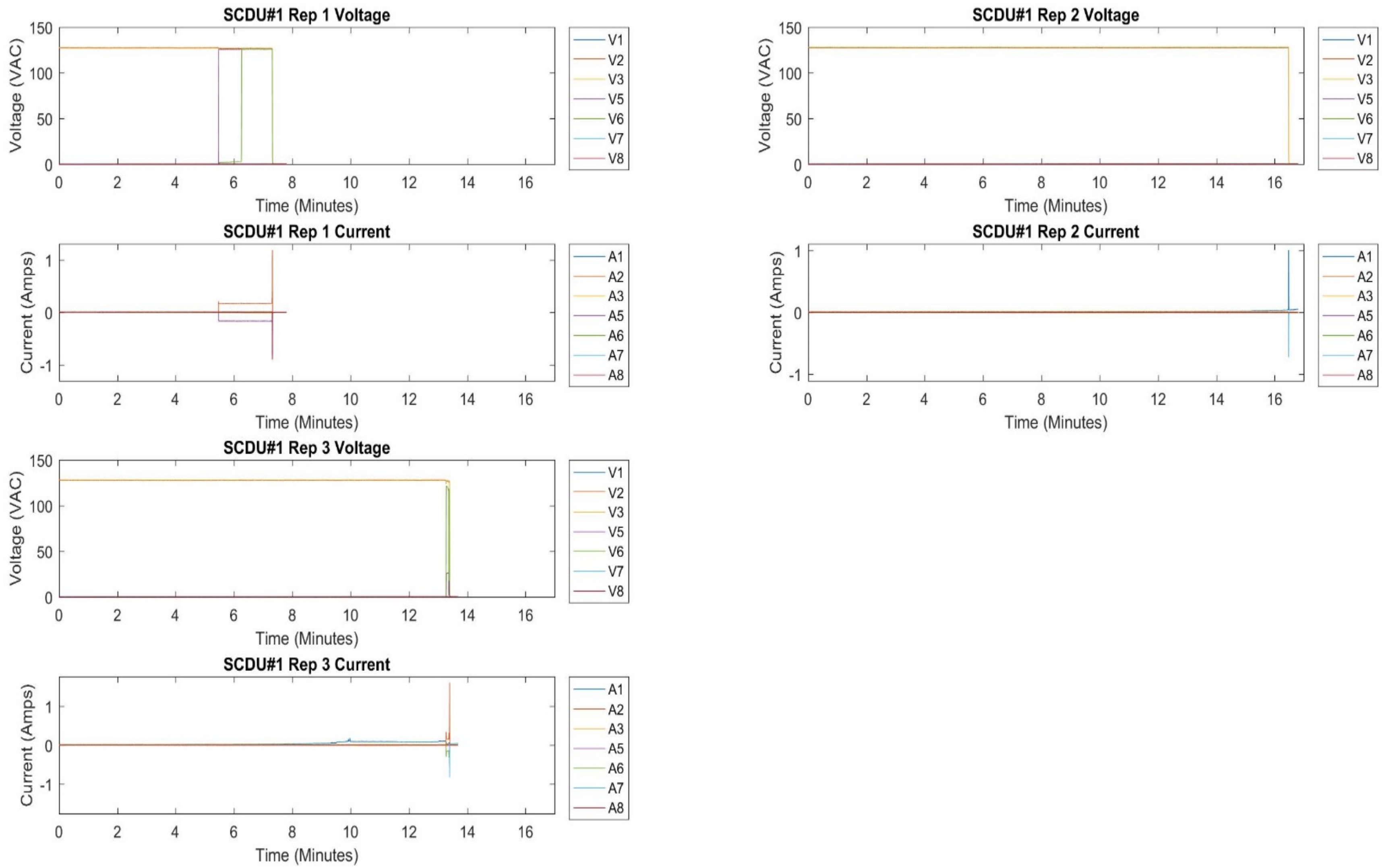


Figure B-6. Experiment configuration 3—Carboline Intumastic 285 coated—1/8th inch thickness—cable 900—thermoplastic.

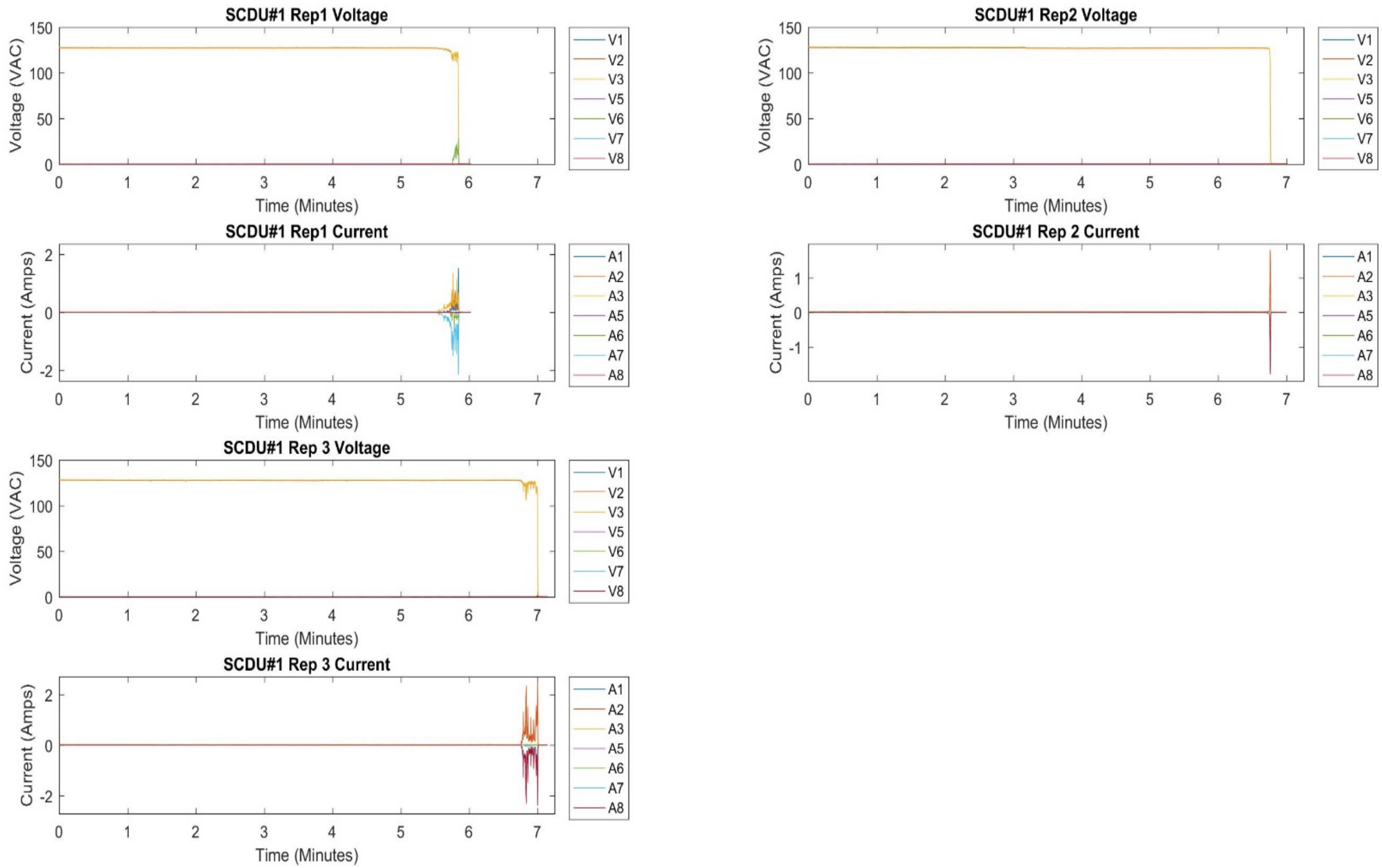


Figure B-7. Experiment configuration 11—Carboline Intumastic 285 coated—1/16th inch thickness—cable 813—thermoset.

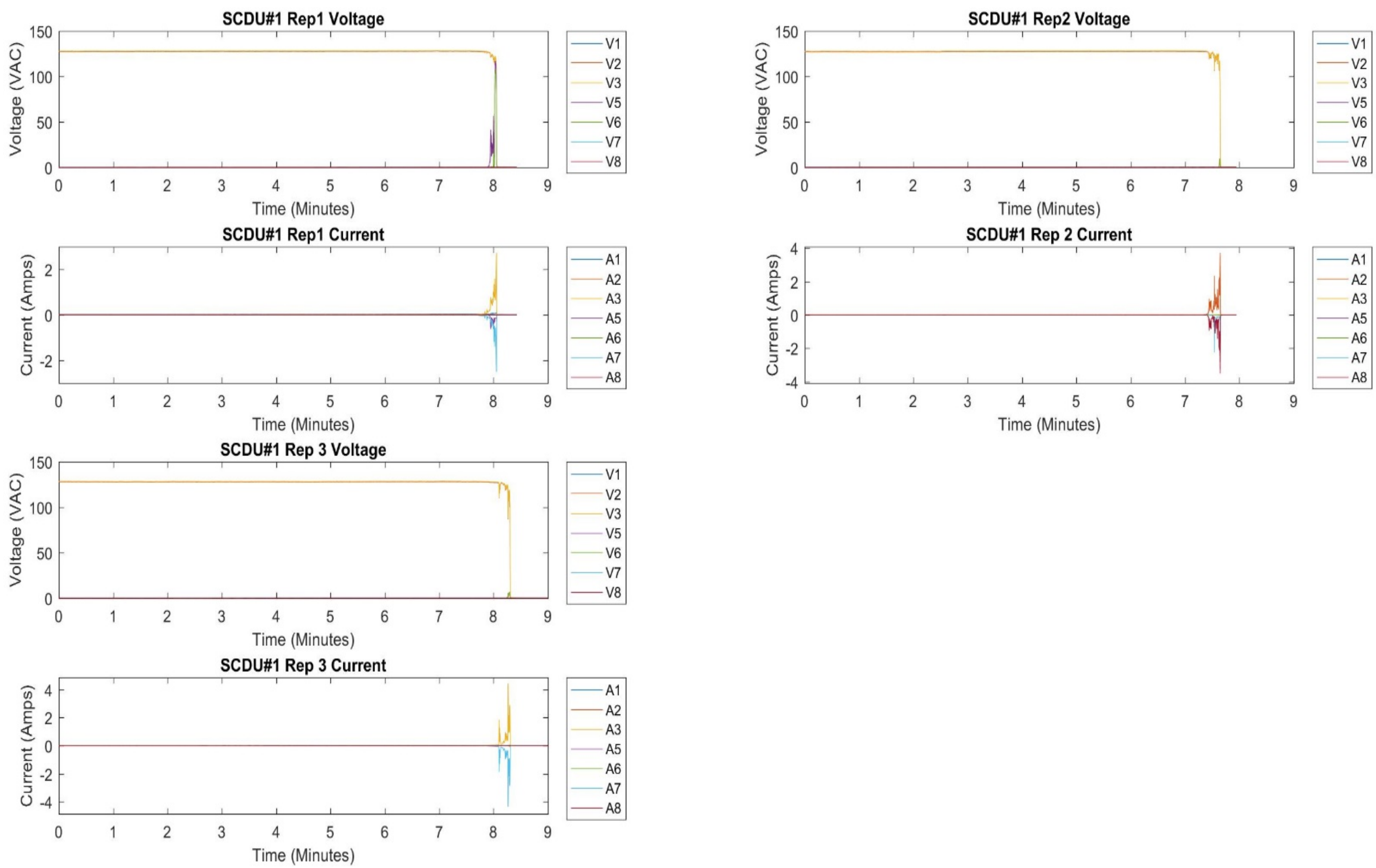


Figure B-8. Experiment configuration 12—Carboline Intumastic 285 coated—1/8th inch thickness—cable 813—thermoset.

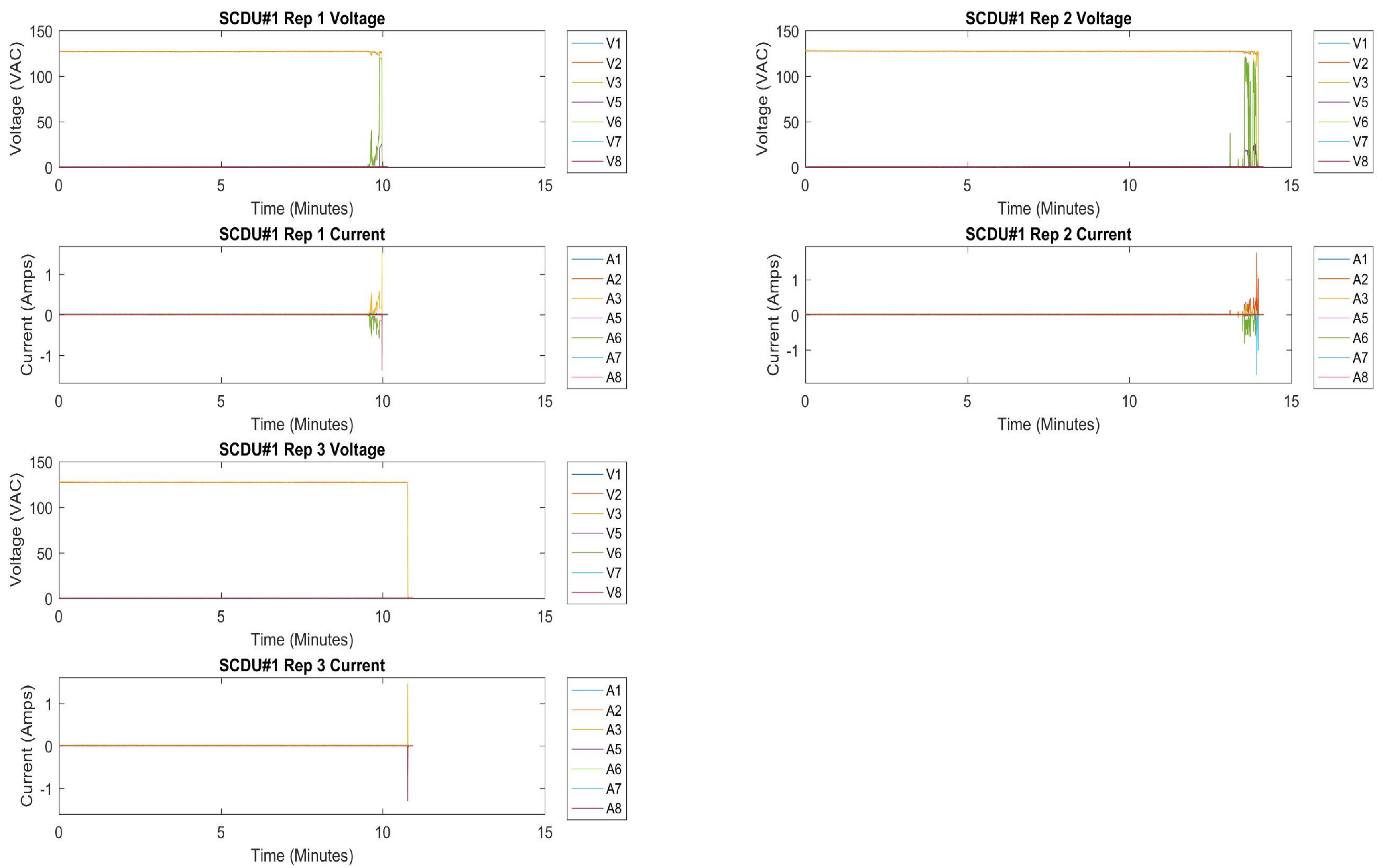


Figure B-9. Experiment configuration 4—Flamemastic 77 coated—cable 900—1/16th inch thickness—thermoplastic.

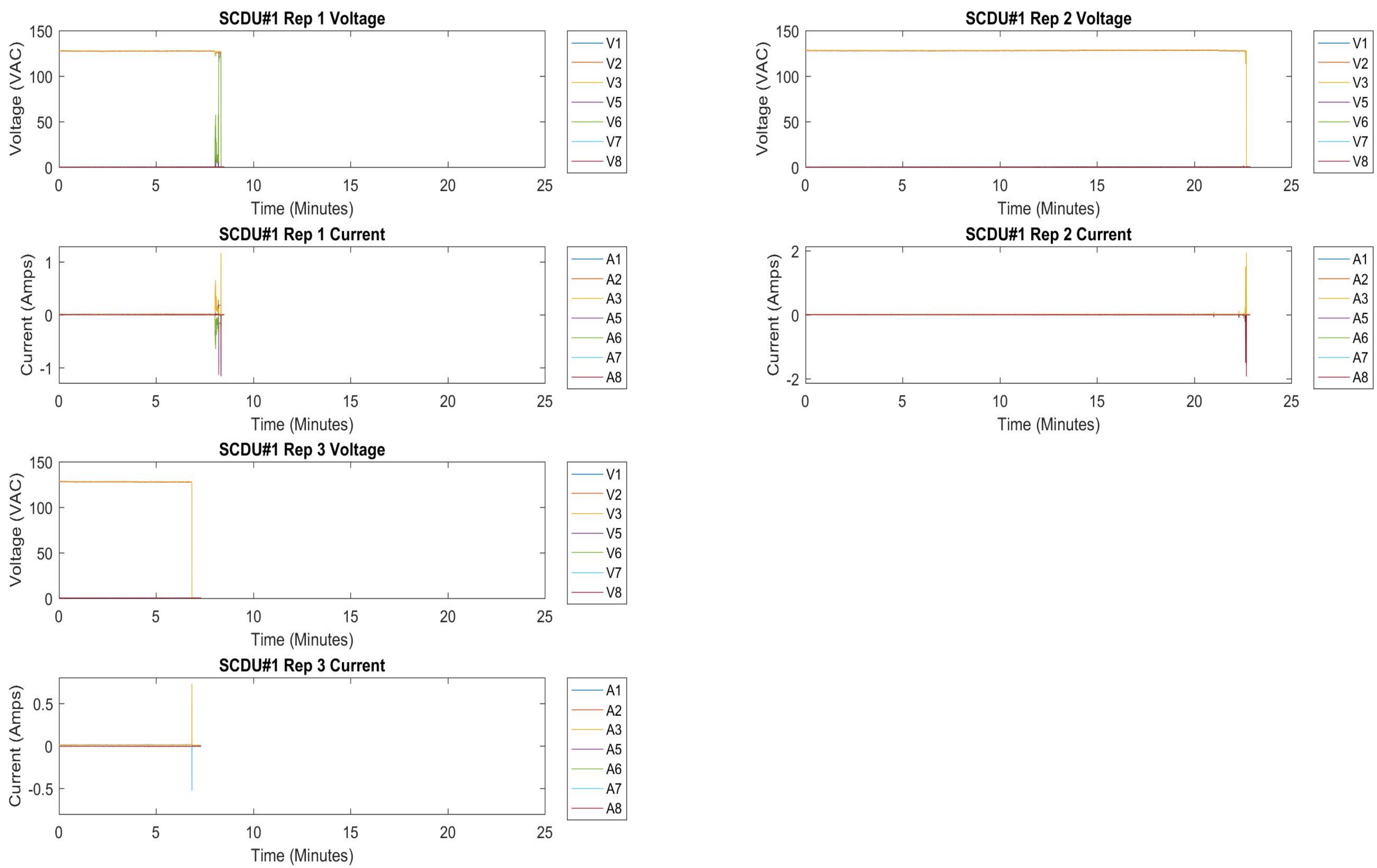


Figure B-10. Experiment configuration 5—Flamemastic 77 coated—cable 900—1/8th inch thickness—thermoplastic.

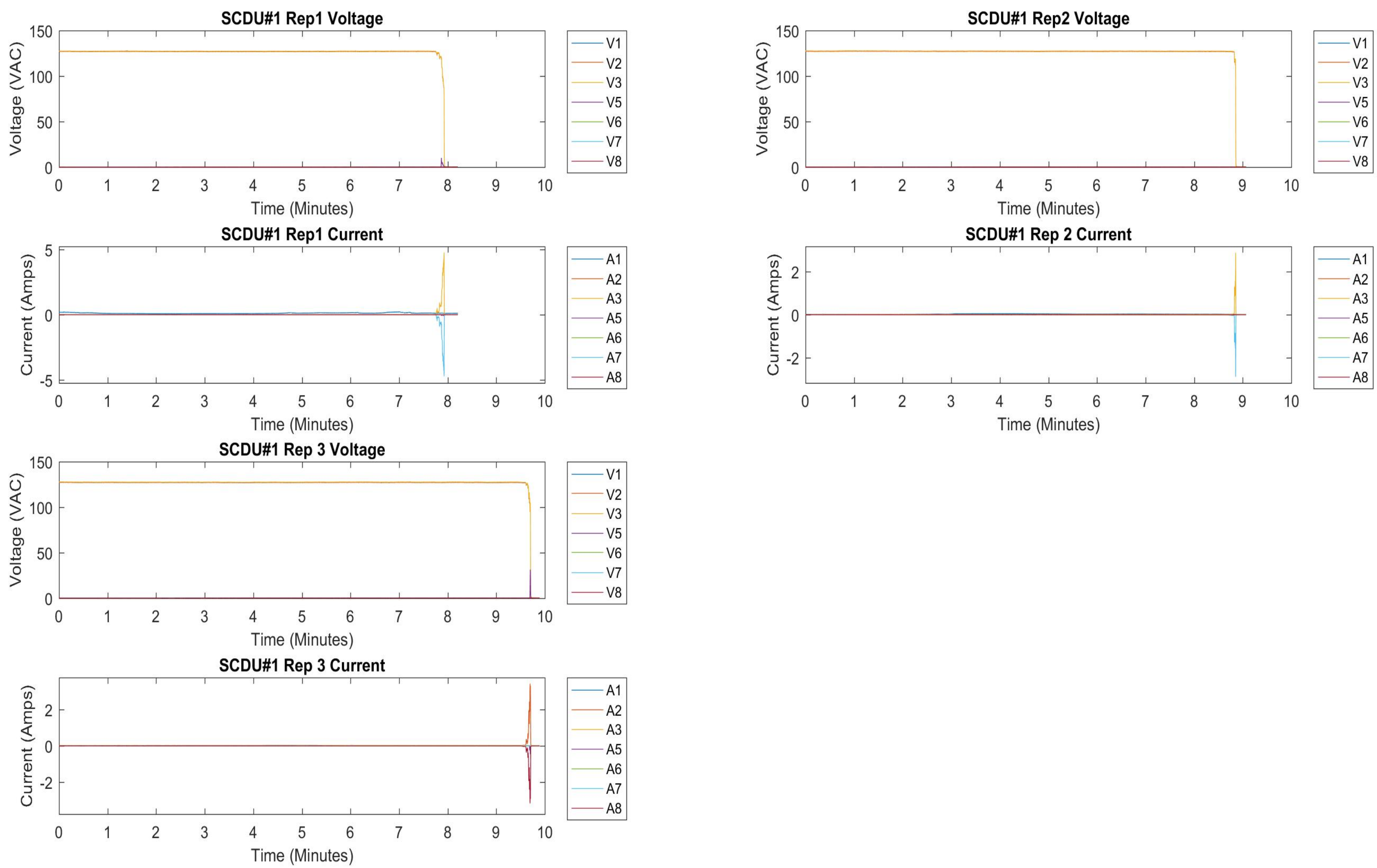


Figure B-11. Experiment configuration 13—Flamemastic 77 coated—cable 813—1/16th inch thickness—thermoset.

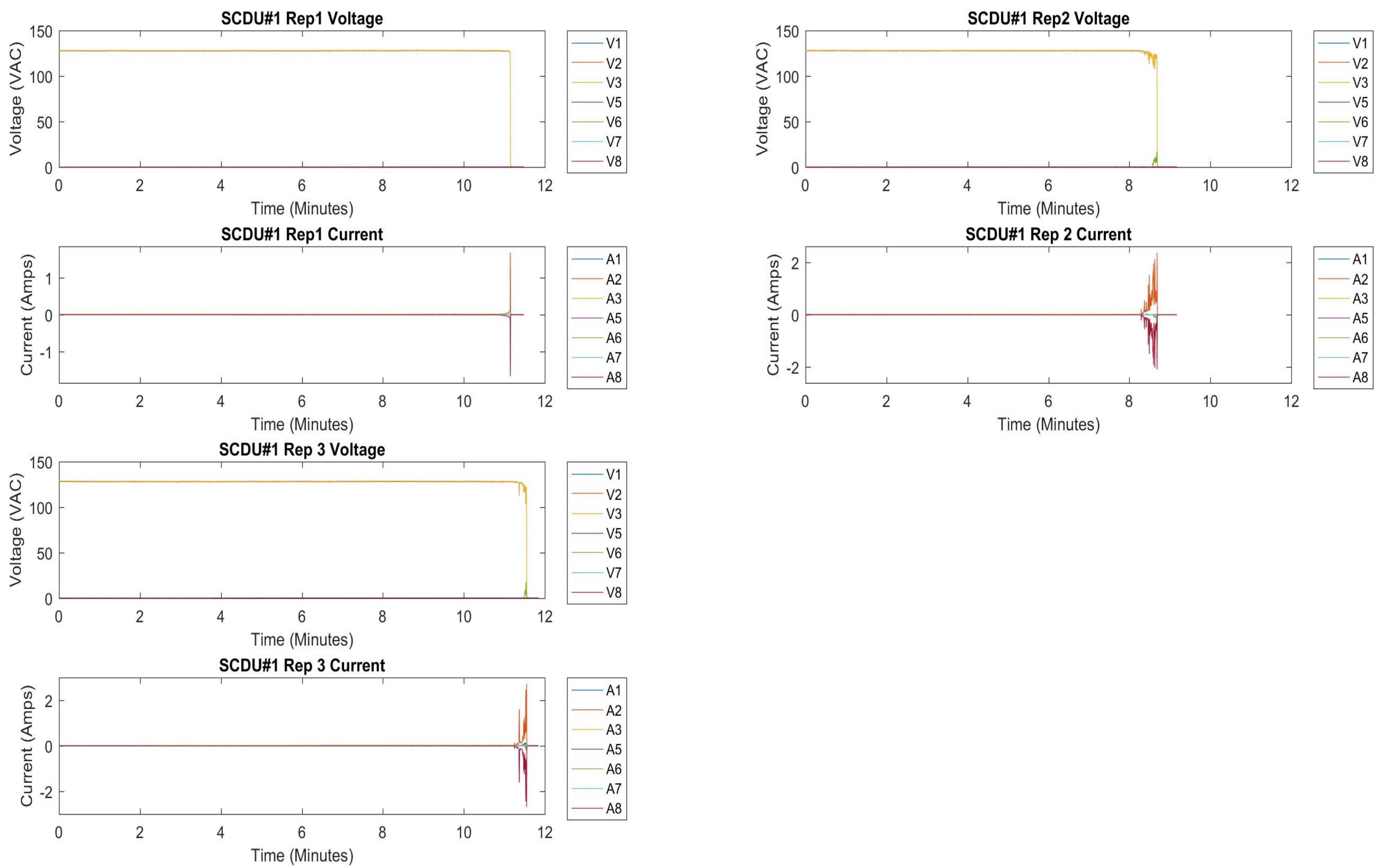


Figure B-12. Experiment configuration 14—Flamemastic 77 coated—cable 813—1/8th inch thickness—thermoset.

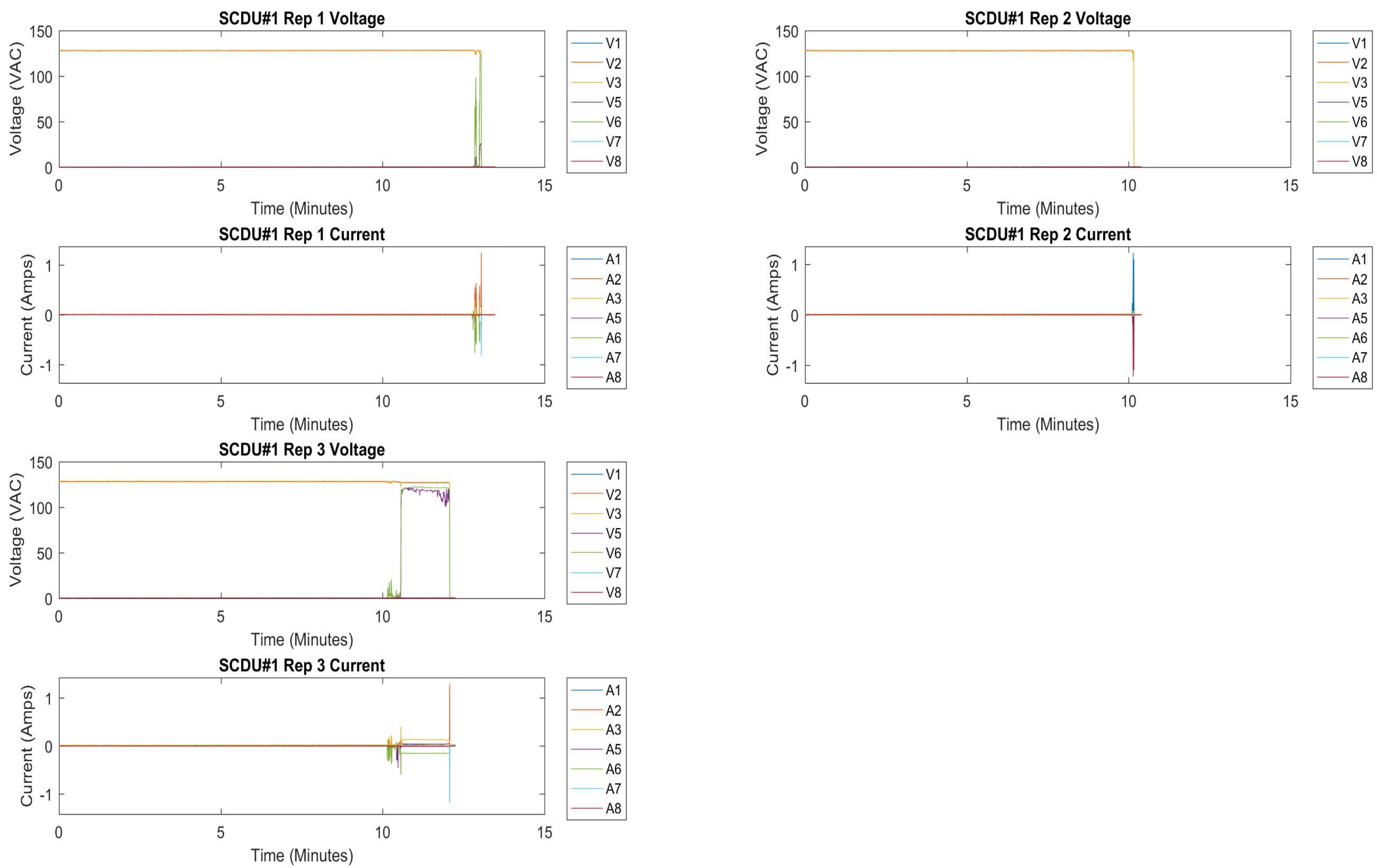


Figure B-13. Experiment configuration 6—FS15 coated—cable 900—1/16th inch thickness—thermoplastic.

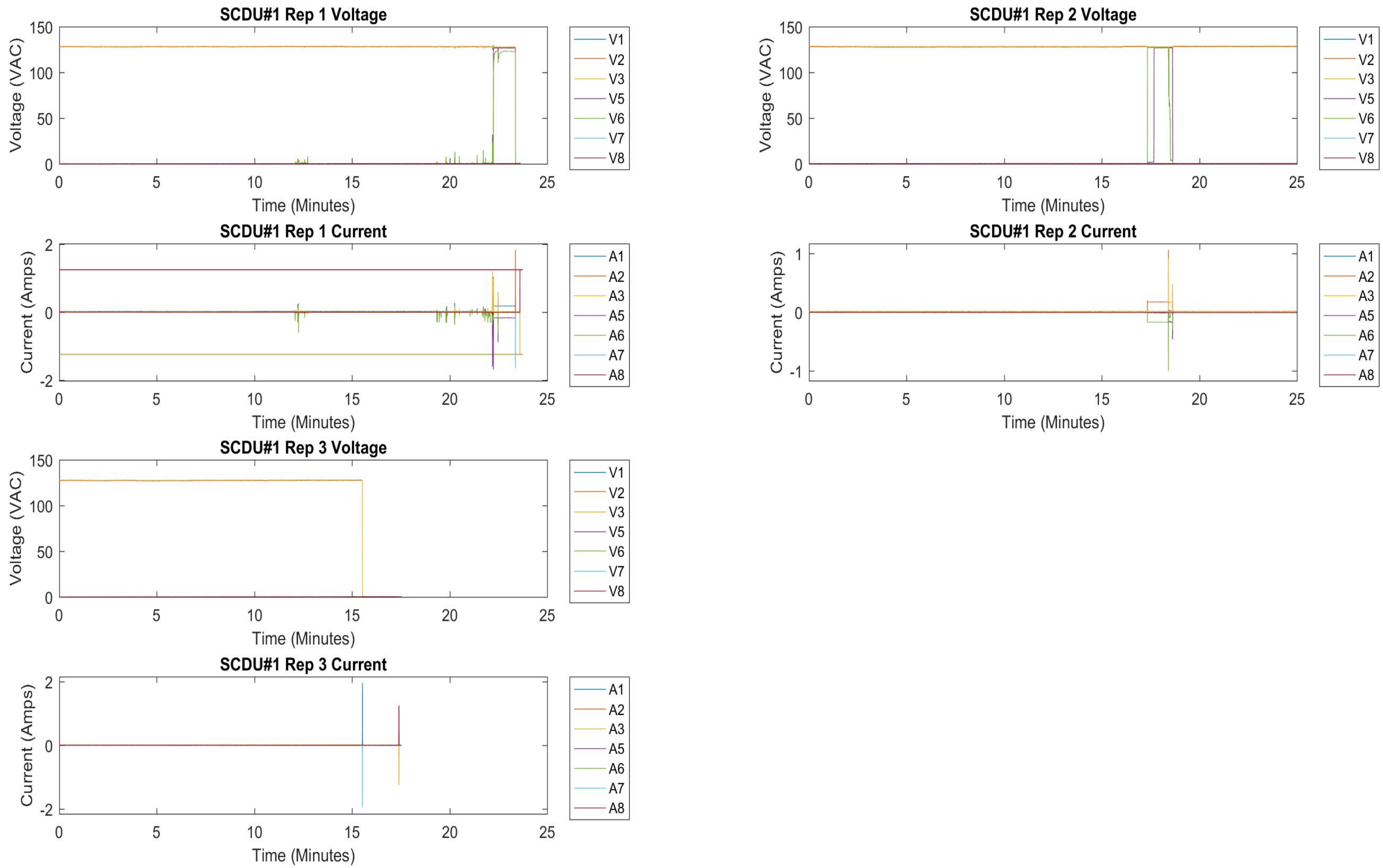


Figure B-14. Experiment configuration 7—FS15 coated—cable 900—1/8th inch thickness—thermoplastic.

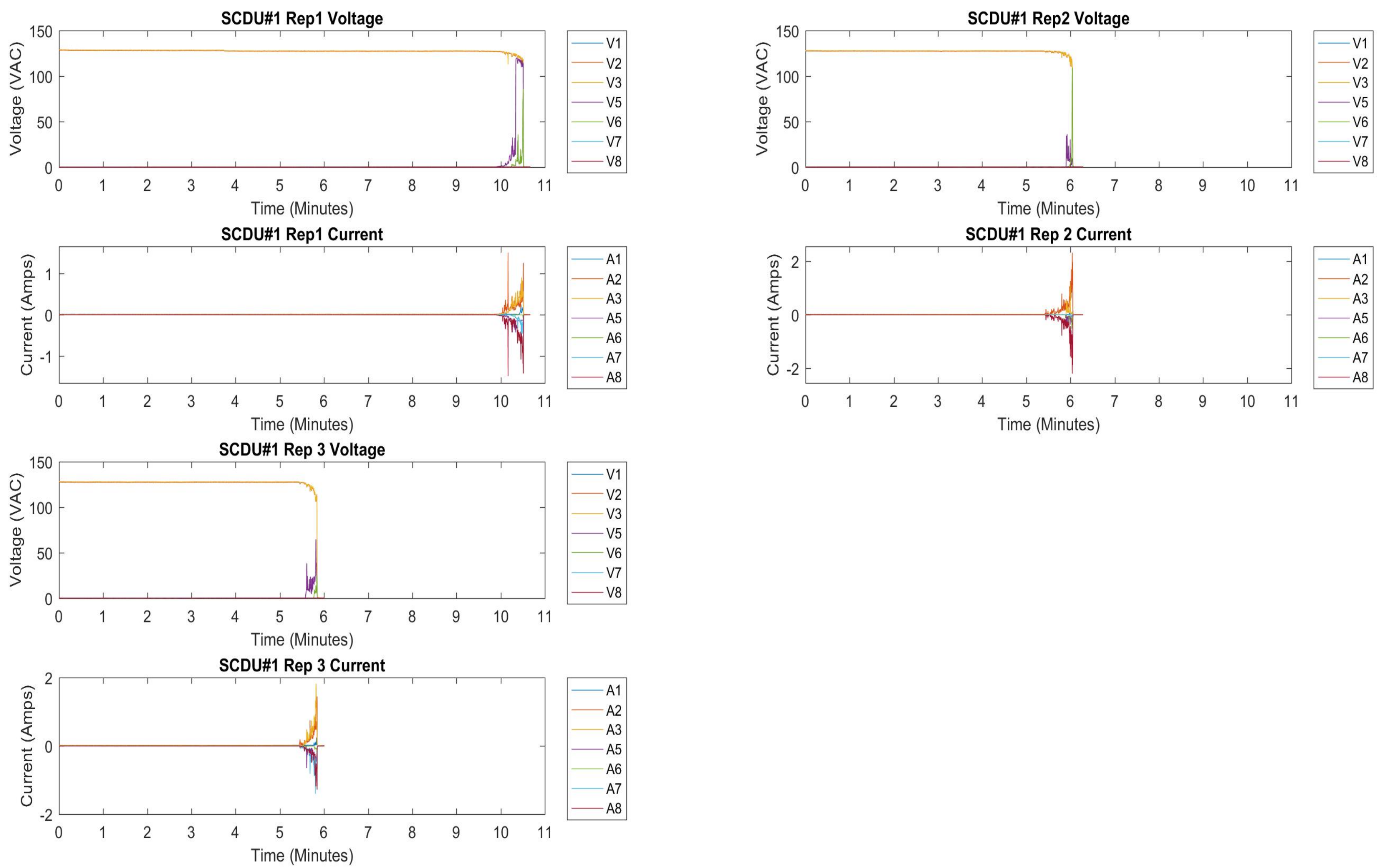


Figure B-15. Experiment configuration 15—FS15 coated—cable 813—1/16th inch thickness—thermoset.

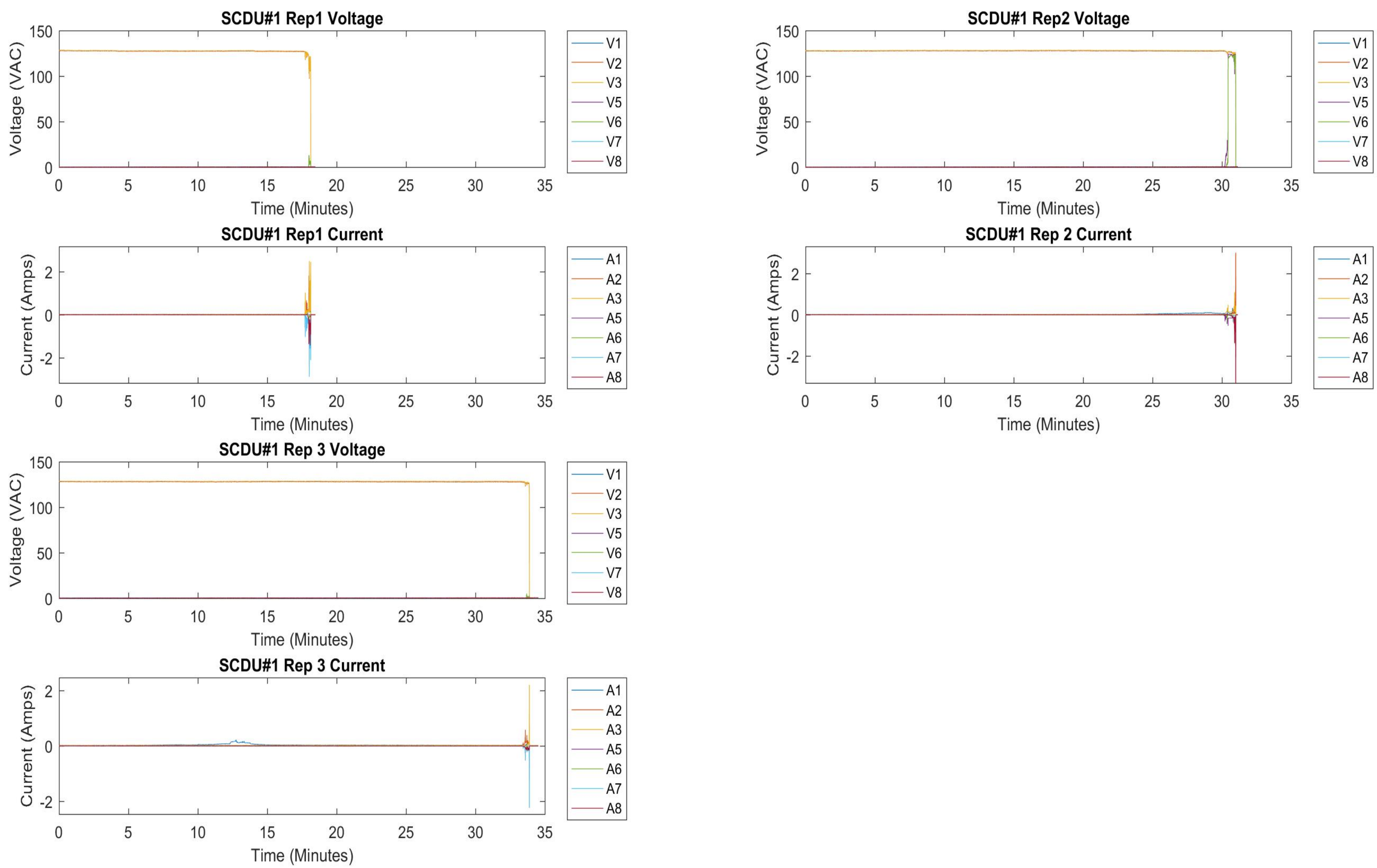


Figure B-16. Experiment configuration 16—FS15 coated—cable 813—1/8th inch thickness—thermoset.

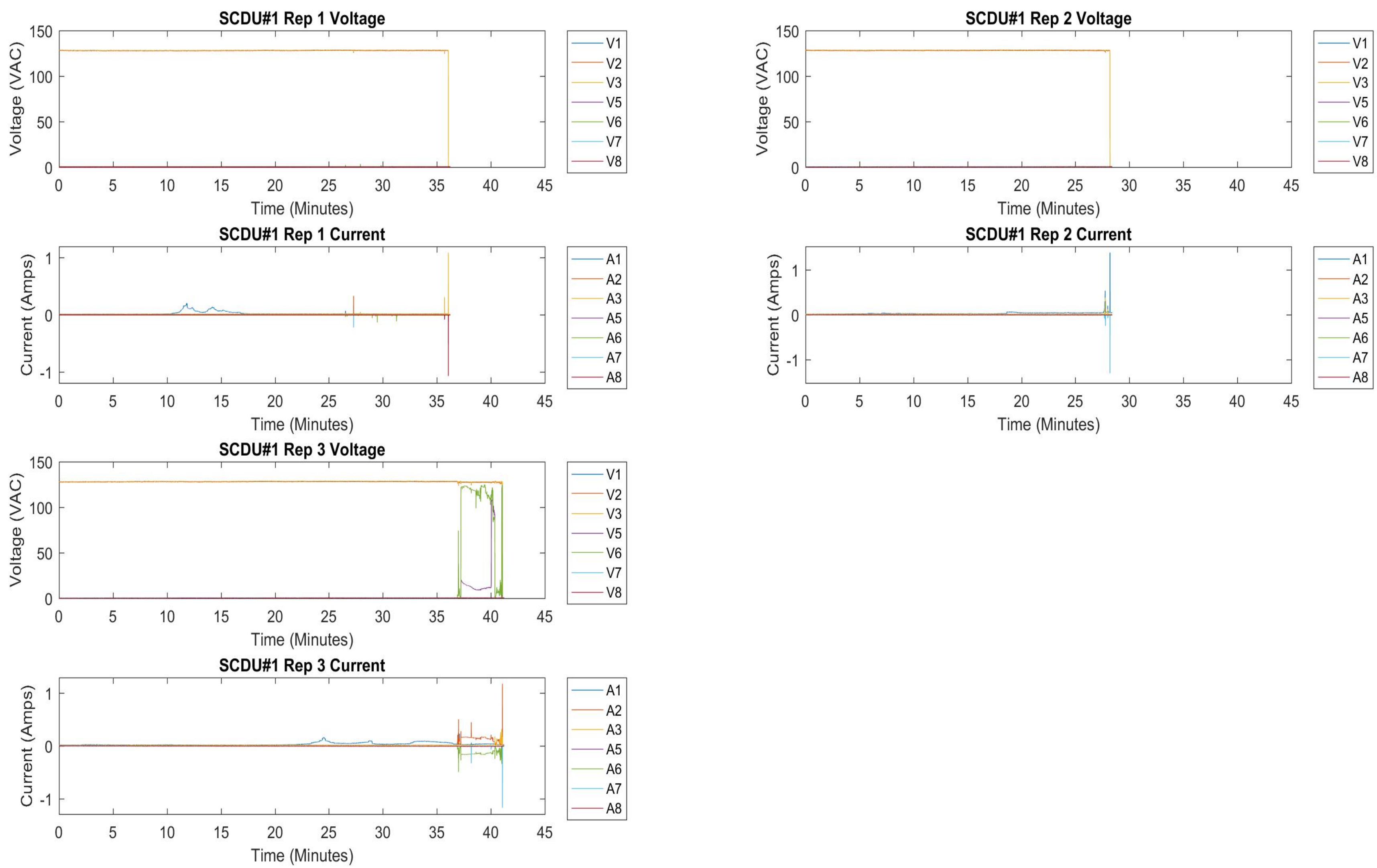


Figure B-17. Experiment configuration 8—Vimasco 3i coated—cable 900—1/16th inch thickness—thermoplastic.

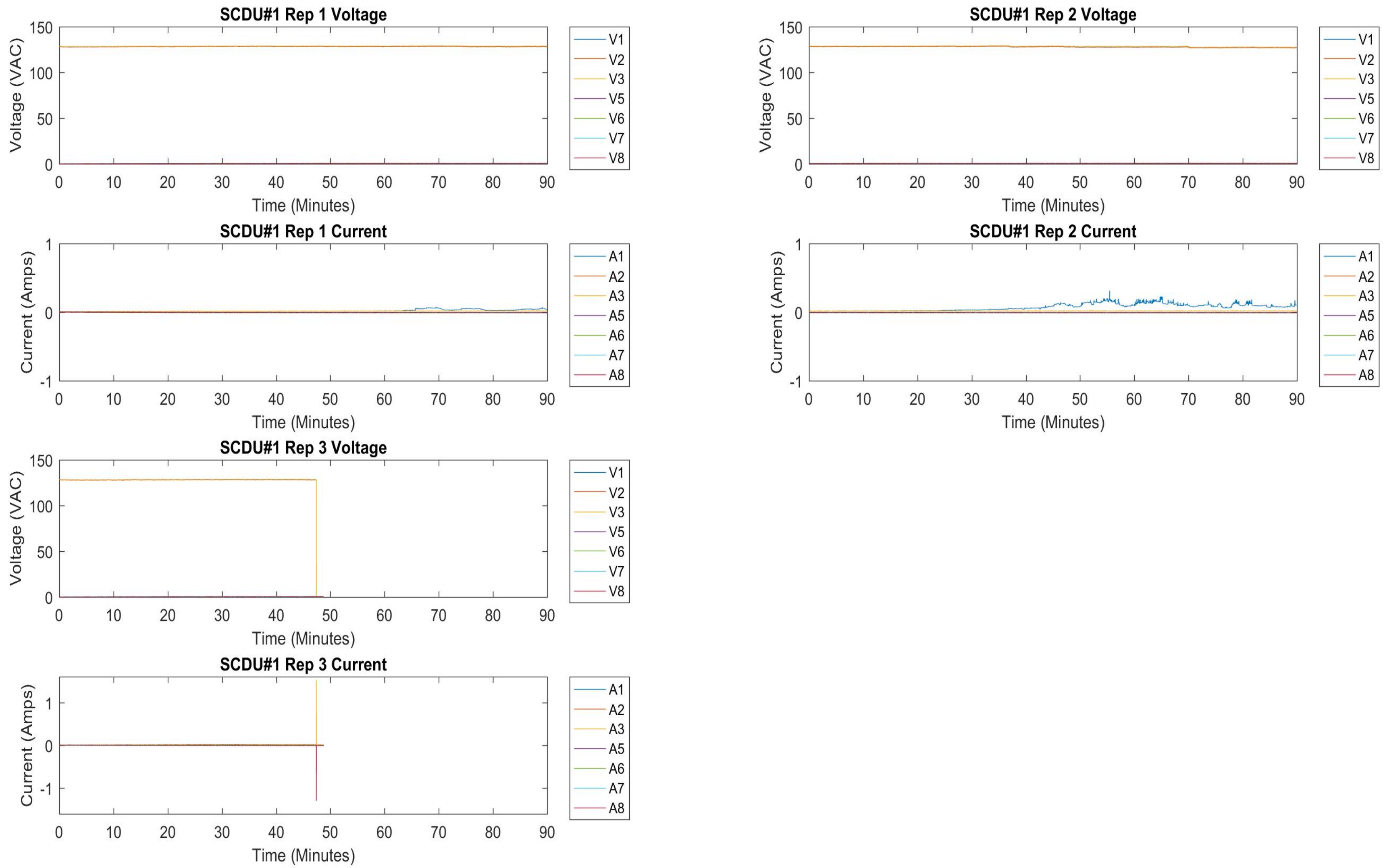


Figure B-18. Experiment configuration 9—Vimasco 3i coated—cable 900—1/8th inch thickness—thermoplastic.

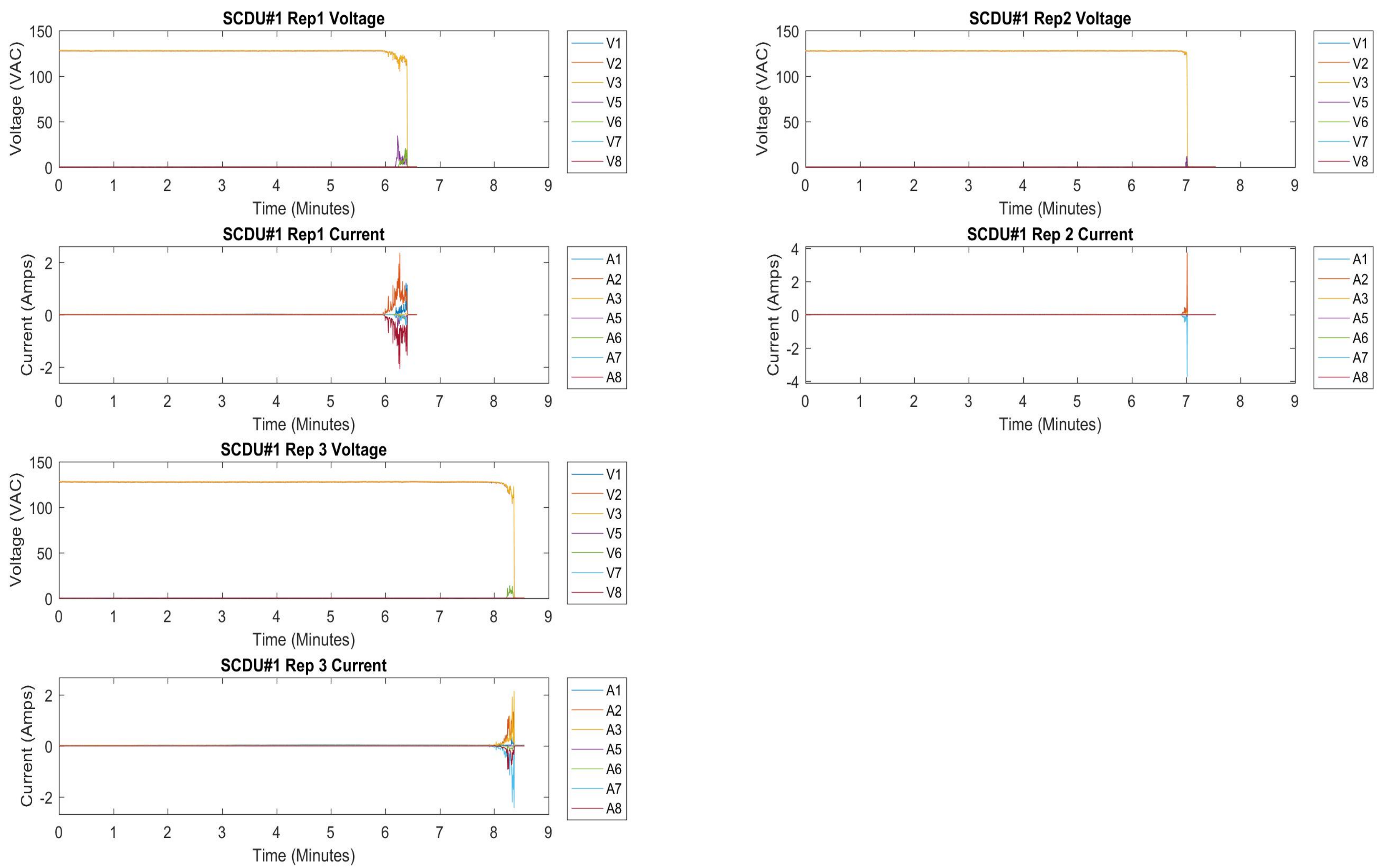


Figure B-19. Experiment configuration 17—Vimasco 3i coated—cable 813—1/16th inch thickness—thermoset.

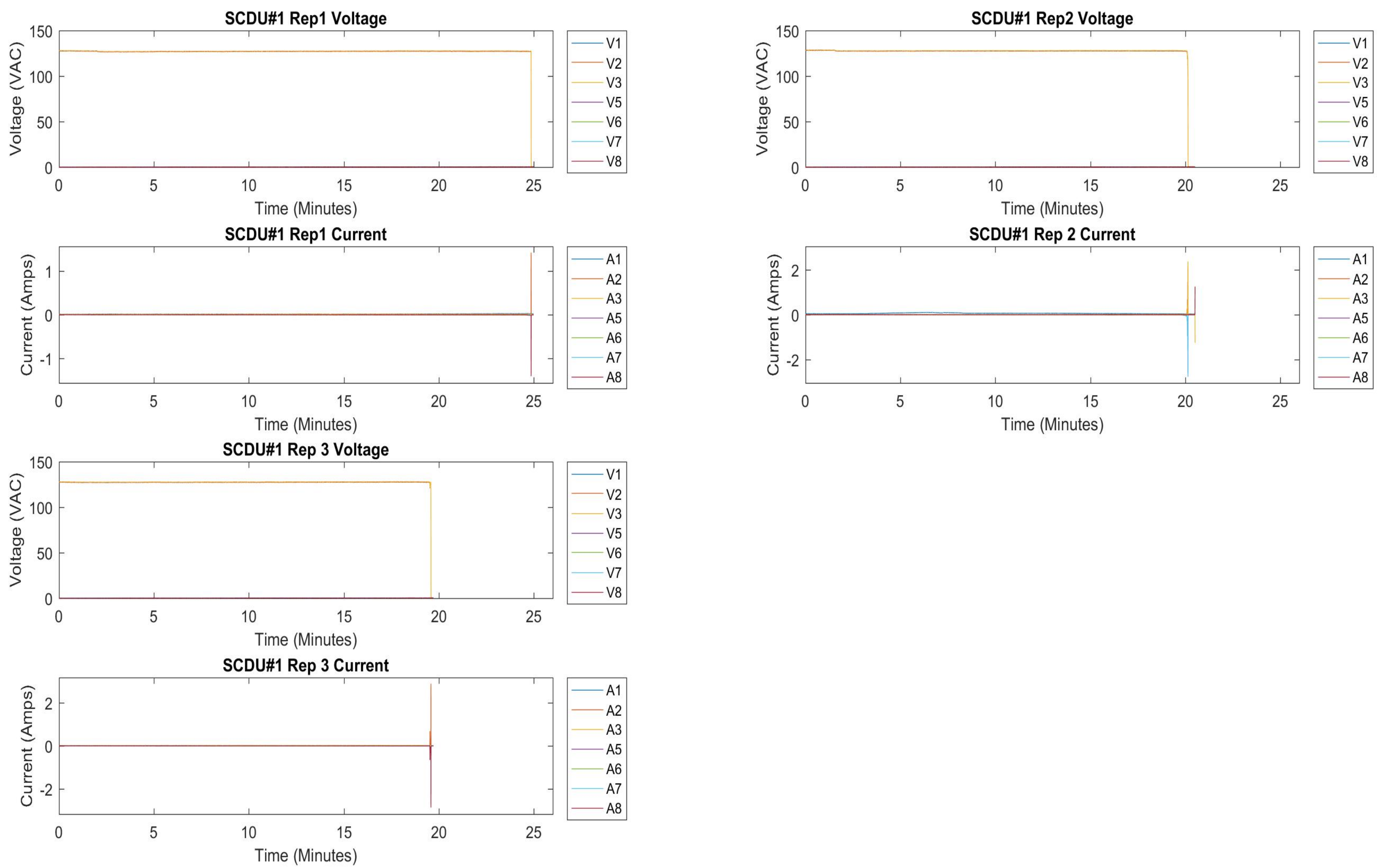


Figure B-20. Experiment configuration 18—Vimasco 3i coated—cable 813—1/8th inch thickness—thermoset.

B.2 Vertical Circuit Integrity Experiment Results

The failure times reported in section 6 were obtained from the data collected from the SCDU. The data from the SCDU are plotted below. Voltages are identified as V1 through V8. Currents are identified as A1 through A8.

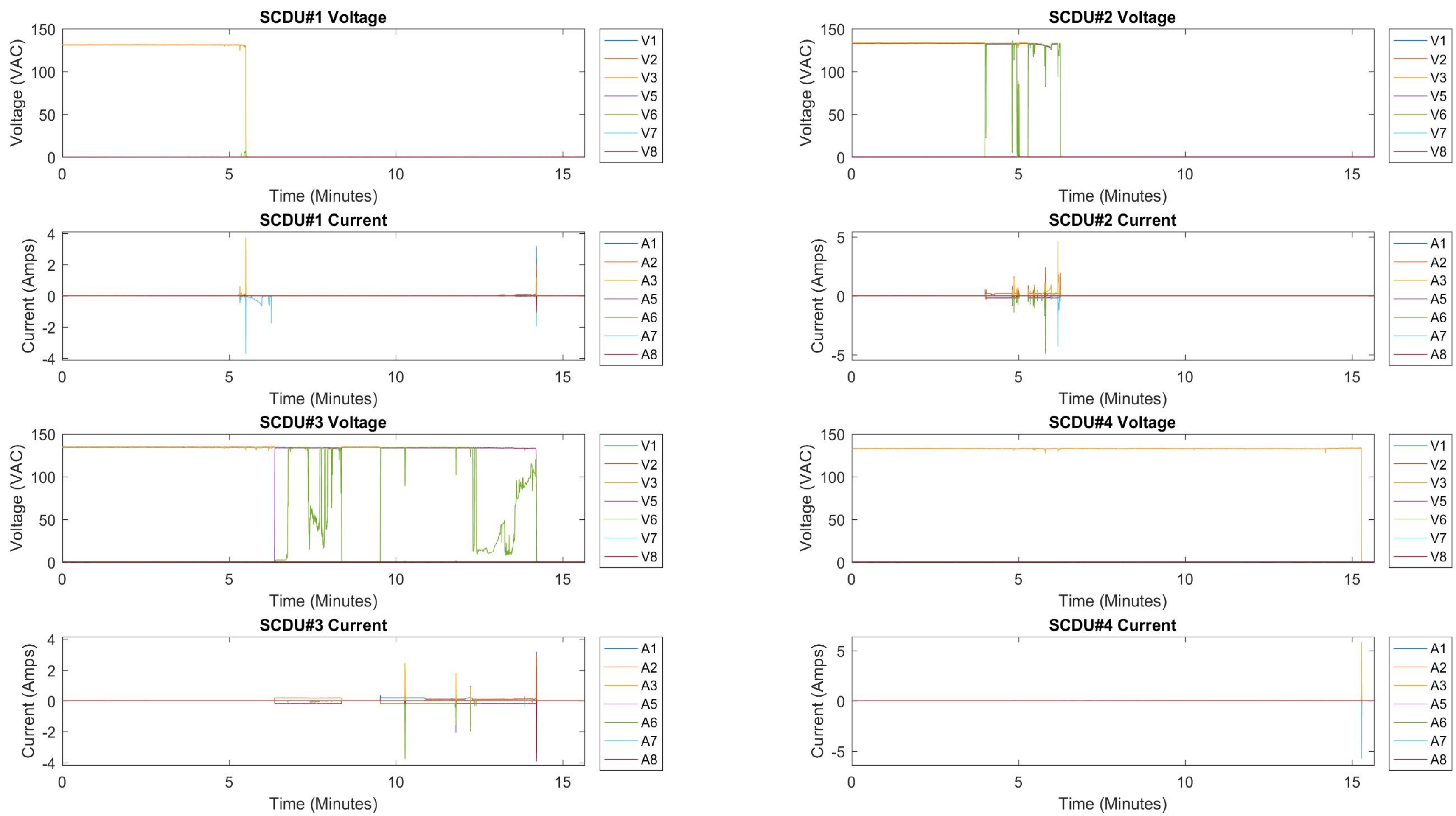


Figure B-21. Experiment II-1—vertical flame spread experiments—bare cable—cable 900—thermoplastic.

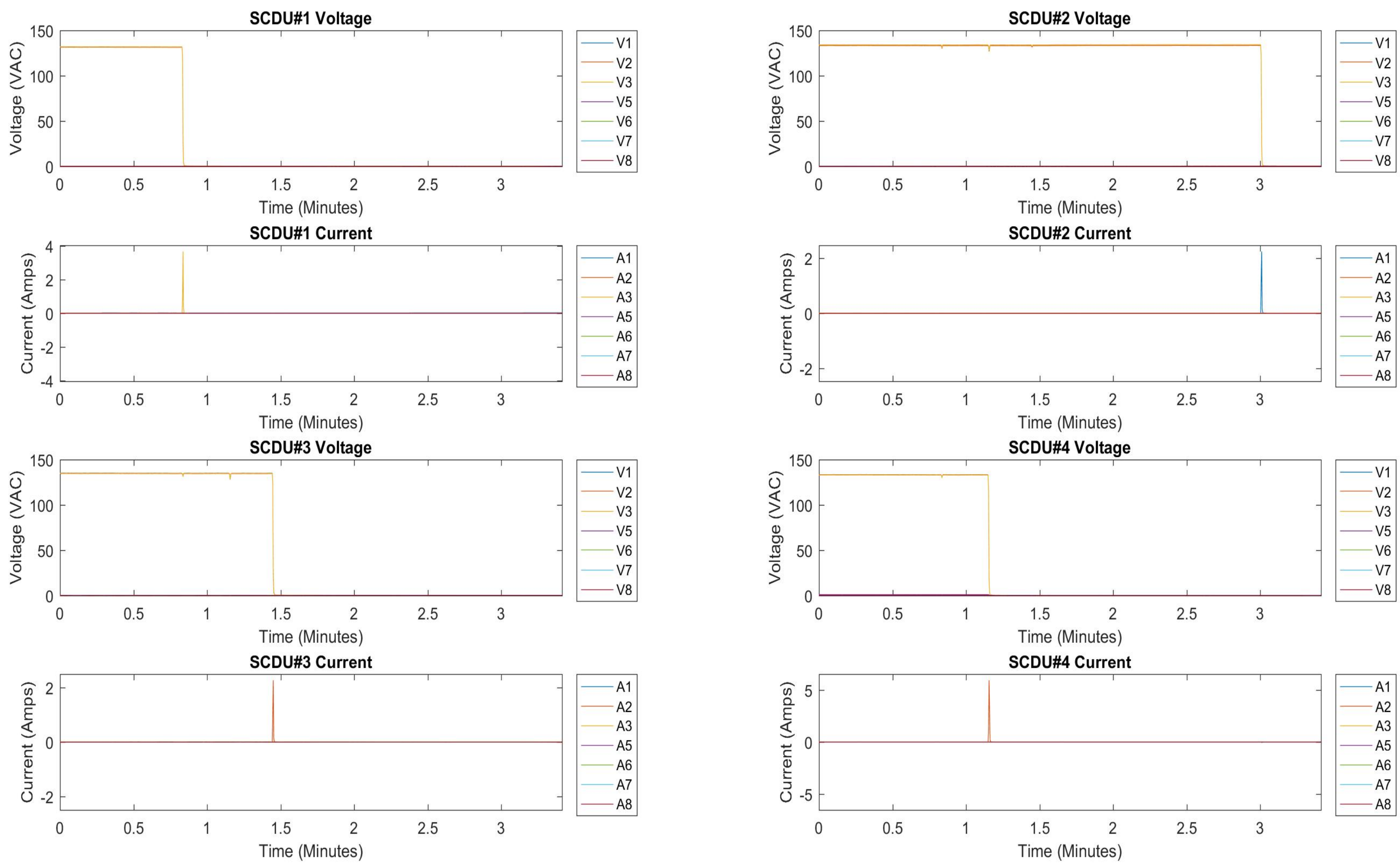


Figure B-22. Experiment II-12—vertical flame spread experiments—bare cable—cable 900—thermoplastic.

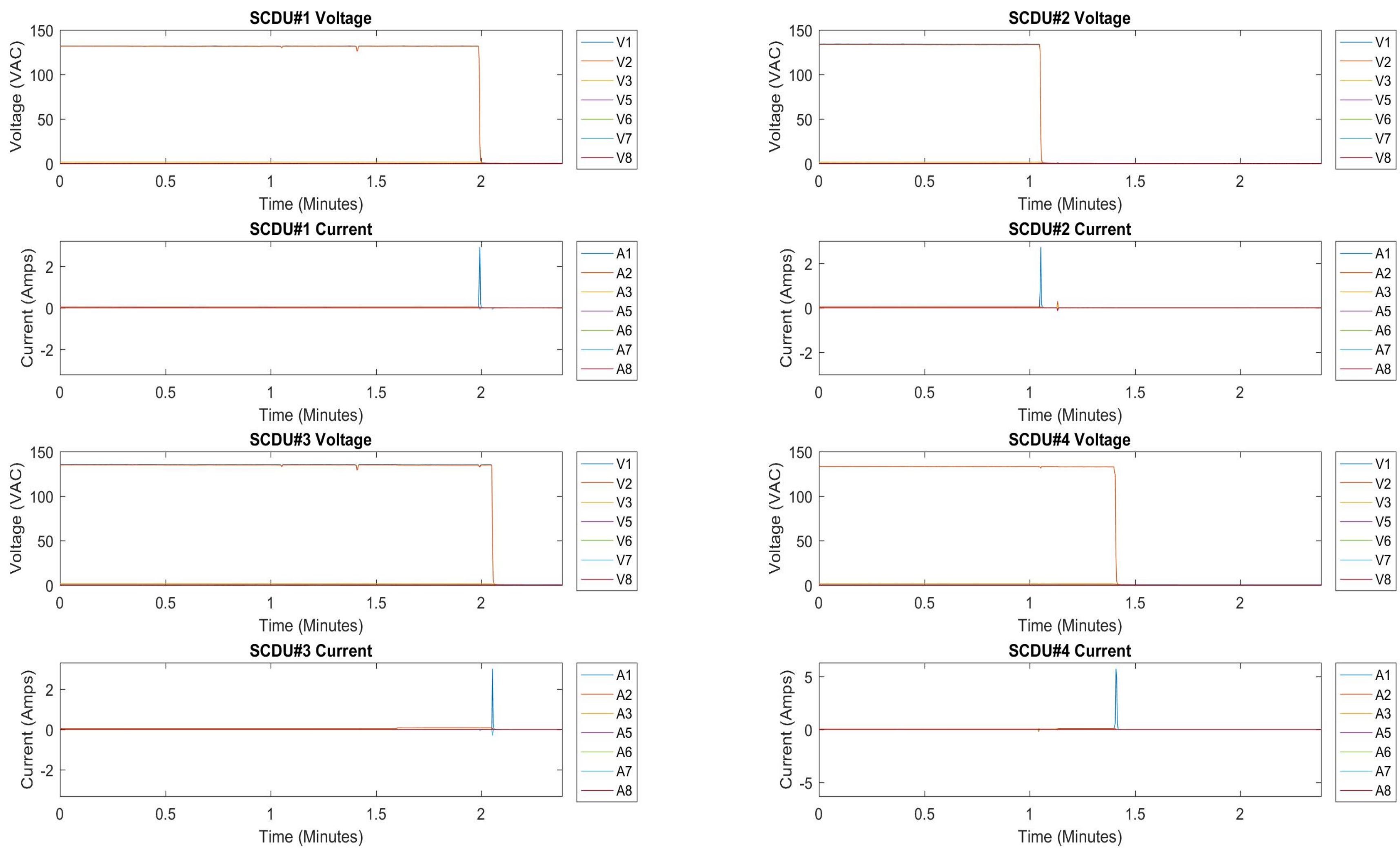


Figure B-23. Experiment II-7—vertical flame spread experiments—bare cable—cable 902—thermoplastic.

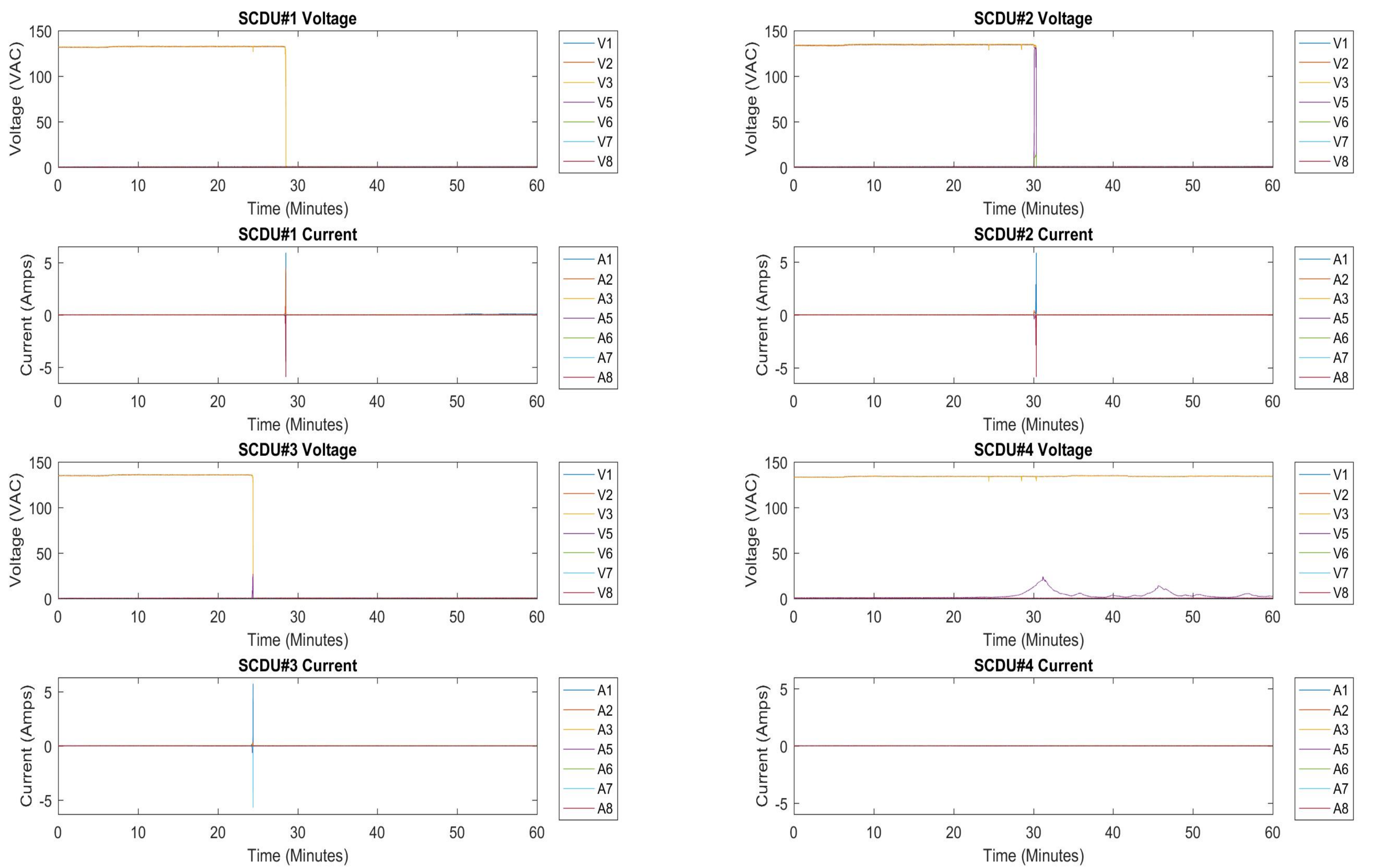


Figure B-24. Experiment II-6—vertical flame spread experiments—bare cable—cable 813—thermoset.

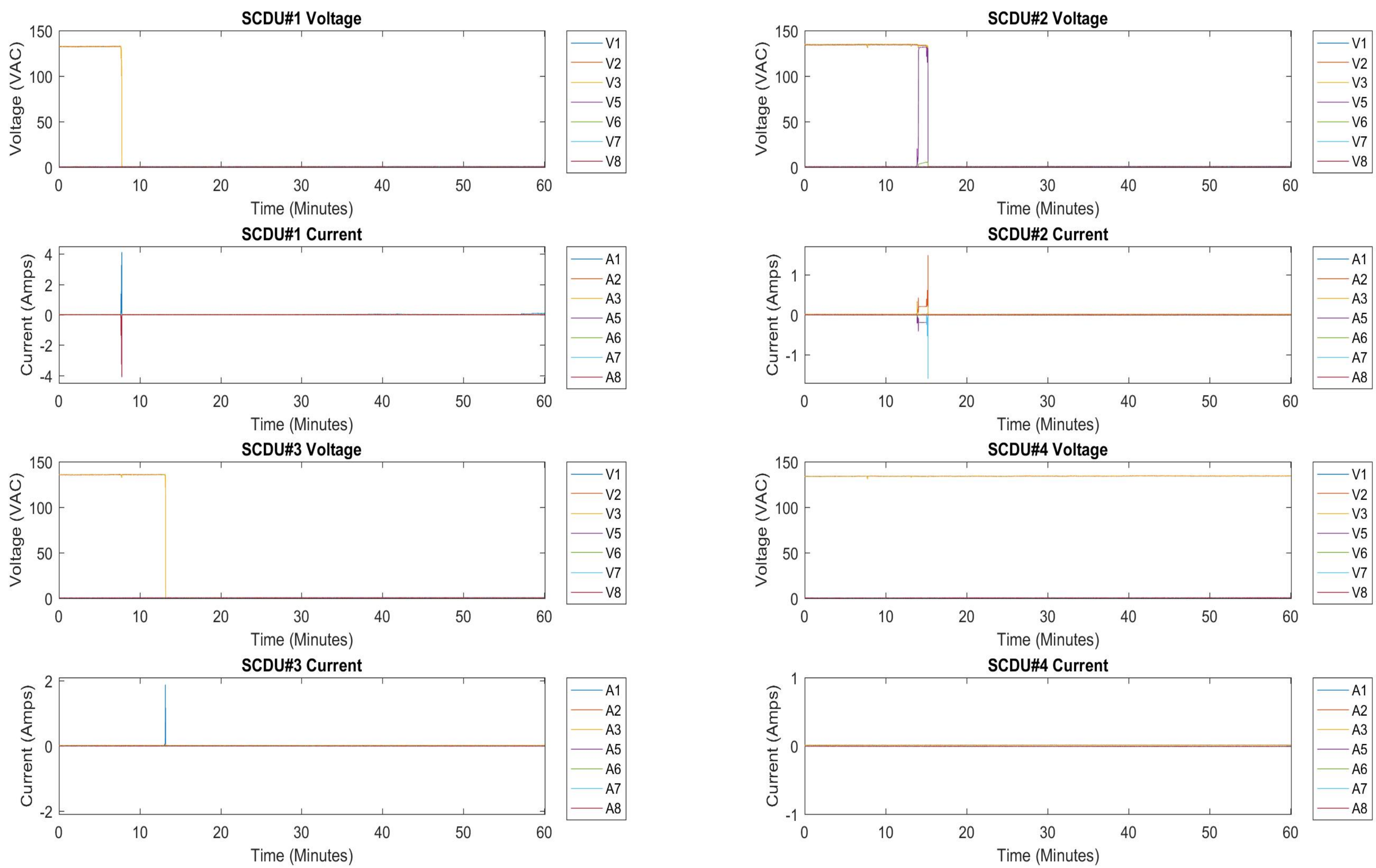


Figure B-25. Experiment II-18—vertical flame spread experiments—bare cable—cable 813—thermoset.

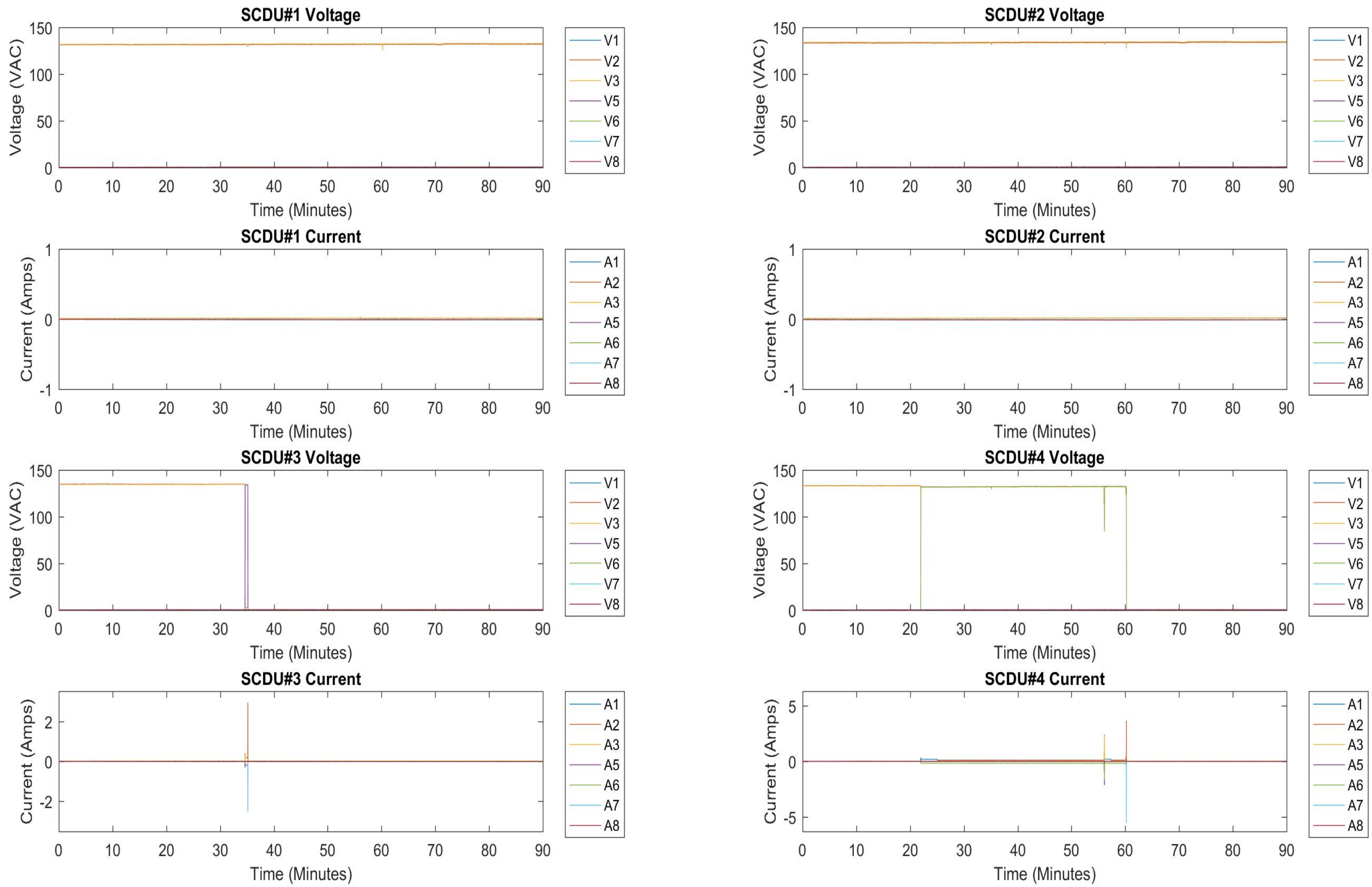


Figure B-26. Experiment II-2—vertical flame spread experiments—FS15 coated—cable 900—thermoplastic.

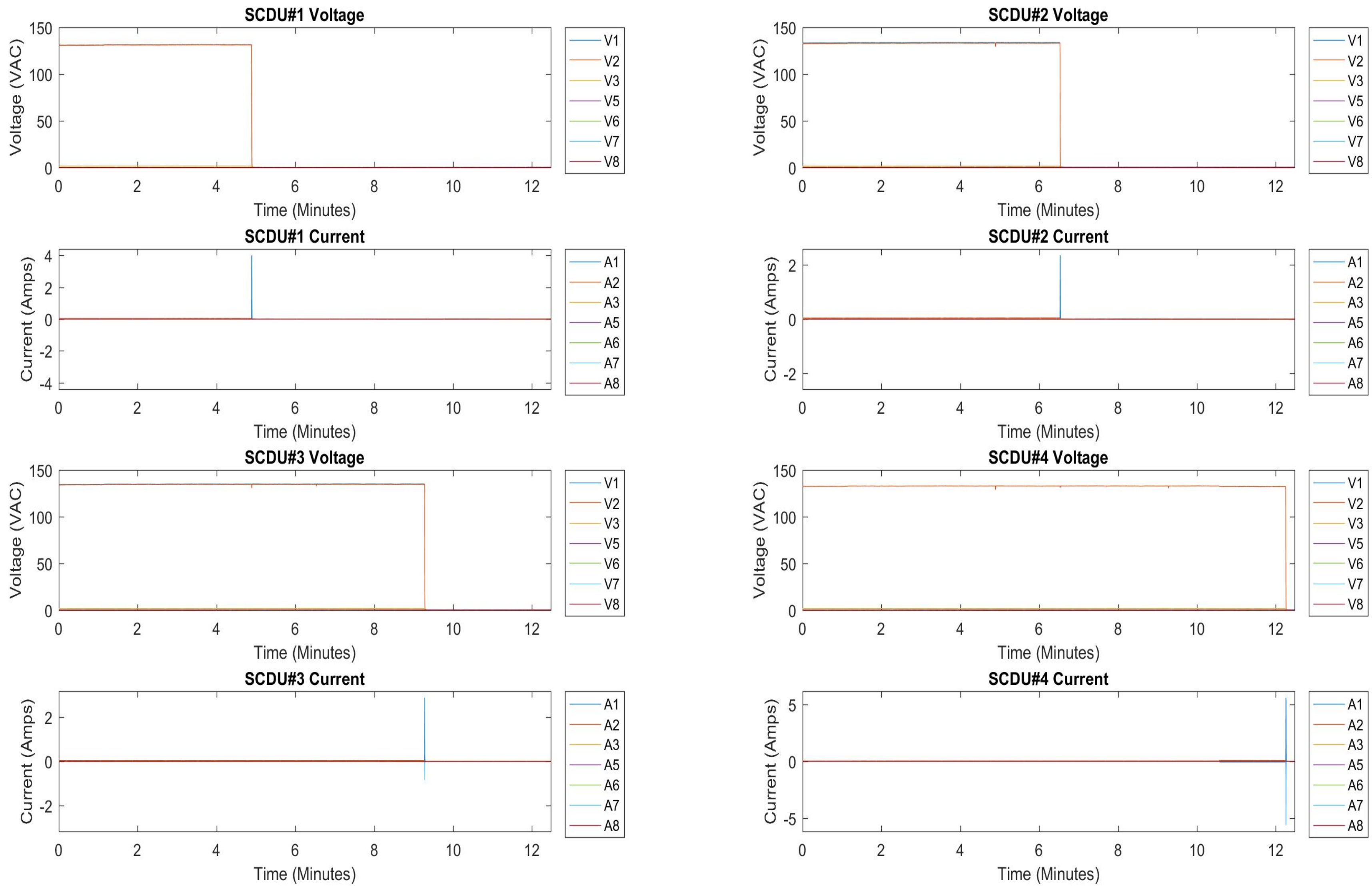


Figure B-27. Experiment II-8—vertical flame spread experiments—FS15 coated—cable 900—thermoplastic.

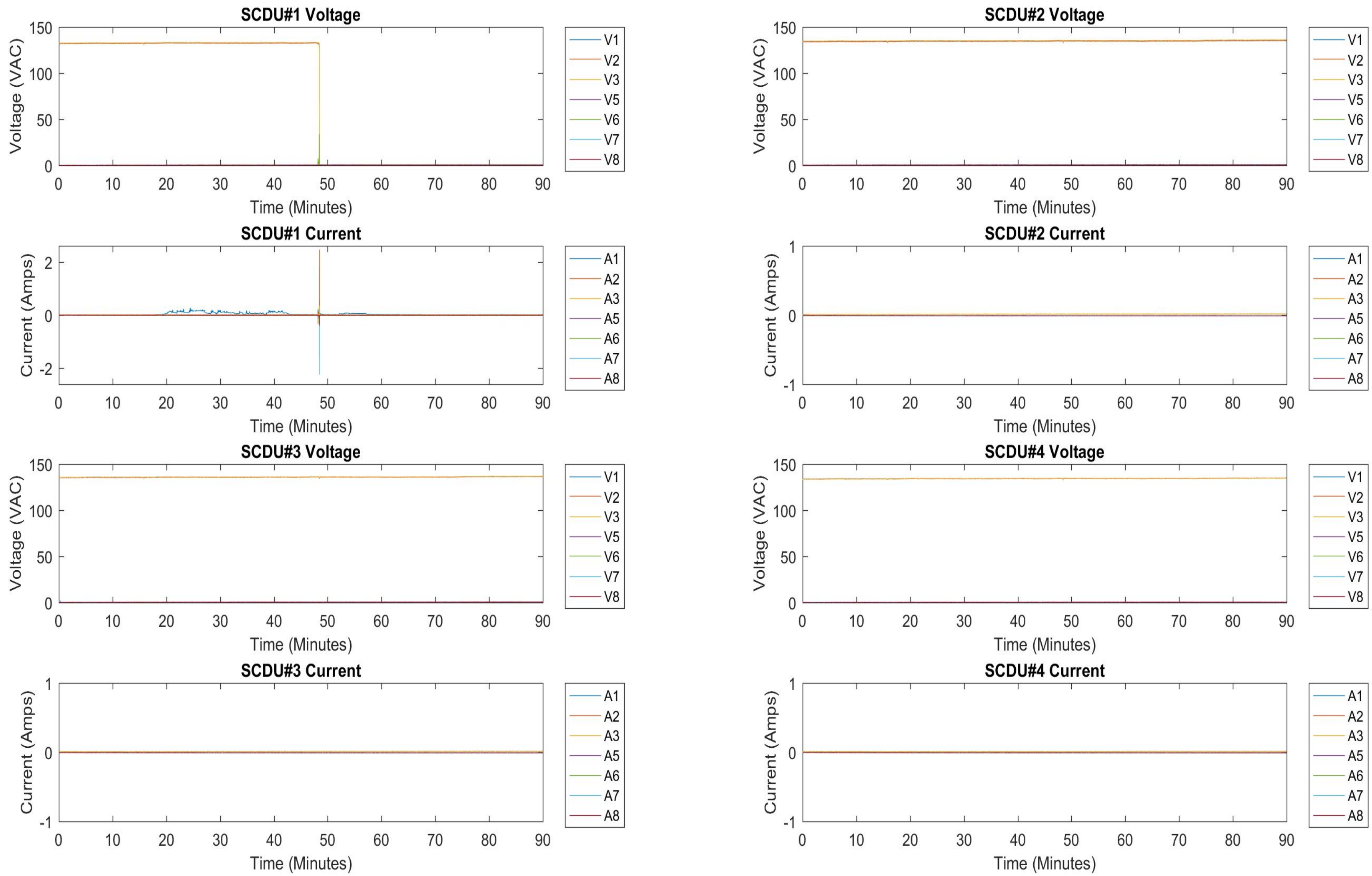


Figure B-28. Experiment II-16—vertical flame spread experiments—FS15 coated—cable 813—thermoset.

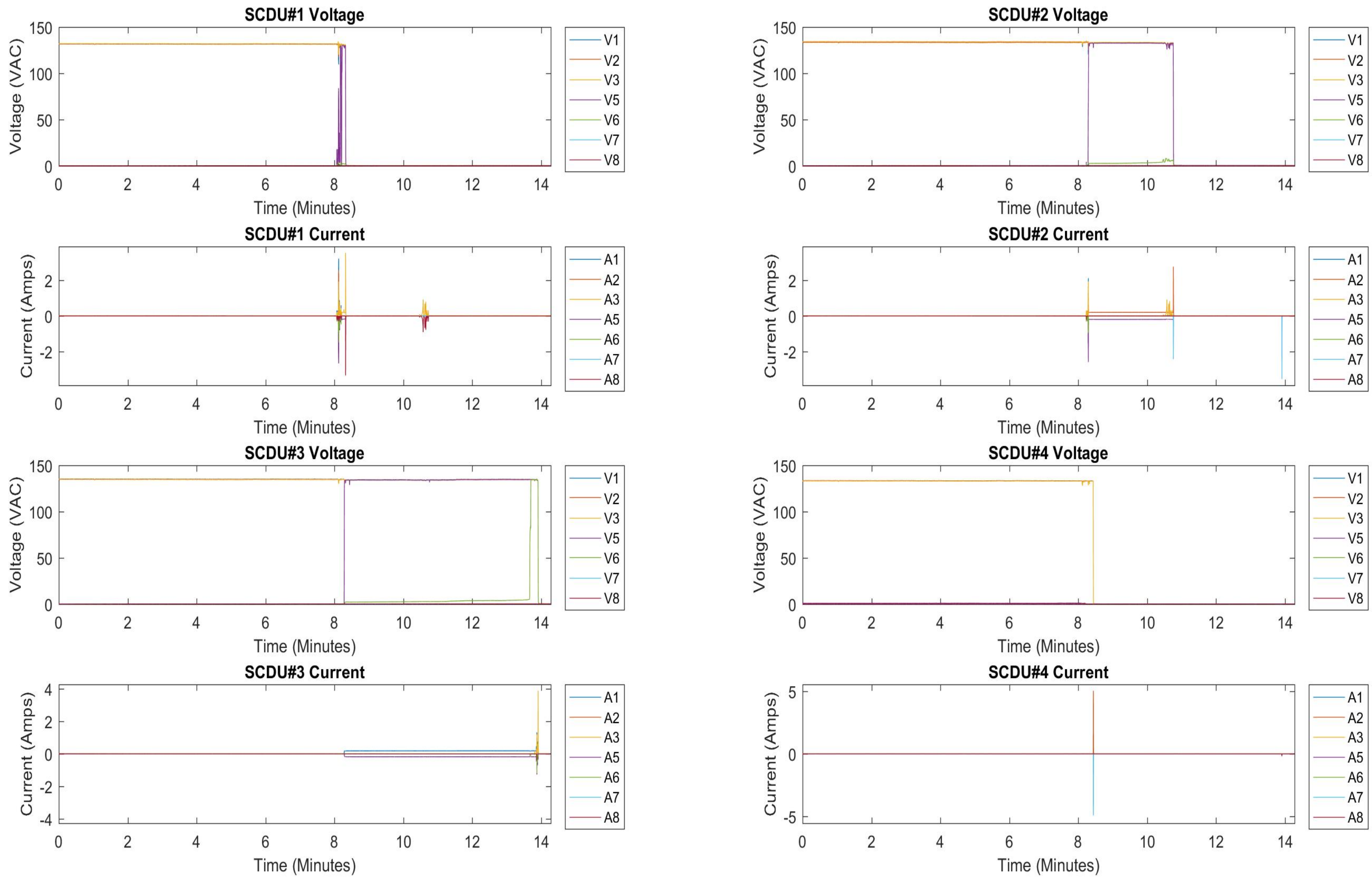


Figure B-29. Experiment II-3—vertical flame spread experiments—Flamemastic 77—cable 900—thermoplastic.

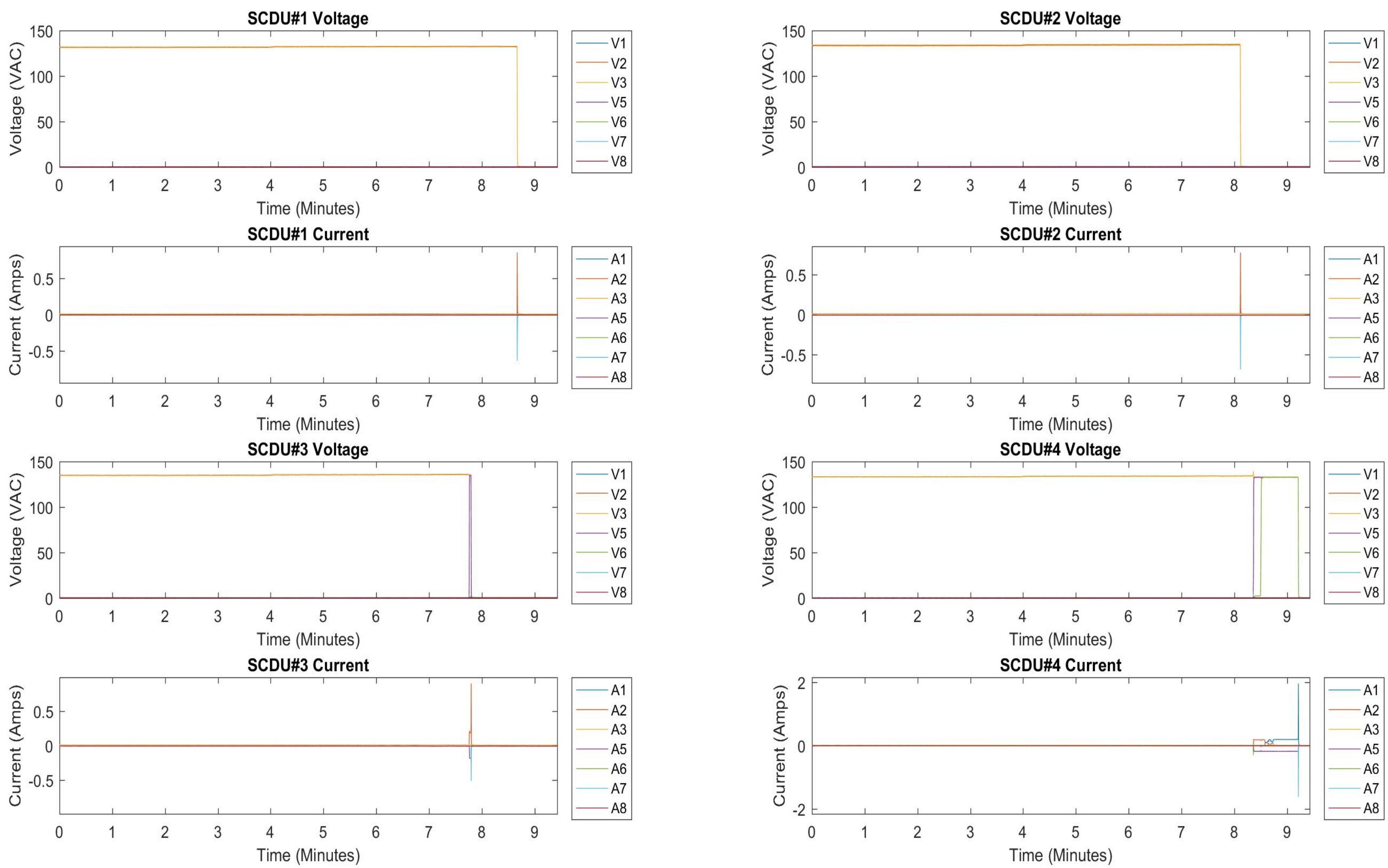


Figure B-30. Experiment II-14—vertical flame spread experiments—Flameastic 77—cable 900—thermoplastic.

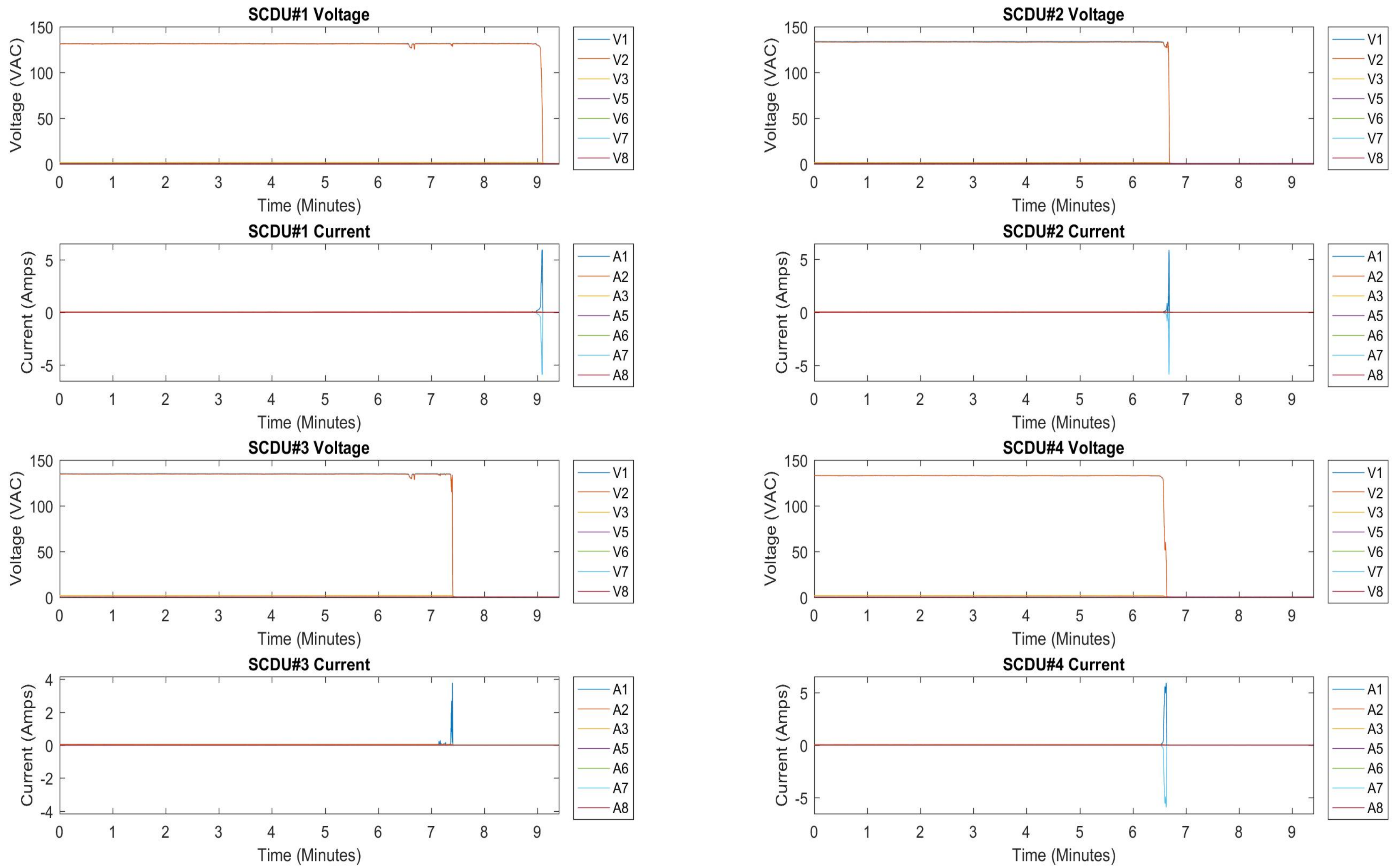


Figure B-31. Experiment II-9—vertical flame spread experiments—Flamemastic 77—cable 902—thermoplastic.

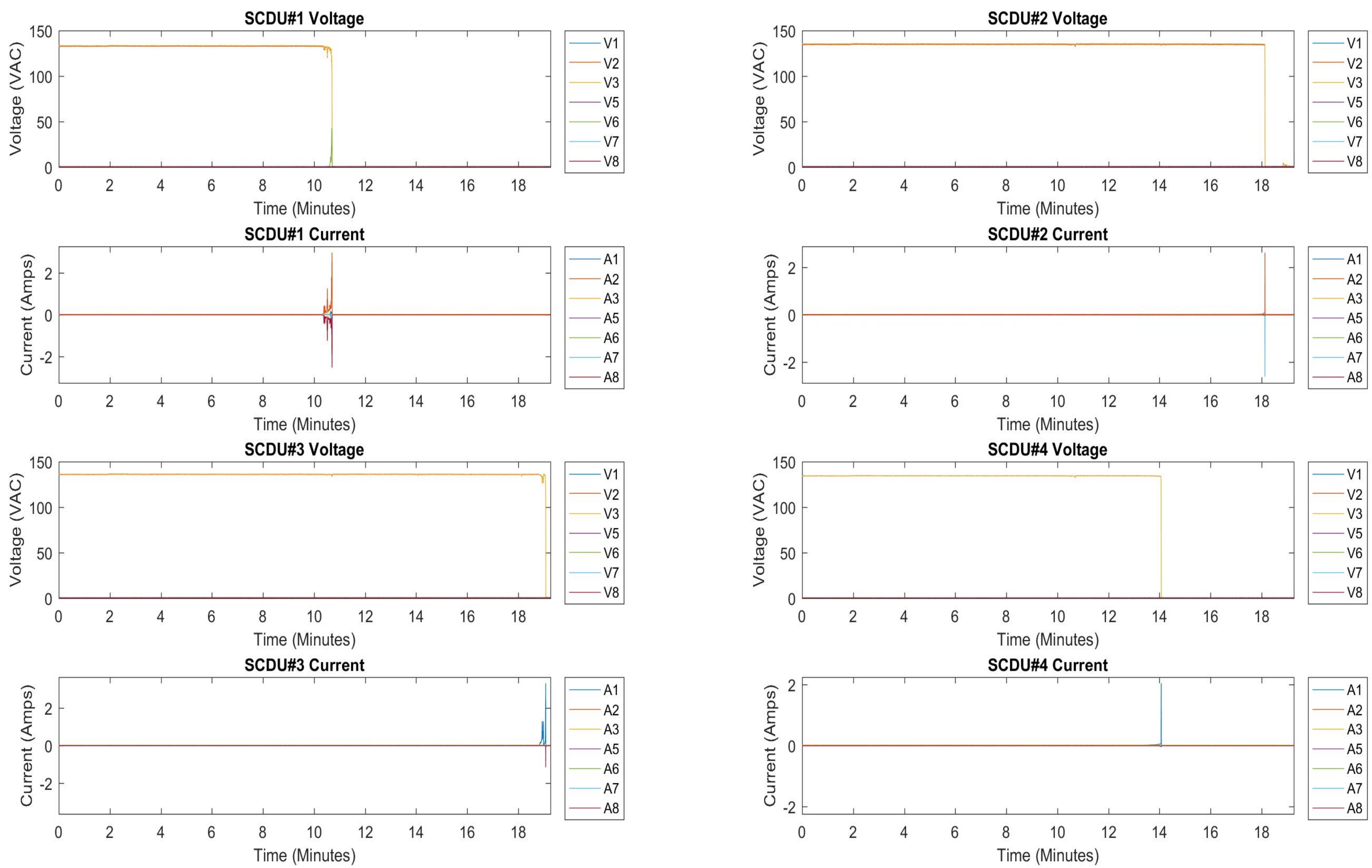


Figure B-32. Experiment II-20—vertical flame spread experiments—Flamemastic 77—cable 813—thermoset.

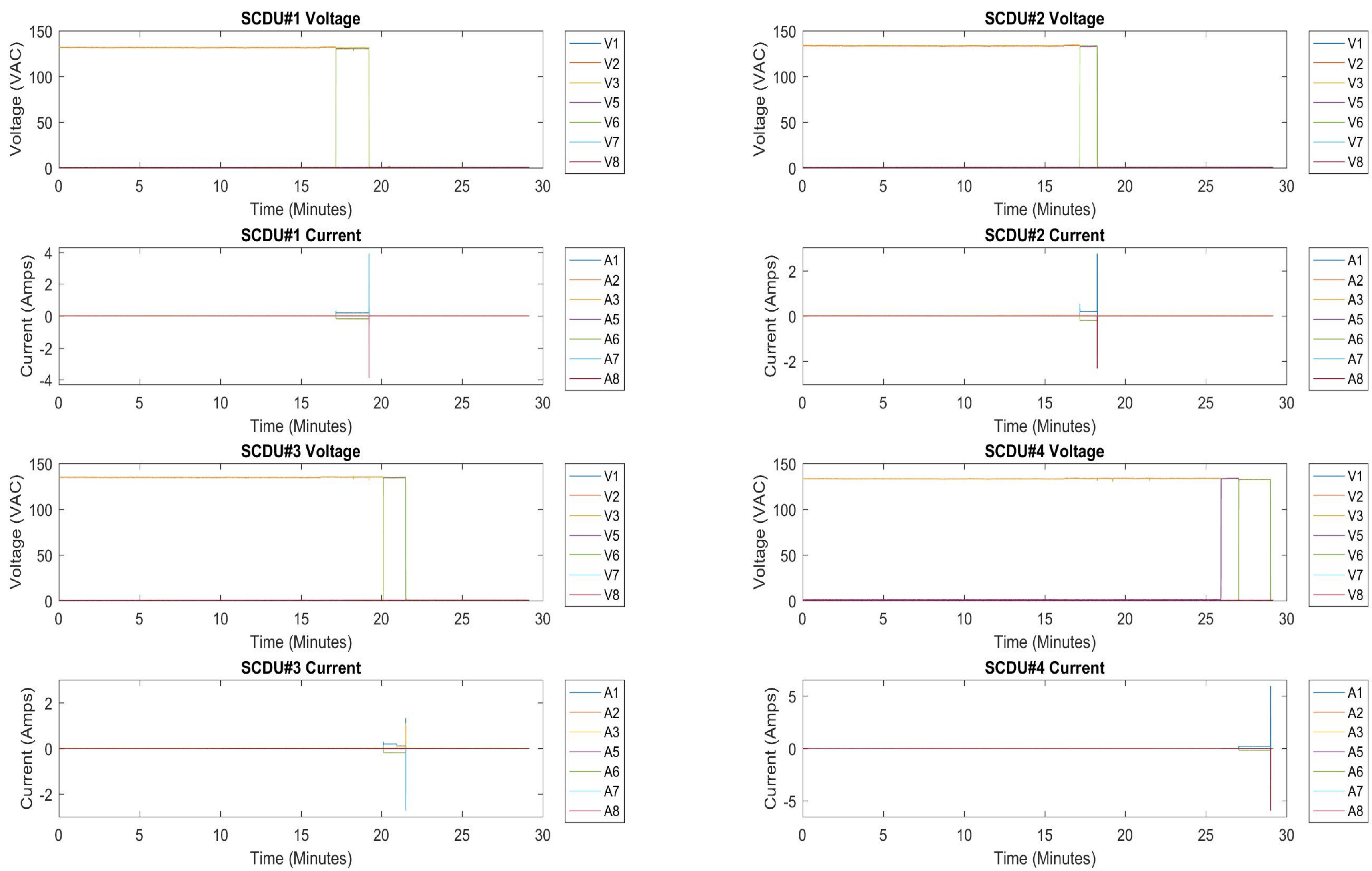


Figure B-33. Experiment II-4—vertical flame spread experiments—Vimasco 3i—cable 900—thermoplastic.

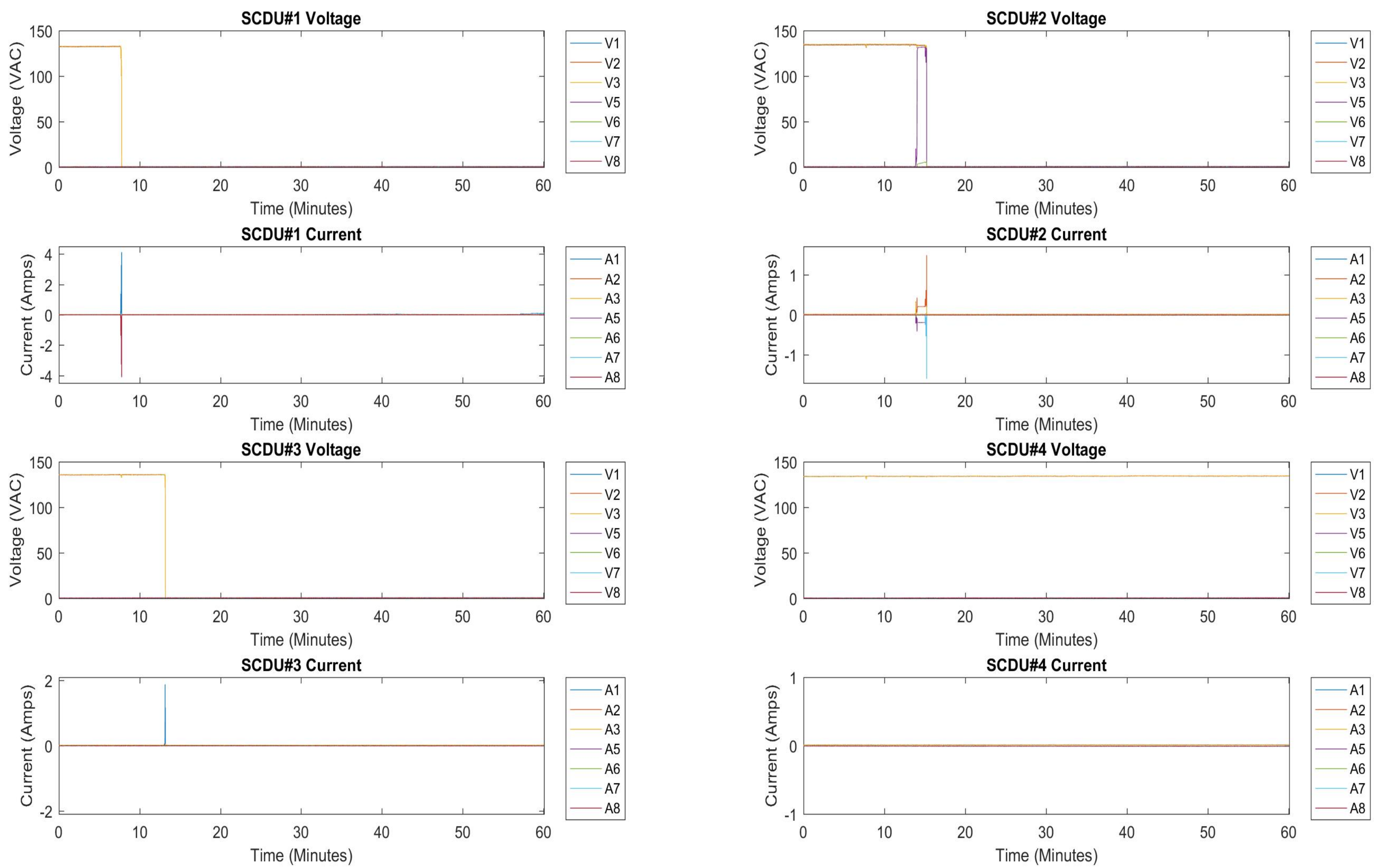


Figure B-34. Experiment II-13—vertical flame spread experiments—Vimasco 3i—cable 900—thermoplastic.

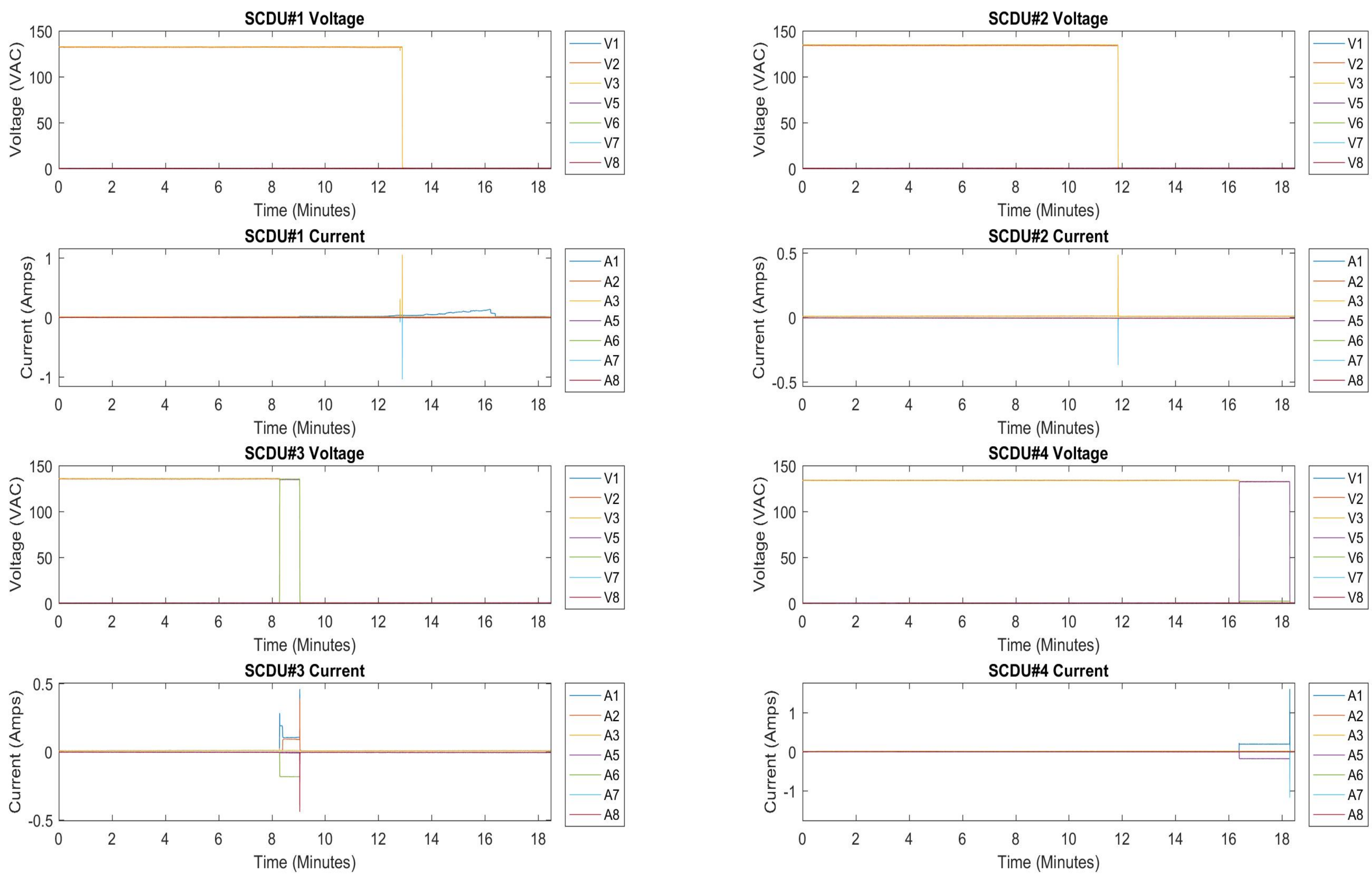


Figure B-35. Experiment II-15—vertical flame spread experiments—Vimasco 3i—cable 900—thermoplastic.

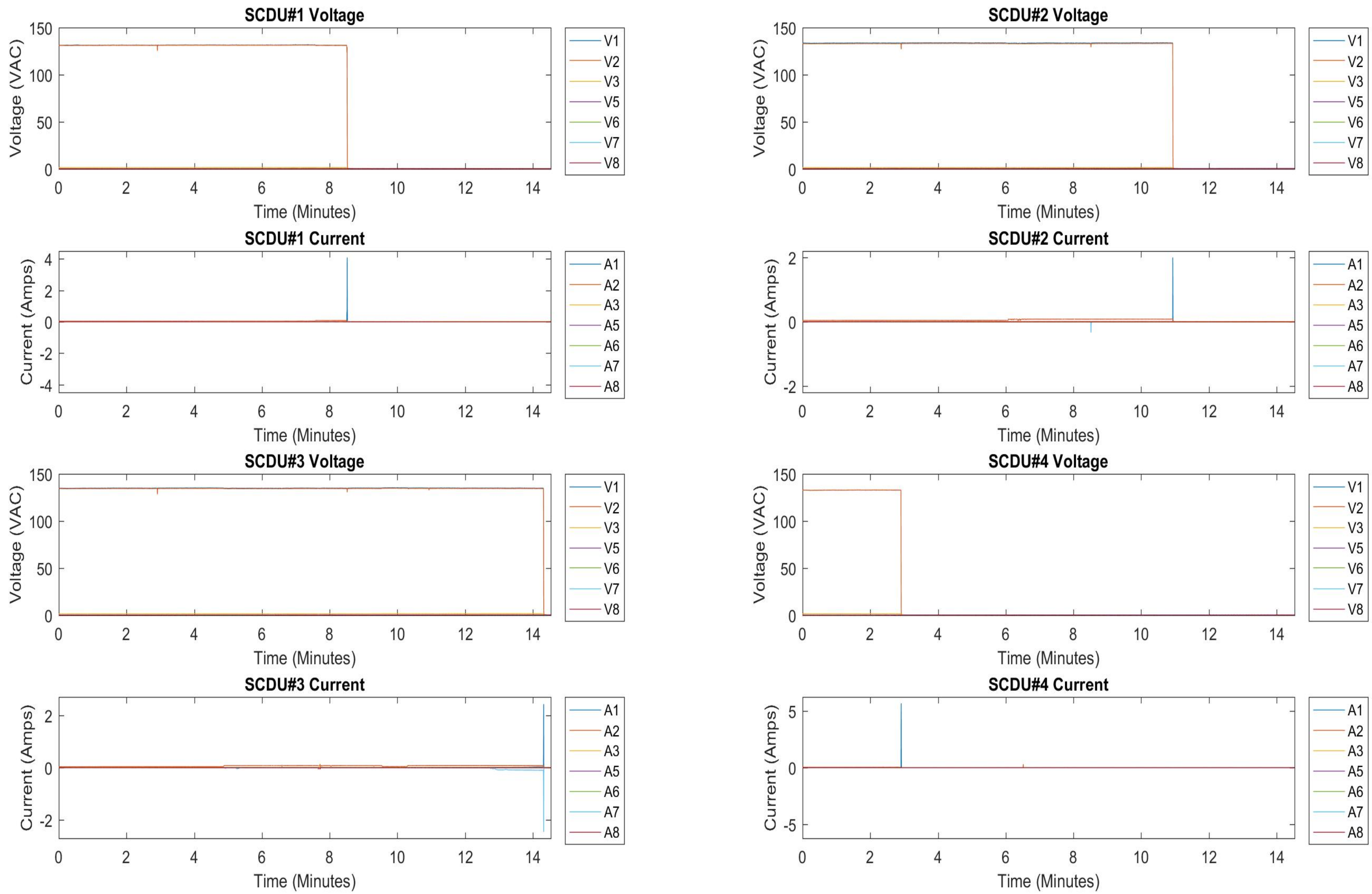


Figure B-36. Experiment II-10—vertical flame spread experiments—Vimasco 3i—cable 902—thermoplastic.

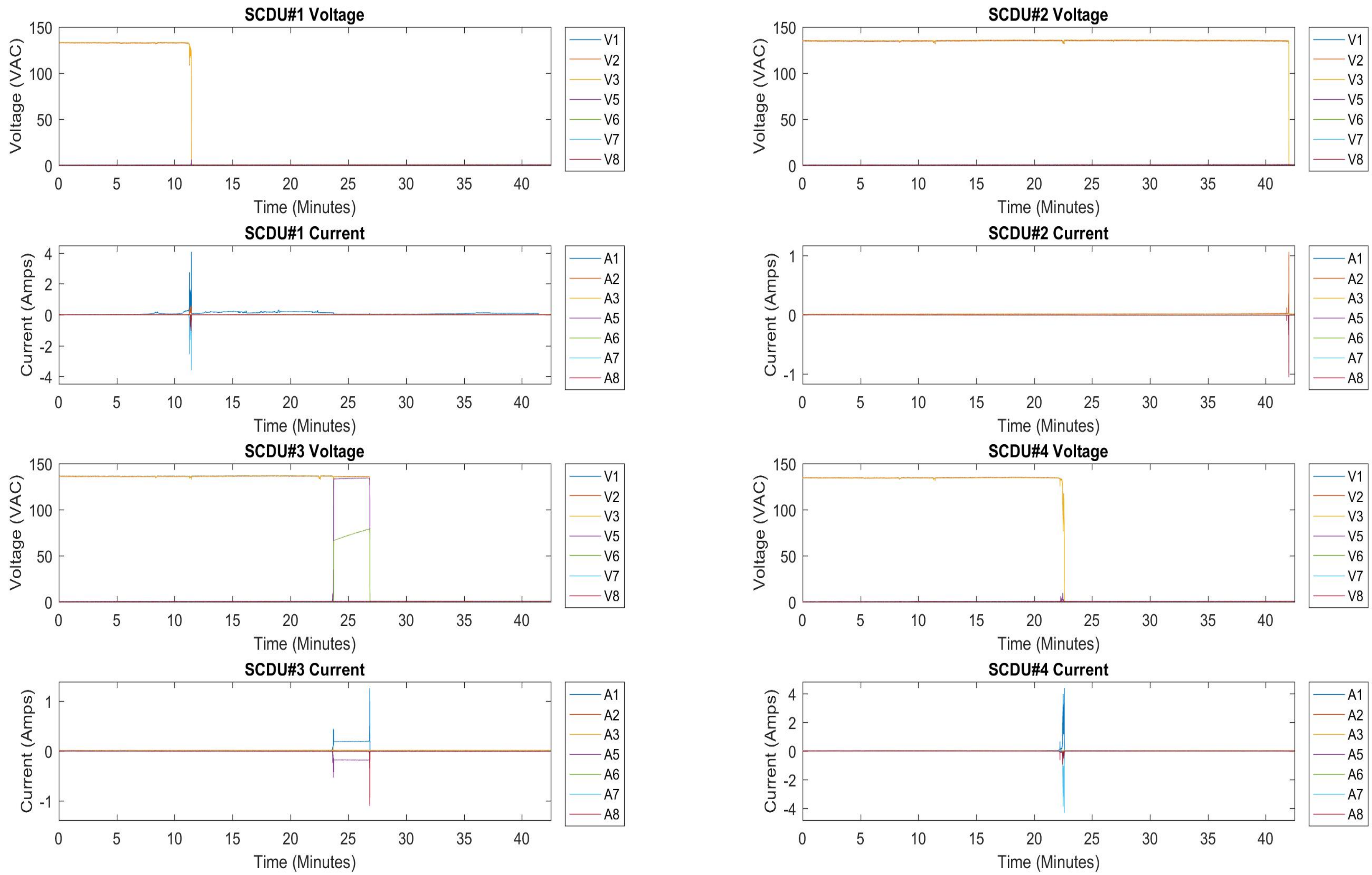


Figure B-37. Experiment II-17—vertical flame spread experiments—Vimasco 3i—cable 813—thermoset.

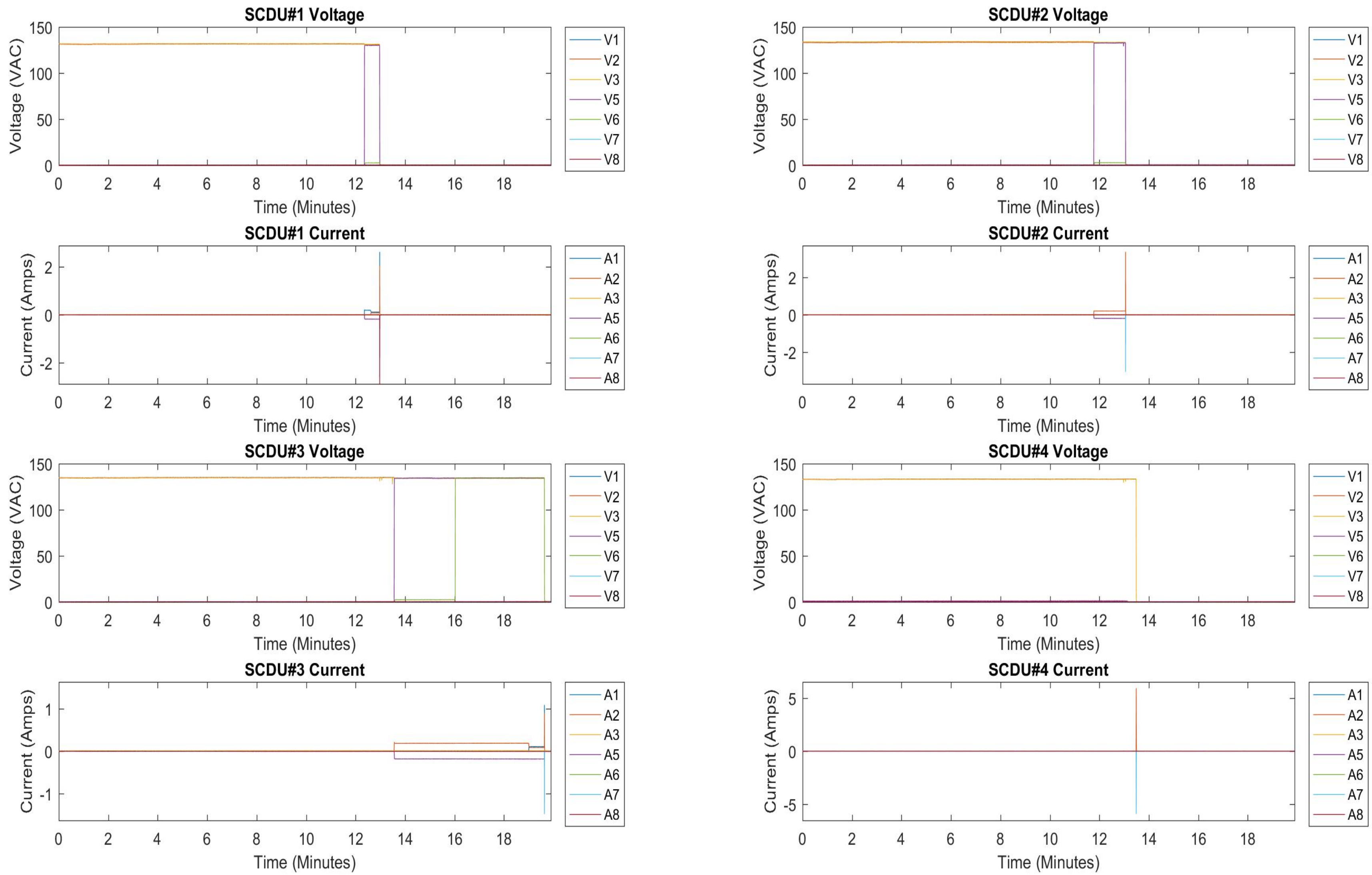


Figure B-38. Experiment II-5—vertical flame spread experiments—Carboline Intumastic 285 coated—cable 900—thermoplastic.

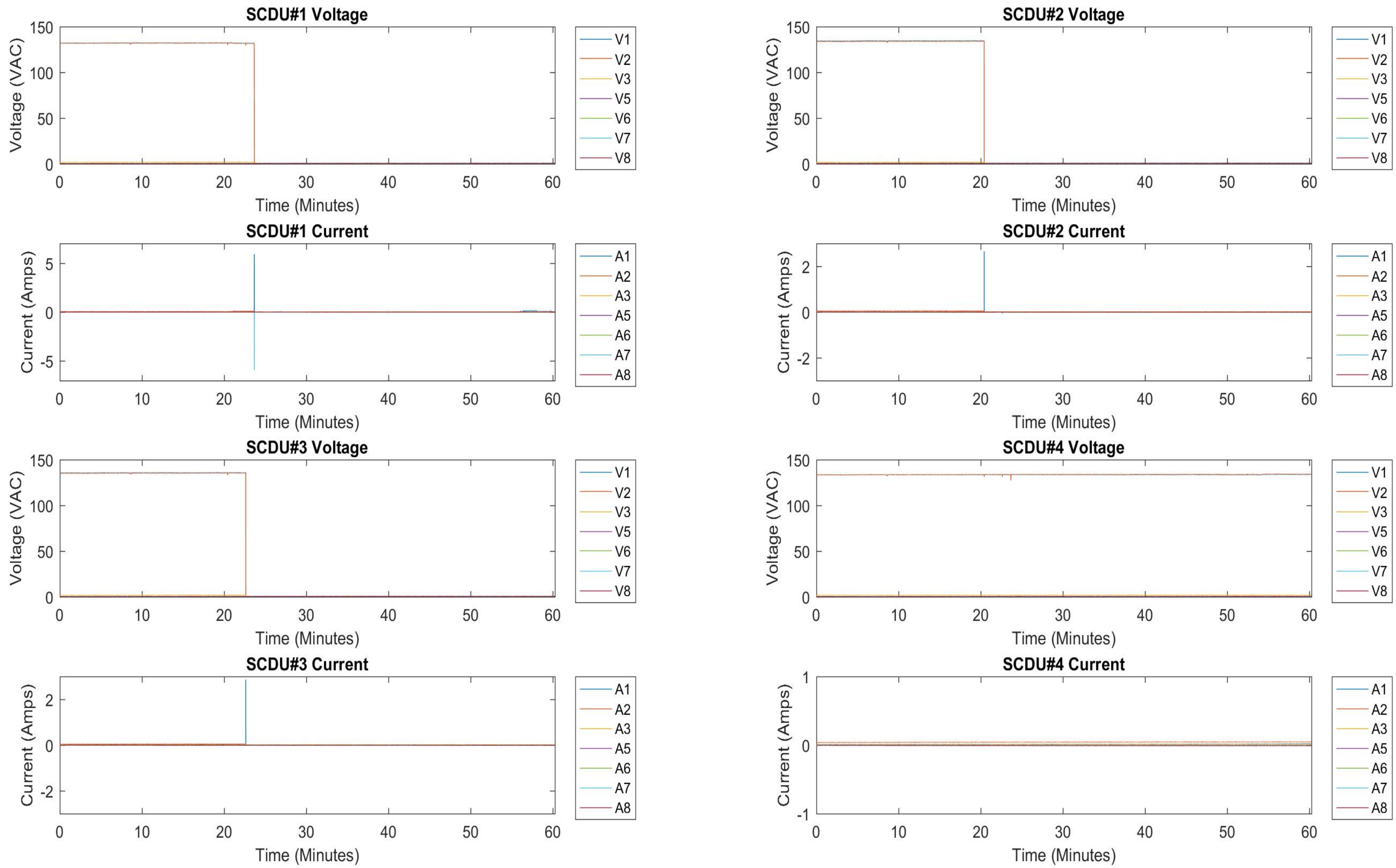


Figure B-39. Experiment II-11—vertical flame spread experiments—Carboline Intumastic 285 coated—cable 902—thermoplastic.

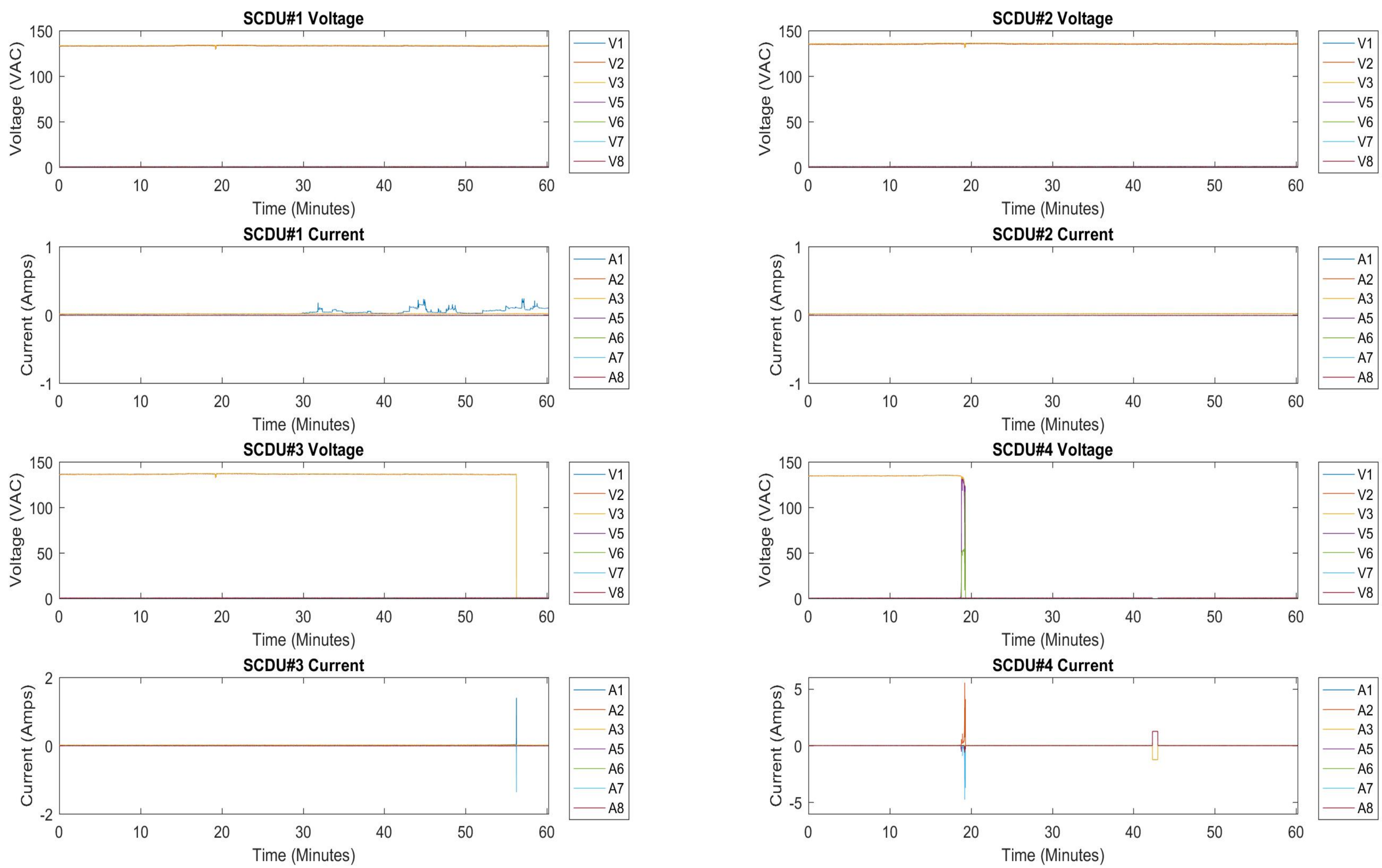


Figure B-40. Experiment II-19—vertical flame spread experiments—Carboline Intumastic 285 coated—cable 813—thermoset.

B.2 Full-Scale Circuit Integrity Results

The failure times reported in section 7 of this report were obtained from the data collected from the SCDU. The data from the SCDU are plotted below. Voltages are identified as V1 through V8. Currents are identified as A1 through A8.

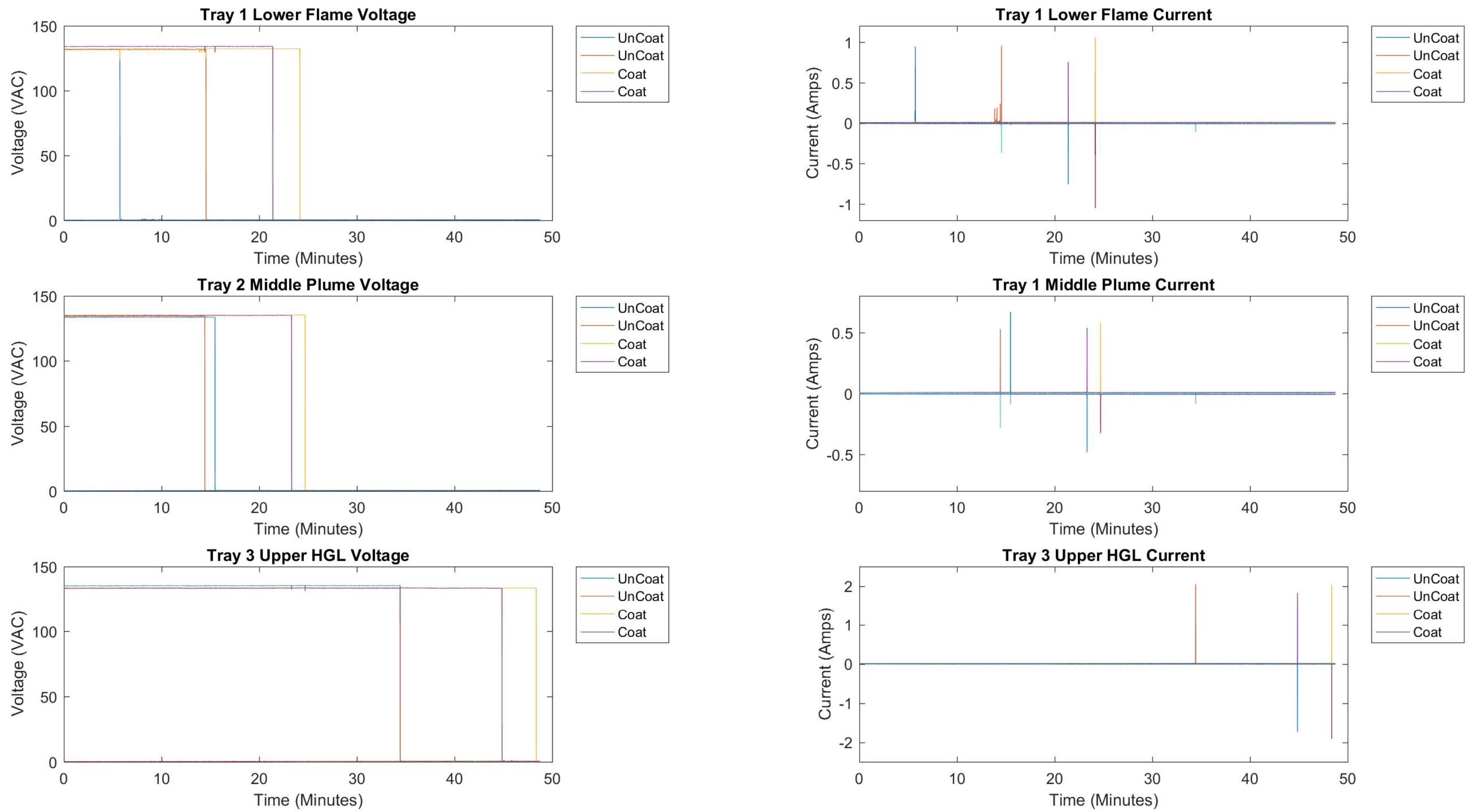


Figure B-41. Full-scale horizontal flame spread experiments—Carboline Intumastic 285—cable 900—thermoplastic—single layer.

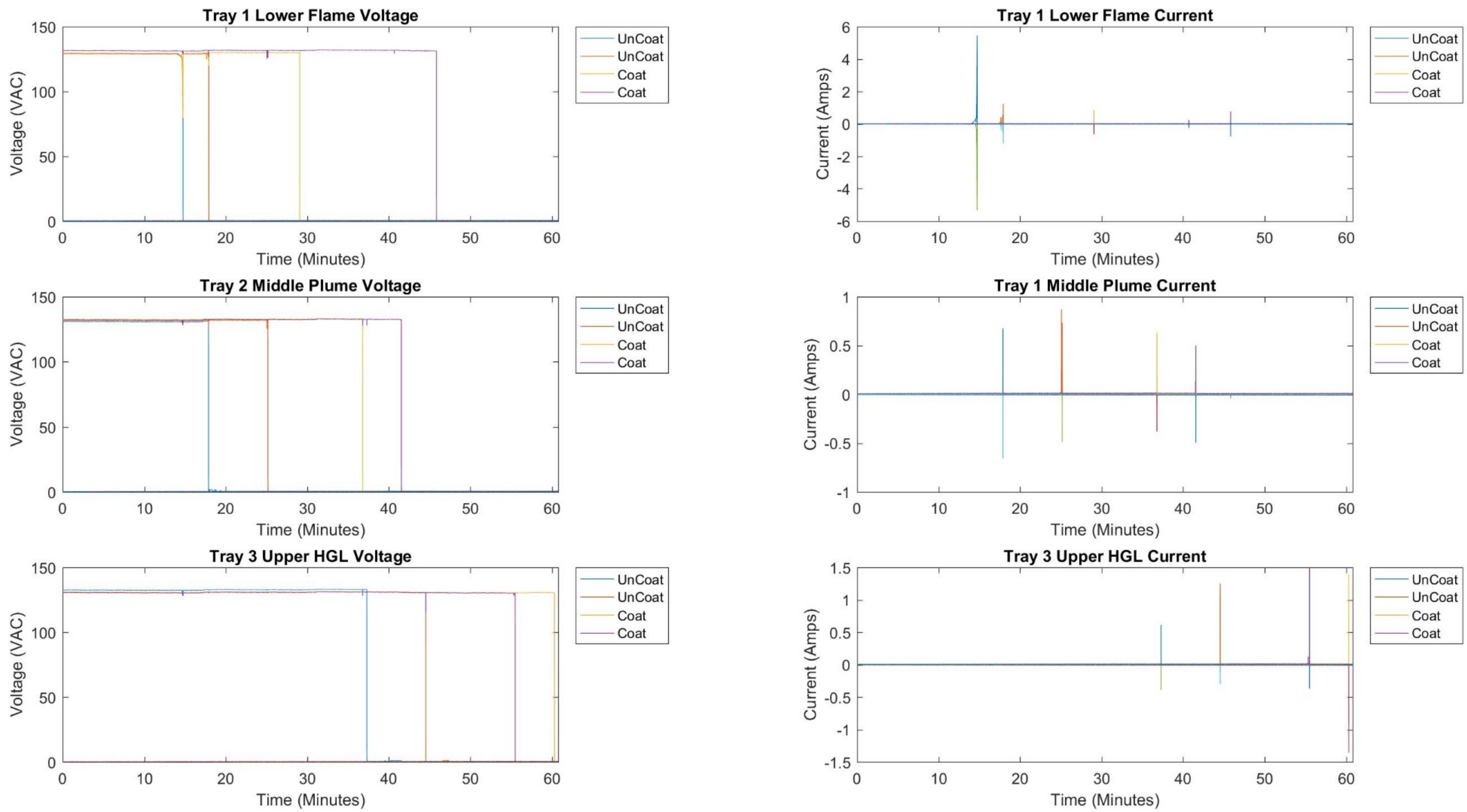


Figure B-42. Full-scale horizontal flame spread experiments—Carboline Intumastic 285—cable 900—thermoplastic—bundle.

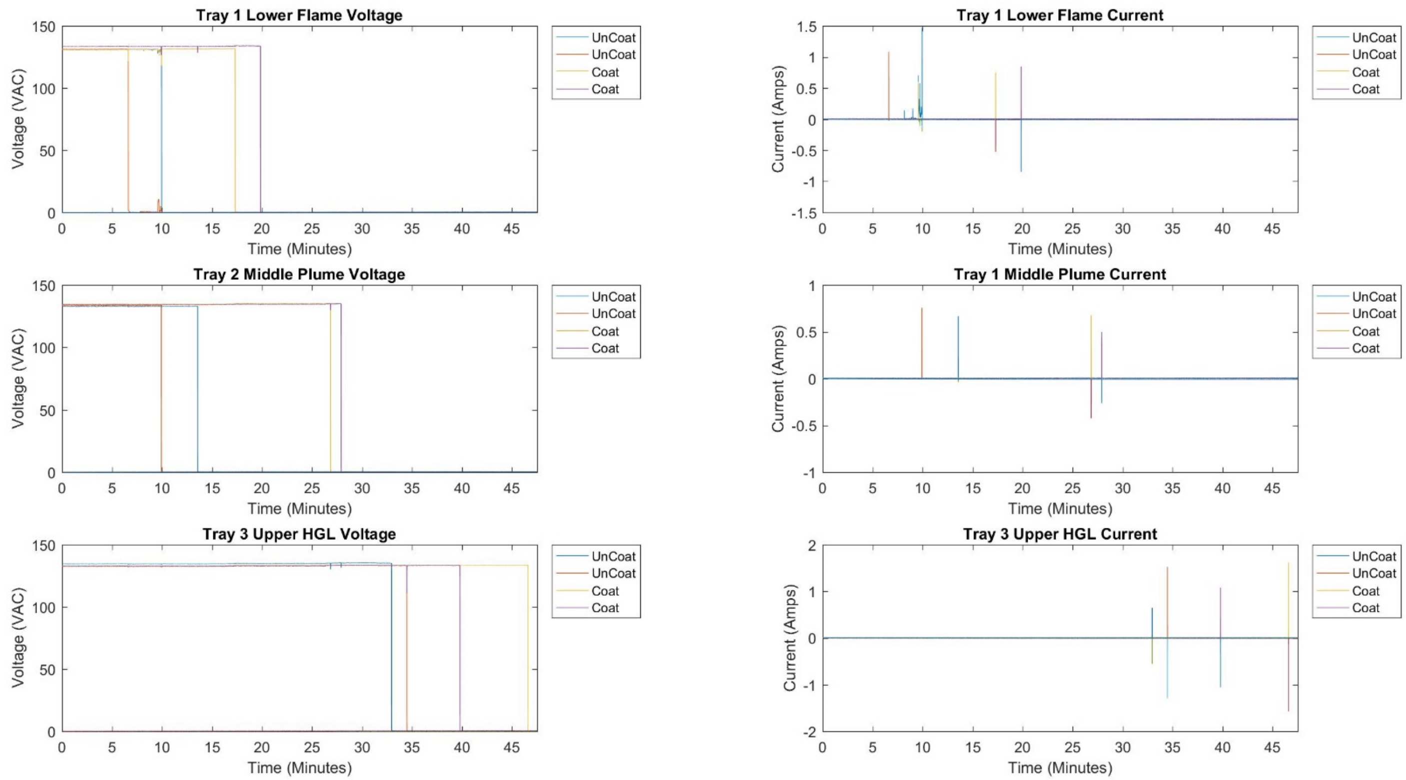


Figure B-43. Full-scale horizontal flame spread experiments—Flamemastic 77—cable 900—thermoplastic—single layer.

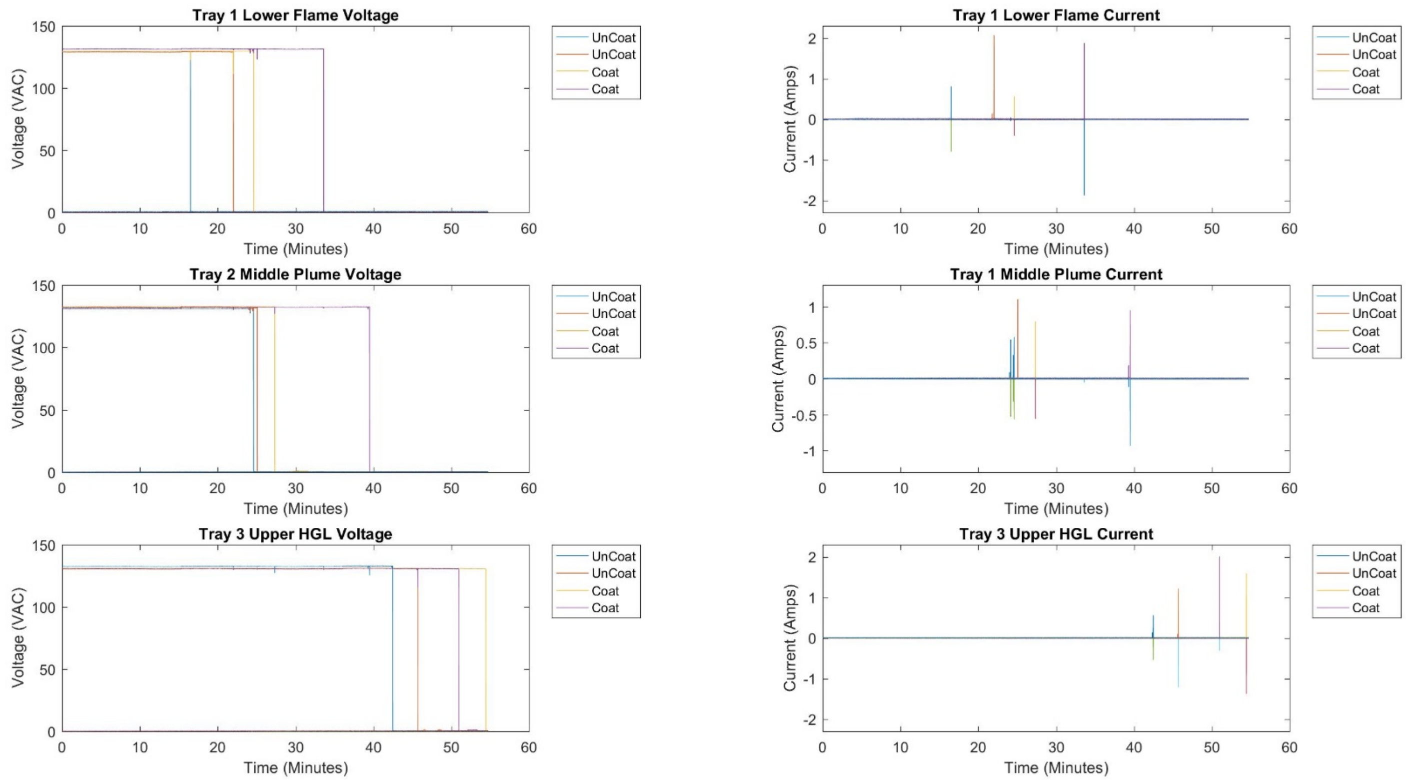


Figure B-44. Full-scale horizontal flame spread experiments—Flamemastic 77—cable 900—thermoplastic—bundle.

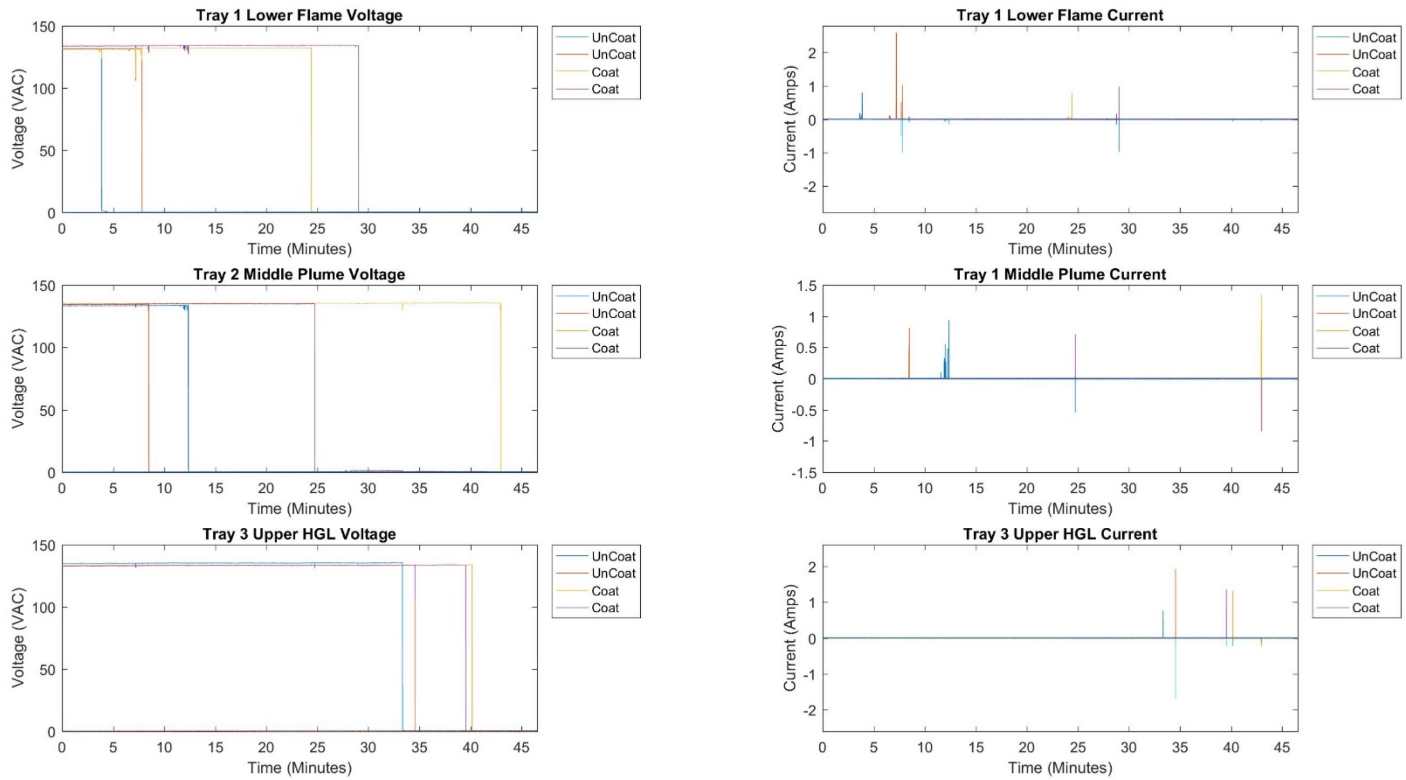


Figure B-45. Full-scale horizontal flame spread experiments—FS15—cable 900—thermoplastic—single layer.

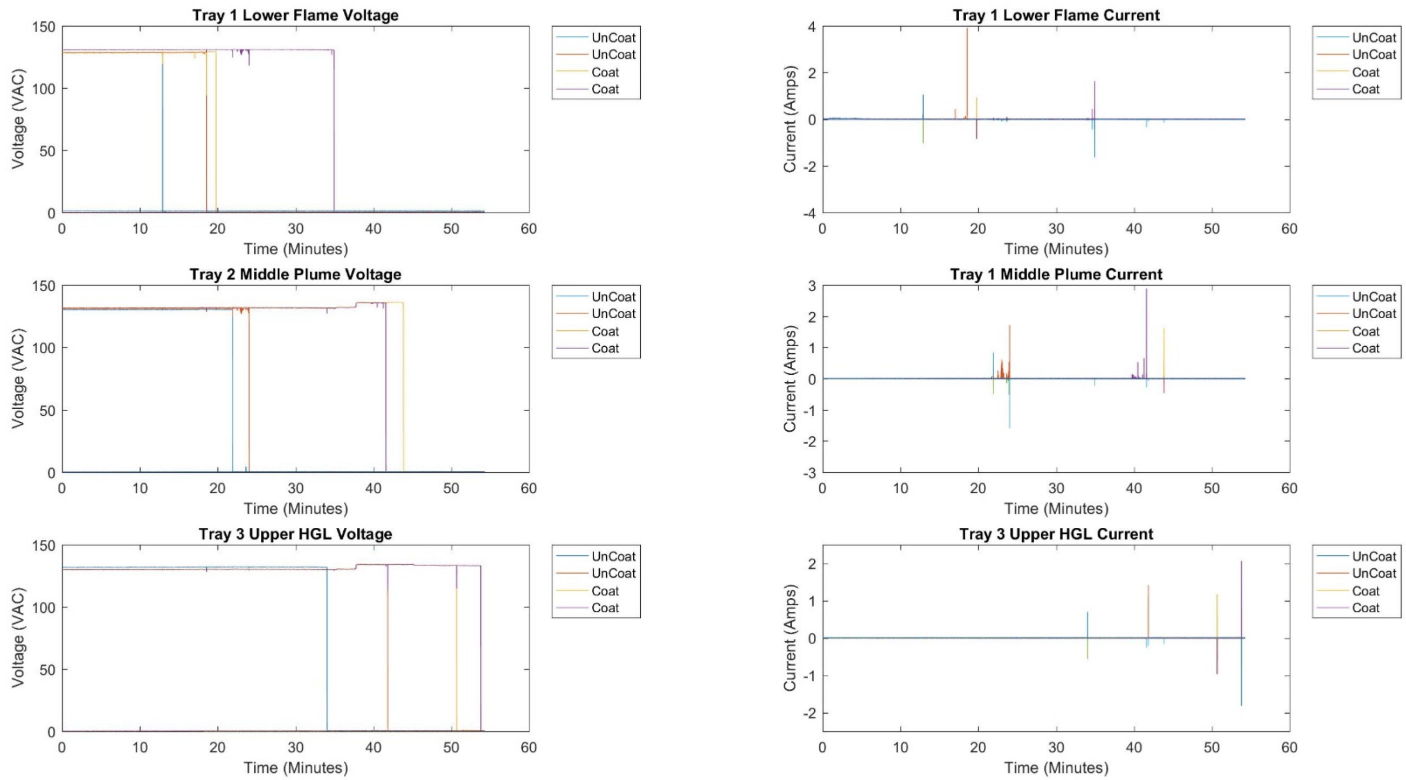


Figure B-46. Full-scale horizontal flame spread experiments—FS15—cable 900—thermoplastic—bundle.

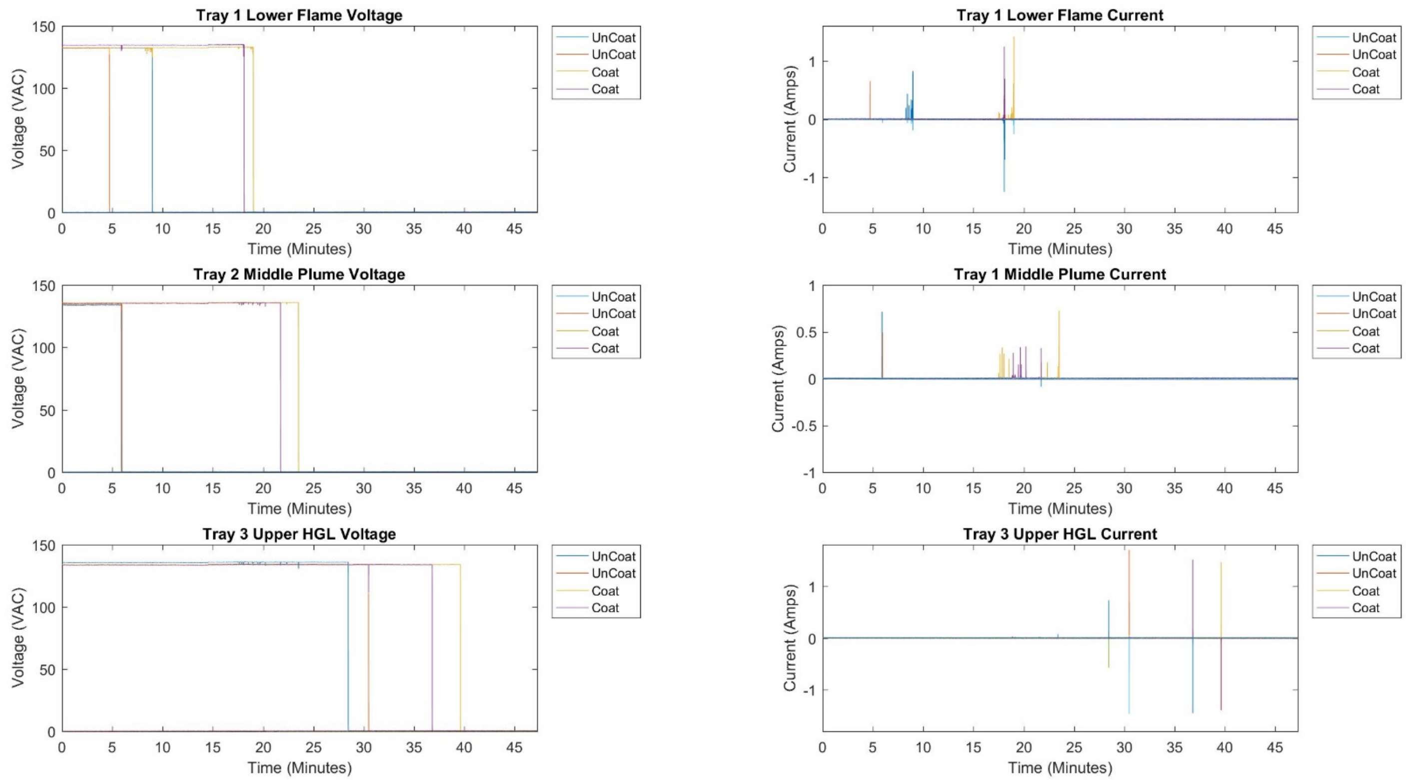


Figure B-47. Full-scale horizontal flame spread experiments—Vimasco 3i—cable 900—thermoplastic—single layer.

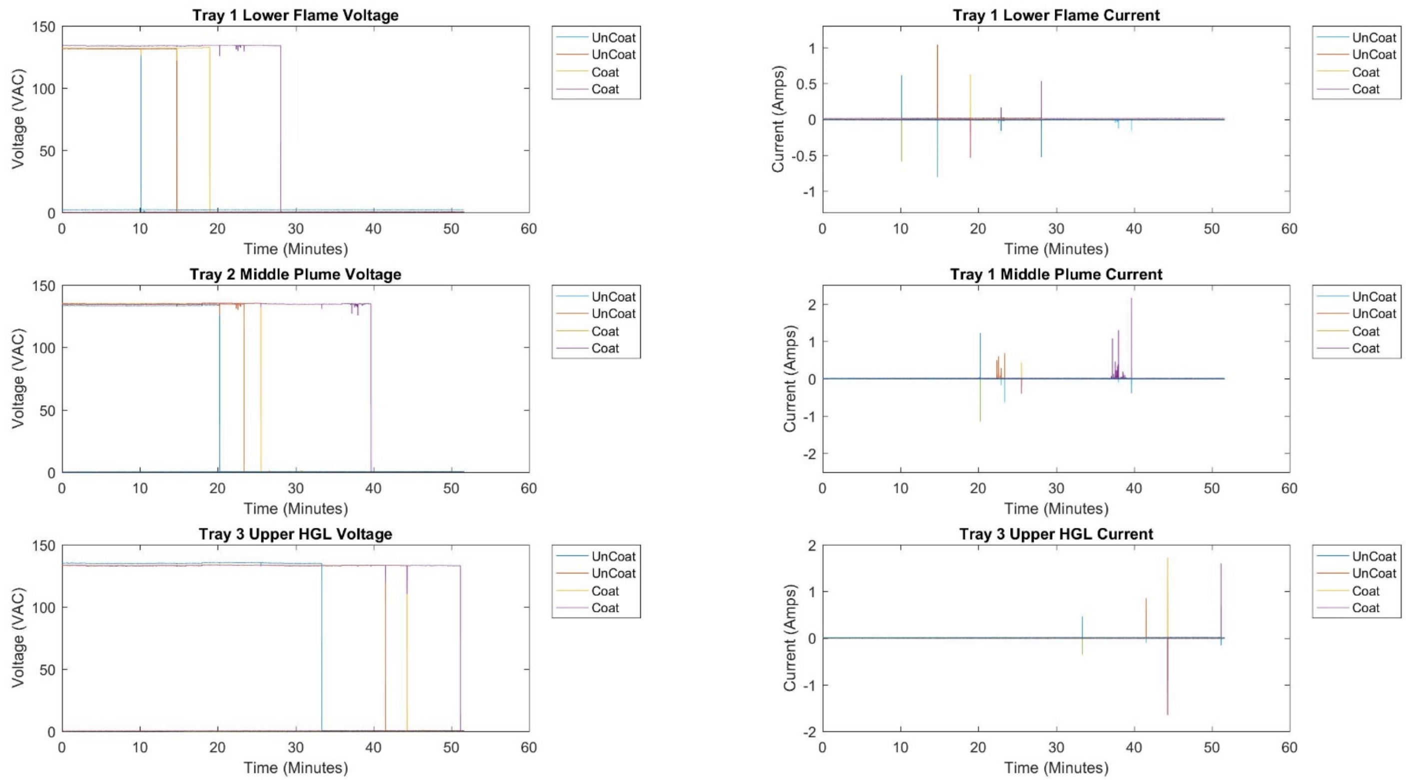


Figure B-48. Full-scale horizontal flame spread experiments—Vimasco 3i—cable 900—thermoplastic—bundle.

Appendix C
Coating Behavior During Radiant Thermal Exposure

Sandia National Laboratories staff prepared this appendix under contract to the U.S. Nuclear Regulatory Commission. This appendix provides results from only one of the experimental series. Section 4 of this report presents a general discussion of the experiments.

This appendix presents experiment results and observations made during the initial radiant energy experimental work presented in section 4. A summary of the experiment results is presented with specific plots chosen to illustrate key aspects of the experiments. The appendix organization is as follows:

- Section C.1 includes the single-cable experiments for both thermoplastic (TP) and thermoset (TS) cables.
- Section C.2 includes the seven-cable bundle experiments.
- Section C.3 includes the final experiment set involving the 10-cable bundle experiment.

Unless otherwise noted, the cable temperature-response plots and data analysis presented here are based on the centrally located cable subjacket thermocouples (TCs). For example, with the single cable experiment data, presentation and analysis are based on TC-1. For the seven-cable bundle experiments, the TC numbers are specific to each cable. For the 10-cable bundle experiments, the only TCs used are central subjacket cable TCs. Prior studies have shown the central subjacket TCs to provide the most reliable and indicative measure of cable response behavior. For Penlight, the central point relative to the shroud is always the hot experiment location given the shroud geometry. Electrical cable failures will also occur at or very near the hot experiment point along a fire-exposed cable because the insulation resistance of polymeric insulators degrades exponentially with increasing temperature (NUREG/CR-6681, "Ampacity Derating and Cable Functionality for Raceway Fire Barriers," issued August 2000, ADAMS Accession No. ML003745784), and electrical breakdown will occur where the insulation resistance is lowest.

Also note that, while the early single-cable and small-bundle experiments included TCs located on the exterior of the cable jacket but under the coating, these TCs proved to be somewhat unreliable. It is difficult to interpret the data from these TCs given that the exact placement of the TC at any point in time cannot be verified. It is likely that these TCs became exposed at some point, but the exact time cannot be determined. Based on the early data analysis, the final experiment set involving the 10-cable bundles eliminated these TCs.

For the purposes of analysis and discussion, an alternate organization of the single-cable and seven-cable bundle experiments is more convenient than the raw experiment matrix. Table C-1 presents the alternate organization, in which the experiments are grouped into cohorts, called "comparison groups," for analysis.[1]

[1] Note that experiments R1, R19, and R20, which were reported as 1a, 19a, 20a, respectively, are not explicitly included in this analysis. That is, the analysis presented here focuses on the results for the repeat experiments rather than the compromised originals.

Table C-1. Alternative organization of the single- and seven-cable bundle experiments into comparison groups for analysis.

Cable Type	Comparison Group	Experiment	Single- or Seven-Cable Bundle	Coating	Electrical Performance System	Experiment Temperature Range (°C)	
						Initial	Final
Thermoset	1	R1a	Single	No Coat	Temperature Only	300	475
		R5		Vimasco		300	475
		R9		Flamemastic		300	500
		R13		Carboline		300	475
		R17	Single	No Coat	IRMS & Temperature	300	475
		R19a		Vimasco		300	475
		R21		Flamemastic		300	475
		R23		Carboline		300	475
	2	R25	Single	No Coat	SCDU & Temperature	450	
		R26		Vimasco		450	
		R27		Flamemastic		450	
		R28		Carboline		450	
	3	R29	Singles (3 cables per experiment, side-by-side)	Vim., Flam., & Carb.	Temperature Only	300	
		R30		Vim., Flam., & Carb.		350	
		R31		Vim., Flam., & Carb.		400	
		R32		Vim., Flam., & Carb.		300	525
	4	R2	Bundle	No Coat	SCDU & Temperature	300	450
		R6		Vimasco		300	475
		R10		Flamemastic		300	475
		R14		Carboline		300	500
Thermoplastic	5	R3	Single	No Coat	Temperature Only	200	525
		R7		Vimasco		200	425
		R11		Flamemastic		200	450
		R15		Carboline		200	450
		R18	Single	No Coat	IRMS & Temperature	200	425
		R20a		Vimasco		200	425
		R22		Flamemastic		200	375
		R24		Carboline		200	450
	6	R4	Bundle	No Coat	SCDU & Temperature	200	450
		R8		Vimasco		200	450
		R12		Flamemastic		200	425
		R16		Carboline		200	500

C.1 Single-Cable Experiments

The first experiment sets to consider are those with single lengths of cable. They include uncoated samples and samples coated with each of the three coatings used in the experiments for both TS and TP cables. The single-length cable experiments are the most closely controlled and most repeatable of the experiments performed and were intended to explore fundamental behaviors of the various coating materials. In practice, the single-cable experiments represent a low-mass thermal system that heats quickly. The single-cable experiments include comparison groups 1, 2, 3, and 5. These four comparison groups are discussed in sections C.1.1 through C.1.4.

C.1.1 Comparison Group 1

The first comparison group includes experiments R1a, R5, R9, R13, R17, R19a, R21, and R23, which were all performed using single lengths of TS cables and the same radiant heating profile (the step-wise increasing profile). These experiments were intended to provide information on the basic behavior of the coating materials given the simplest of possible application conditions, which is a single, individually coated cable. The experiment results were unexpected but provided a critical insight into the materials.

Initial analysis of this comparison group showed that the coatings had, effectively, **no impact on either the time to ignition or time to electrical failure**. Table C-2 summarizes these results for comparison group 1. Note that while there are minor variations, all ignition times fall within a timeframe of roughly +/-2 minutes with a similar variance on the failure times. Also note that the coatings do not consistently produce the longer ignition and failure times. Instead, the uncoated samples fall in the center of the range. Overall, the differences are small and generally fall within anticipated experiment-to-experiment variability.

Again, this was an unexpected result because it had been expected that the coatings would provide some consistent delay in both the time to cable ignition and the time to electrical failure. On closer examination, it was found that, while the end point (time to ignition or electrical failure) was effectively the same for the coated and uncoated samples, the path followed to that end point was not. The explanation for these results requires a much closer look at the actual temperature traces for the coated versus uncoated samples.

Table C-2 Times to cable ignition and electrical failure for comparison group 1—the single TS cable, step-wise profile experiments.

Experiment #	Coating Material	Time to Cable Ignition (minute)	Time to Electrical Failure (minutes)
R1a	No Coating	37.80	-
R17	No Coating	37.65	38.00
R9	Flamemastic	40.33	-
R21	Flamemastic	38.80	39.78
R5	Vimasco	36.10	-
R19a	Vimasco	37.13	39.15
R13	Carboline	35.28	-
R23	Carboline	35.22	36.28

Figure C-1 illustrates the typical subjacket cable temperature-response behavior observed for all three coating products in the comparison group 1 experiments. This particular figure shows experiments R17 (uncoated) and R19a (Vimasco coated).

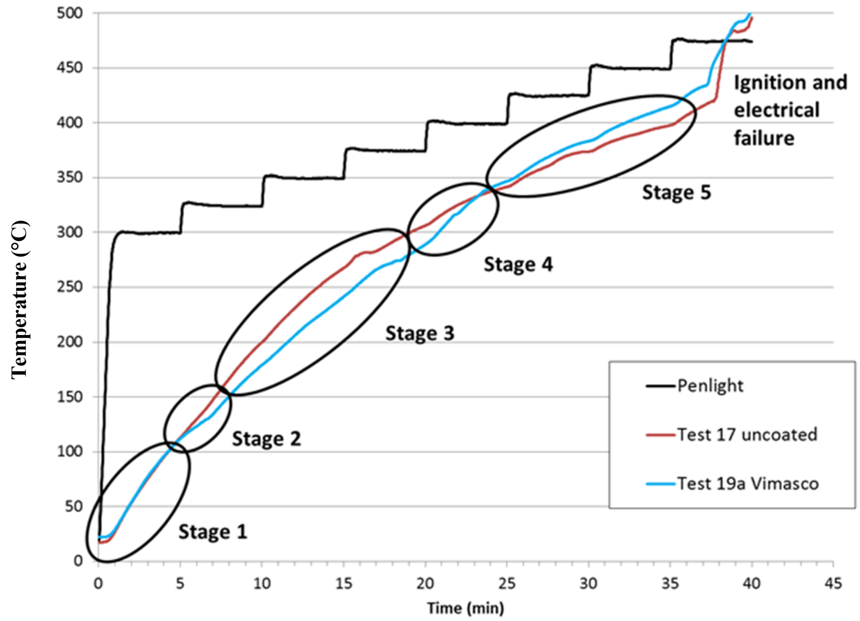


Figure C-1. Temperature response for a single TS cable comparing an uncoated cable to a cable coated with Vimasco.

Another data stream that helps with data interpretation is the rate-of-temperature rise, that is, the time/temperature derivative of the temperature-response data shown in Figure C-1. Figure C-2 illustrates that derivative information. Note that the derivative data clearly reflect the step increases in the Penlight shroud temperature as corresponding jumps in the cable temperature rate of rise every 5 minutes. Beyond this artifact of the heating profile, there are other significant differences to be noted.

Returning to Figure C-1, the uncoated cable (the red line) follows a fairly consistent and steady heating behavior that tracks but lags the Penlight shroud temperature. In Figure C-2, the uncoated cables show a relatively consistent rate-of-rise behavior that reflects the heating profile temperature steps as jumps in the rate of rise. Otherwise, experiments show a fairly consistent downward trend as the cable temperature continuously approaches shroud temperature. The response of the coated cable (the blue line) is rather more complex.

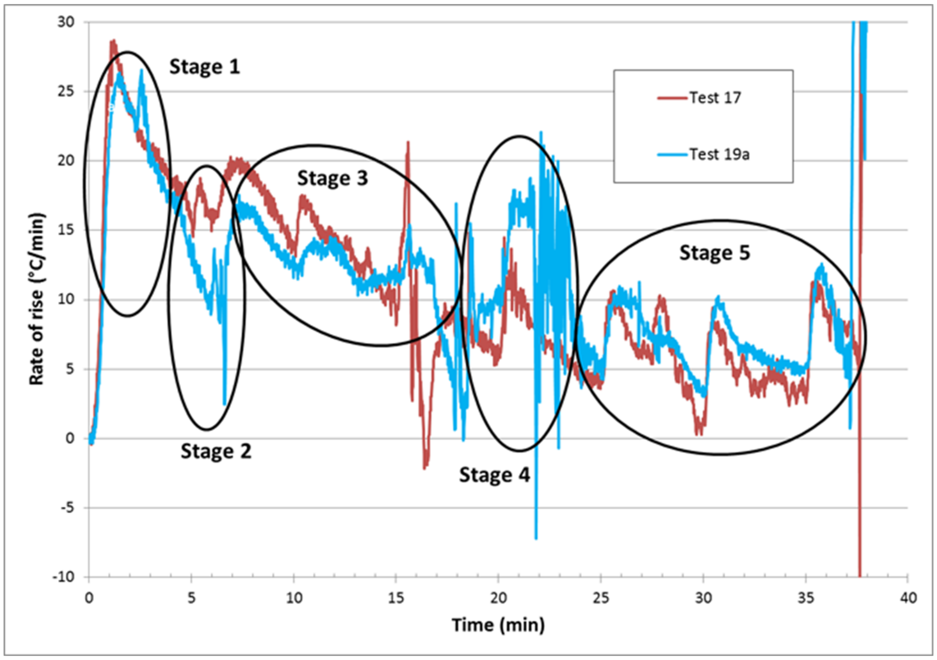


Figure C-2. Rate-of-rise plot corresponding to temperature response shown in Figure C-1.

For the coated cable, the temperature response reflects, in effect, a five-stage heating process. Both Figure C-1 and Figure C-2 highlight the stages. The interpretation of the temperature response for the coated cables is tied to the nature of the coating products; that is, all three products in the experiment are intumescent materials. The coating is applied to the cables in a very thin layer. Once heated beyond a certain temperature (typically somewhere near 200 degrees Celsius (°C) (392 degrees Fahrenheit (°F)) but product specific), the coating material undergoes a chemical/physical change and expands many times in thickness (as much as 600 to 700 percent based on manufacturer's literature). At the end of the expansion process, a low-density char layer is left that acts as an insulating layer. These behaviors are reflected in the following observed experiment data:

- Stage 1. During approximately the first 5 minutes, the coated cables essentially match the temperature response of the uncoated cables, with little deviation (well within experimental variability). During this stage, the coating is in its pristine, unexpanded state and has very little impact on heating behavior because, in the unexpanded state, the coating provides little or no insulating value. The match between the response of the coated and uncoated cables is also reflected (Figure C-2), where both cables show essentially identical temperature rate-of-rise values during stage 1.

- Stage 2. During the next 2 to 3 minutes, the temperature of the coated cable stabilizes and rises at a much lower rate than the temperature of the uncoated cable. Figure C-2 shows this clearly as a period when the rate of rise for the coated cable is much lower than that of the uncoated cable. This stage likely reflects the period of coating expansion. During expansion, some of the coating material transitions to the gas phase and that process carries some heat away from the thermal system. Hence, the coated cable heats more slowly than the uncoated cable during stage 2.

- Stage 3. During the third stage, the coated cable resumes a rate of temperature rise (Figure C-2) similar to, but slightly lower than the rate for the uncoated cable. Figure C-1 shows that the temperature response for the coated cable roughly parallels that of the uncoated cable during this time, but it is offset by several minutes.

- Stage 4. During the fourth stage, a rather unexpected behavior is noted. At a certain point (approximately 1,200 seconds), the rate of temperature rise for the coated cable increases sharply and clearly exceeds that of the uncoated cable (Figure C-2). Over a period of about 5–7 minutes, the coated cable temperature catches up to, and in some cases including that shown here, actually surpasses the temperature of the uncoated cable at the corresponding time in the experiment shown in Figure C-1. An explanation for this behavior is further described below.

- Stage 5. During the fifth stage, the coated cable again roughly parallels the temperature response of the uncoated cable, with the differences falling within the bounds of experimental error and experiment-to-experiment variability. This stage ends with ignition and electrical failure of the cables, which, in this case, occurred at approximately the same time for the coated and uncoated cable.

Stage 4 of this heating behavior is the key to interpreting the observed experiment results. During this stage, a sudden increase in the rate of temperature rise occurs for the coated cable that is not reflected in the uncoated cable. The only possible explanation for this behavior is that a new source of heat has been introduced into the coated cable thermal system that is not present for the uncoated cable. That is, the change in temperature response is not an anomaly (it is seen consistently across all of the coated single-cable experiments), and it is not associated with a change in the exposure environment. An explanation for this behavior was postulated and confirmed by results of cone calorimeter experiments.

Literature from each manufacturer provides ASTM flammability experiment ratings for their products. All three products provide a flame spread rating under ASTM E84, “Experiment Method for Surface Burning Characteristics of Building Materials,” and the Vimasco 3i product also cited a rating under ASTM E162, “Standard Experiment Method for Surface Flammability of Materials Using a Radiant Heat Energy Source.” The E162 experiment is of particular interest to this discussion because it is a combined experiment that measures both flame spread and heat release. For Vimasco 3i, the E84 and E162 ratings are 15 and 16, respectively. These ratings indicate low flammability and a combustible material. That is, the material experiences limited burning, and the E162 results indicate that the material releases energy when it burns (if the material released no heat, the E162 rating would be 0).

Given these insights, it can be postulated that ignition and burning of the coating material would represent a new energy source introduced to the coated cable thermal system that is not present for the uncoated cable and that would explain the behavior seen during stage 4 of the response behavior. While the other products do not specify E162 ratings, the similarity of their behavior implies that all three coatings will burn and will contribute some limited heat to the system.

For confirmation, the National Institute of Standards and Technology (NIST) performed cone calorimeter experiments for the same coating materials and for the same cables used in the Sandia experiments. A review of those results confirm that the coatings burn and contribute a limited amount of heat to the thermal system. Volume 2 of this report presents these results. Figure C-3 shows a typical result for the Vimasco coating. In these experiments, the cured coating itself is the only material present in the experiment; that is, there are no cables, just a layer of the cured coating. The heat release measured is clearly non-zero, indicating that the material burns exothermically. Similar results were also obtained from the cone calorimeter for the other two coating materials as shown in Figure C-4 for Flamemastic and in Figure C-5 for Carboline, where only the cured coating is present.

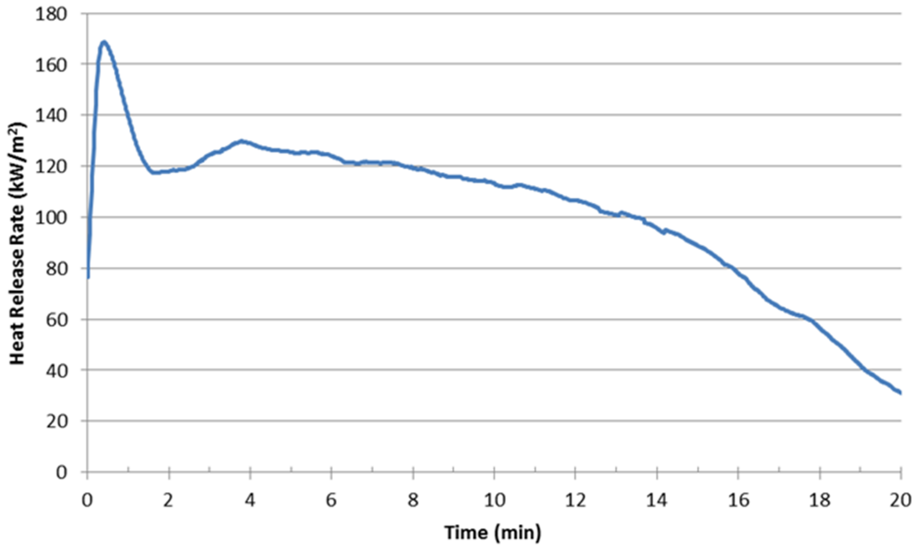


Figure C-3. Cone calorimeter experiment results for the Vimasco coating (cured coating only).

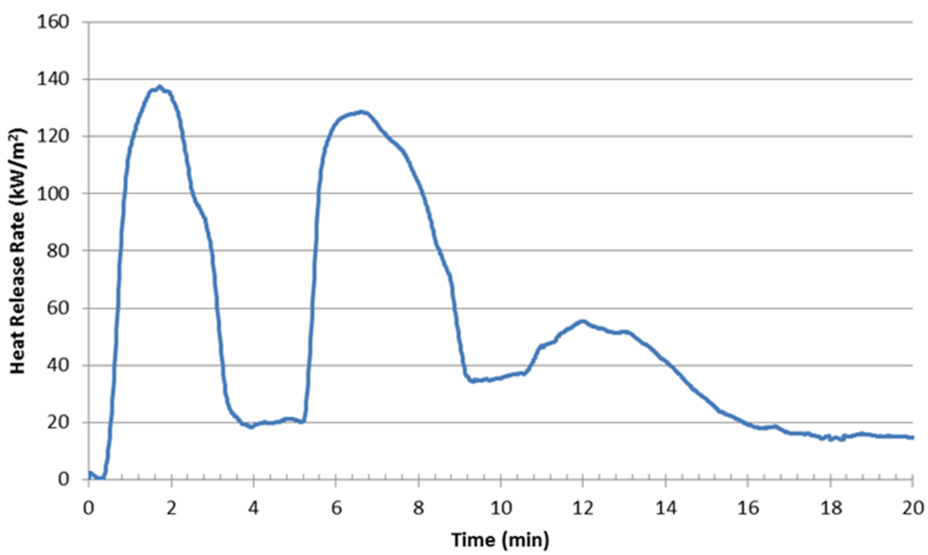


Figure C-4. Cone calorimeter experiment results for the Flamemastic coating (cured coating only).

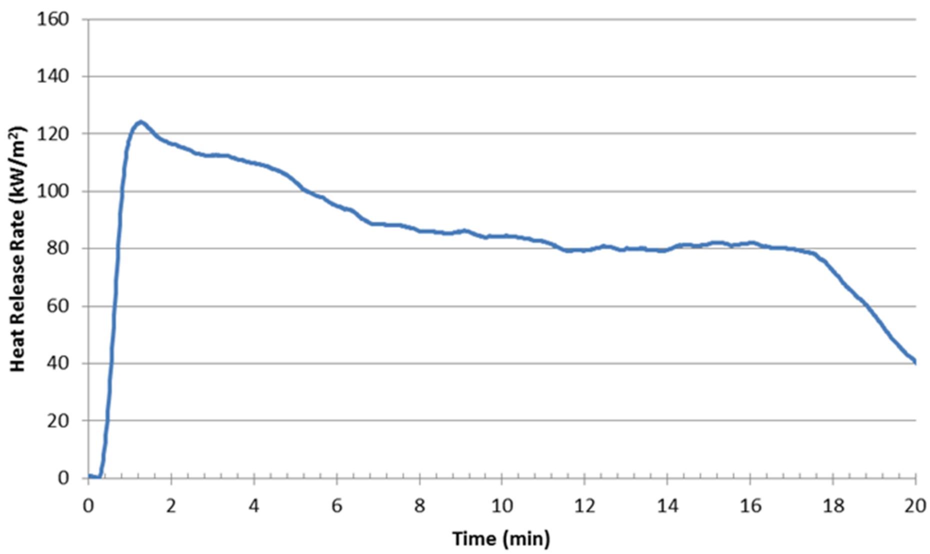


Figure C-5. Cone calorimeter experiment results for the Carboline coating (cured coating only).

Similar results were obtained in the single-cable experiments. Figure C-6 shows a comparison between the uncoated cable in experiment R17 to the Flamemastic coated cable in experiment R9. Figure C-7 shows a similar comparison for the Carboline-coated cable in experiment R23. In both figures, the same general five-stage heating process is evident and highlighted.

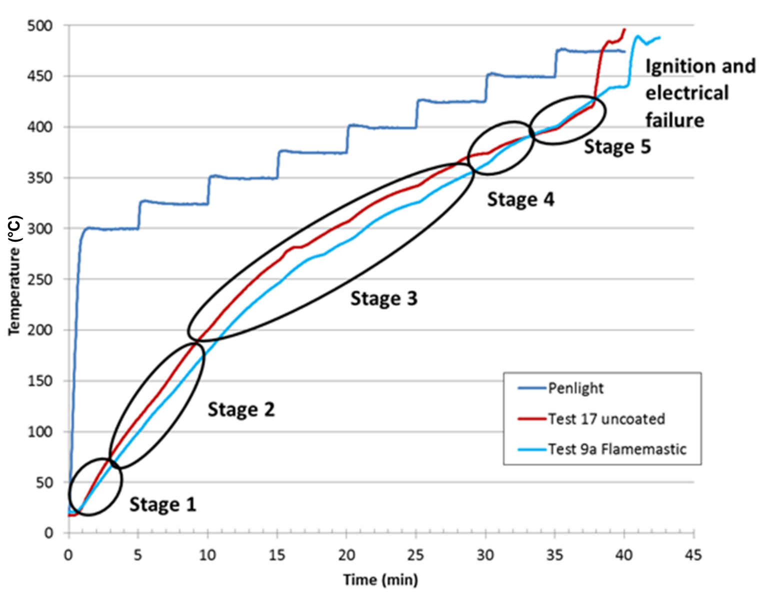


Figure C-6. Comparison of single cable uncoated versus Flamemastic coated.

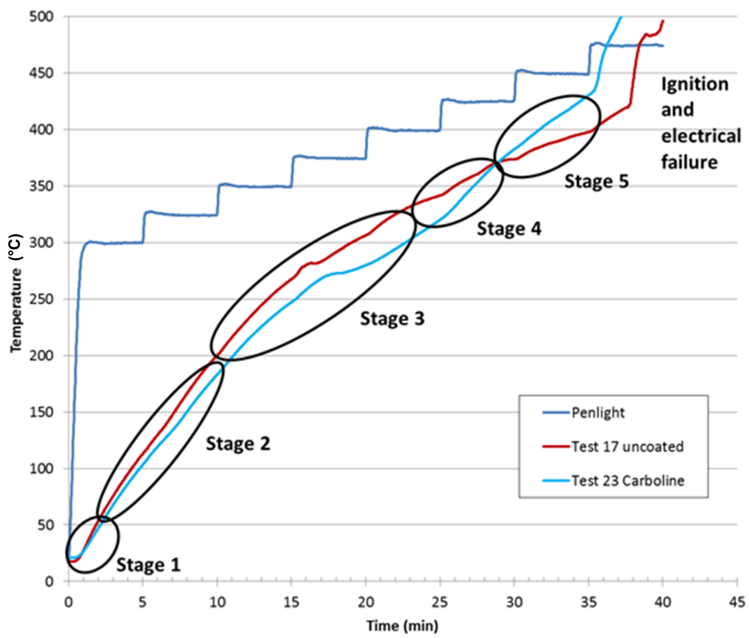
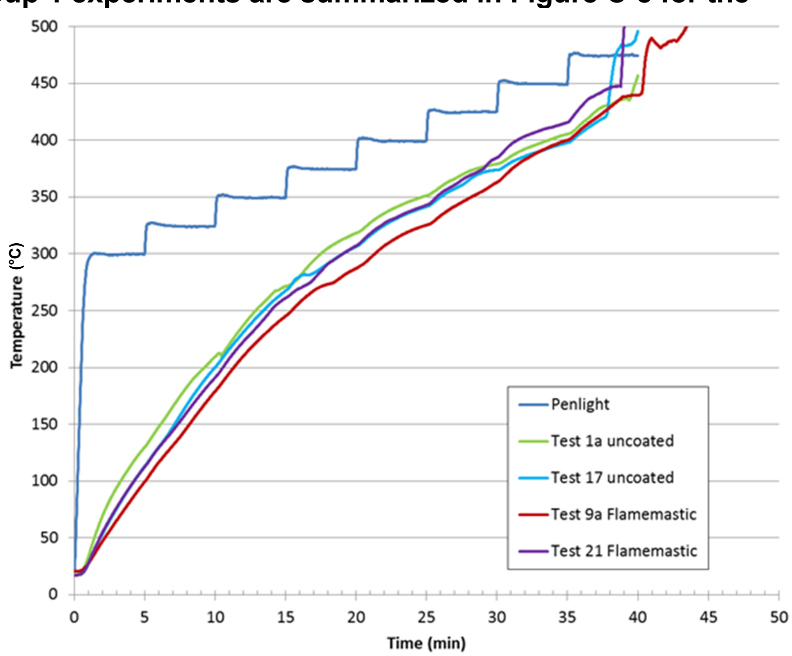


Figure C-7. Comparison of single cable uncoated versus Carboline coated

The NIST calorimetry experiments confirm that the coatings are combustible and burn exothermically. Hence, it is concluded that, for a small thermal mass system under typical fire exposure conditions, and with respect to electrical failure times, the coatings provide, at best, a temporary benefit that will be negated once the coating itself ignites. At worst, combustion of the coating may actually lead to shorter failure and ignition times.

The results for comparison group 1 experiments are summarized in Figure C-8 for the



Vimasco experiments,

Figure C-9 for Flamemastic, and Figure C-10 for Carboline. In each case, the figures compare experiments with the uncoated cables (experiments R1a and R17) to the experiments with the corresponding coated cables.

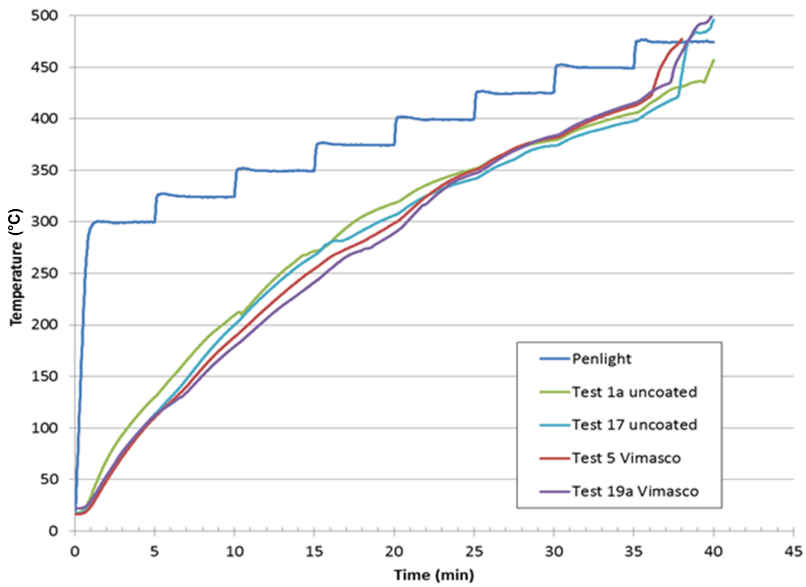


Figure C-8. Temperature history of single TS cables, comparing the uncoated experiments (1a and 17) to cables coated with Vimasco (R5 and R19a).

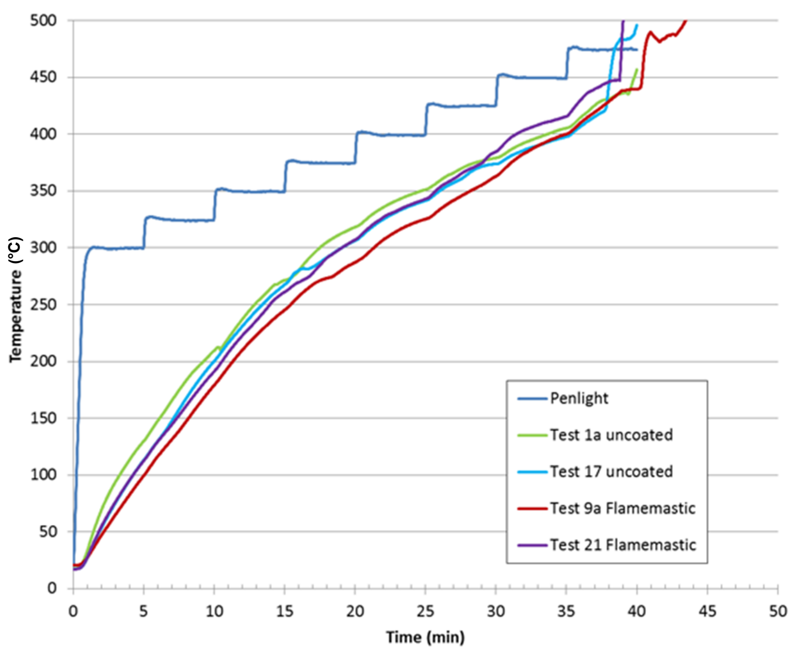


Figure C-9. Temperature history of single TS cables comparing the uncoated experiments (1a and 17) to cables coated with Flamemastic (experiments R9 and R21).

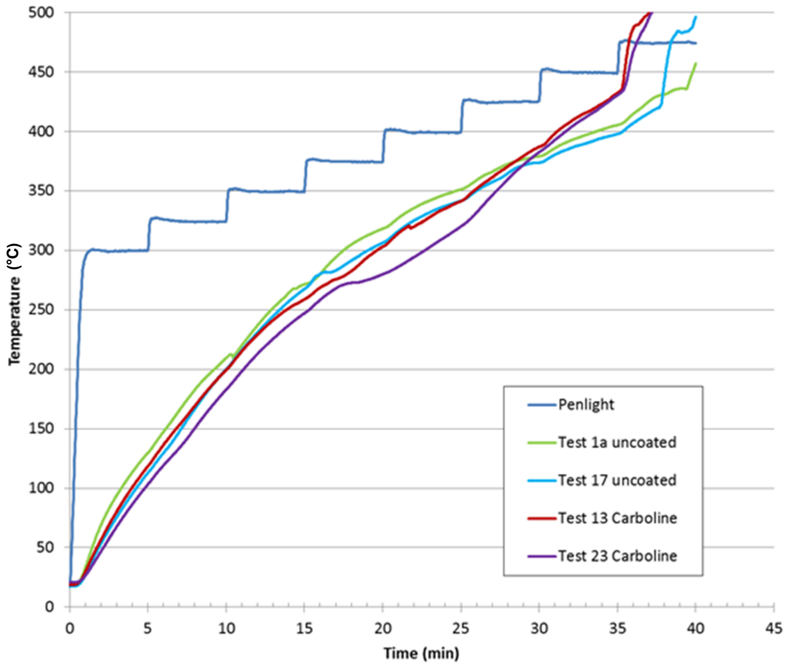


Figure C-10. Temperature history of single TS cables comparing the uncoated experiments (1a and 17) to cables coated with Carboline (experiments R13 and R23).

C.1.2 Comparison Group 2

The second comparison group is made up of experiments R25–R28. These four experiments all used single lengths of TS cable and a heating profile during which the radiant chamber was raised from ambient to 450°C (842°F) within 2 minutes and held constant for the duration of the experiment. Note that the shroud temperature of 450°C (842°F) corresponds to a heat flux of 12.64 kilowatts per square meter (kW/m^2) (1.11 British thermal units per square foot (Btu/ft^2)). This is a far harsher exposure condition than that associated with comparison group 1, so the resulting cable temperature rise is much faster.

Figure C-11 shows the results for the four experiments in comparison group 2. Note that the coated cables all show a more consistent and pronounced delay in the heating profile. Note also that the uncoated cable ignited in fewer than 7 minutes, a shorter time than the 5 minutes after the temperature hold point of 450°C (842°F) was reached.

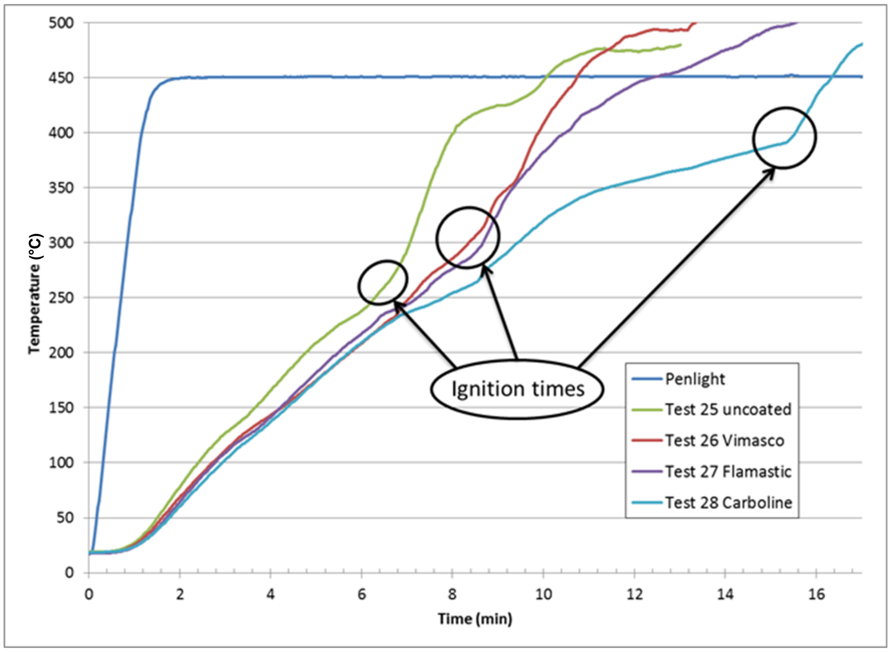


Figure C-11. Temperature-response data for the four experiments in comparison group 2.

There are no repeats for this comparison group; however, there is one experiment for each coating configuration (one uncoated and one for each of the three coating products). Nonetheless, it appears that, under these extreme exposure conditions, a greater and more consistent net impact is seen. Table C-3 gives the results for ignition and electrical failure for this comparison group.

Table C-3. Times to cable ignition and electrical failure for comparison group 2.

Experiment #	Coating Material	Time to Cable Ignition (minutes)	Time to Electrical Failure (minutes)
1a	No Coating	6.4	11.6
9	Flamemastic	8.3	15.1
5	Vimasco	8.6	14.3
23	Carboline	15.3	19.0

Two effects account for this comparison group's coatings having a more consistent impact on both the ignition and failure times. First, the extreme heat flux condition caused the coatings to expand much earlier in the experiment (within the first 1 to 3 minutes), so that the protection was present for a greater percentage of the experiment time, potentially amplifying the beneficial effect. Second, the uncoated cable ignited quickly under these conditions, while the coatings clearly delayed ignition. Since the TS cables typically failed after they ignited, and assuming some impact of the coatings on burn intensity, a delay in the electrical failure time is also seen.

Overall, the rapid, near step-change increase in temperature conditions shows that the coatings can impact cable thermal response even for a low-mass system. However, these exposure conditions are not considered typical of most NPP fires, which tend to grow over time. With the exception of certain special fire types, such as high-energy arc faults or liquid fuel spills, fires tend to begin at relatively low intensity and then grow over time. This is reflected in fire probabilistic risk assessment practice, which typically assumes fire growth times within an ignition source that range from 4 to 15 minutes, depending on the nature of the fire source.

C.1.3 Comparison Group 3

Comparison group 3 includes experiments R29 through R31. In these experiments, three single lengths of the TS cable were placed side by side in a common cable tray. Each cable was coated with one of the three coating products so that all three products were present in each experiment; no uncoated cable was present.

The experiments varied in their exposure conditions. The first three experiments, R29 through R31, used a single-step change condition in which the radiant chamber was set to an elevated temperature of 300°C (572°F), 350°C (662°F), and 400°C (752°F), respectively, and held constant. Note that, at 300°C (572°F) and 350°C (662°F), neither ignition nor electrical damage would be expected for the TS cable used in the experiments. The last experiment in this set used a step-wise increasing temperature profile that started at 300°C (572°F) and ended at 525°C (977°F).

These experiments were run because a number of coated single-cable samples remained after the other single-cable experiments in the series had been completed. The experiments were intended to provide side-by-side comparisons of the three coating products. Insights to be gained from this comparison group are minimal. The three cables were not in symmetrical locations, so direct comparison is difficult. The central cable in this configuration would see the most severe exposure, and the two outboard cables, while symmetrically located, would see a less severe exposure than the central cable. Contact the NRC project manager for more information regarding the data for these experiments.

C.1.4 Comparison Group 5

The fifth comparison group includes experiments R3, R7, R11, R15, R18, R20a, R22, and R24. These are the corresponding single-cable TP experiments and represent a complement to the experiments in comparison group 1. The exposure conditions involved the step-wise increasing temperature profile starting from an initial setpoint of 200°C (392°F). The various experiments in this comparison group end at different setpoints depending on total experiment duration, but all are consistent through a minimum of 375°C (707°F); all but one experiment, R22, are consistent through 425°C (797°F) (experiment R22 ended at a setpoint of 375°C (707°F)).

The results for this experiment set mirror those seen for the TS cable experiments. With the TP cables, electrical failures occur at much lower temperatures; that is, the TP cable is expected to fail at cable temperatures of 260°C to 300°C (500°F to 572°F), compared to the TS cable, which is expected to fail at cable temperatures of 370°C to 400°C (698°F to 752°F). Figure C-12 shows the results for the two uncoated experiments that will be used as a basis for comparison against the coated cases. Note that the two experiments are quite consistent.

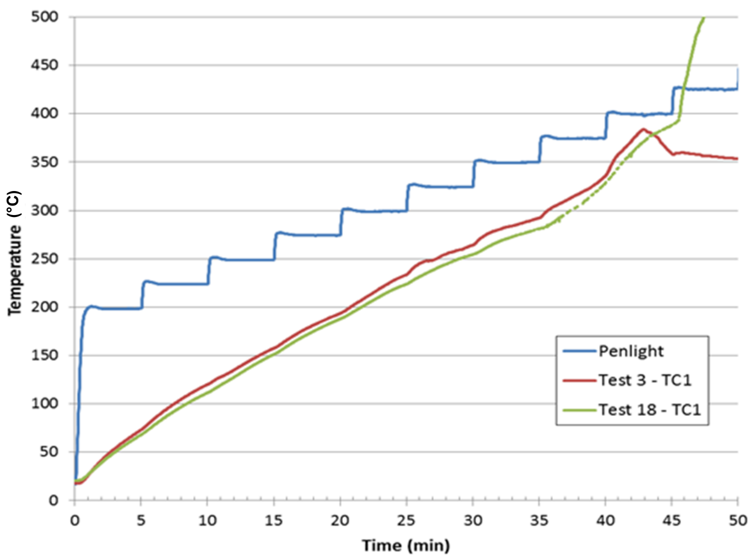


Figure C-12. Experiment results for the uncoated TP single-cable experiments R3 and R18.

Figure C-13 compares the results of the uncoated cable from experiment 3 to the cables coated with Vimasco, Flamemastic, and Carboline from experiments 7, 11, and 15, respectively. There were differences in the temperature behavior between each of the coated cables compared to the uncoated cable, and the differences persisted throughout the experiment. The Flamemastic product shows a different response behavior compared to the other coatings. In particular, the Flamemastic-coated cable initially started along the same temperature profile as the coated cable for the first 20 minutes, whereas the other coated cables diverged from the uncoated cable profile within the first 2 to 3 minutes. Later in the experiment, the Flamemastic cable was closer to the uncoated cable temperature. For example, at 2,300 seconds (38.3 minutes), before ignition of the uncoated cable, the Flamemastic cable was about 23°C (73°F) cooler than the uncoated cable. By comparison, at that same point in time, the temperature difference was approximately 30°C (86°F) for the Vimasco cable and approximately 38°C (100°F) for the Carboline cable. Overall, the differences among these four experiments are not profound, and with only one experiment per configuration, no strong conclusions can be made.

The corresponding results for the two-cable (single-length) experiments, 18, 20a, 22, and 24, were similar, as shown in Figure C-14. In this case, the Vimasco and Flamemastic cables deviated little from the uncoated cable heating profile; behaviors were nearly indistinguishable.

In the case of the Carboline experiment, a more pronounced difference in thermal response was apparent. However, it should be noted that experiment 24 began normally, but soon after the Penlight controller was set to the first temperature rise setpoint, 200°C (392°F), one of the three main Penlight power fuses open circuited, and the heating lamps shut down. No faults in the power circuit were detected, the power fuses were all replaced, and the experiment restarted. However, because the initial Penlight heating cycle had preheated the Carboline cable to about 48°C (118°F), care must be taken in the interpretation of this experiment because the other cables generally started each experiment at about 20°C (68°F). If the cable had not been preheated, it is likely that the deviation between the coated and uncoated cable would be greater, although the net effect is likely modest.

Two challenges exist for this comparison group in terms of cable ignition and damage times. First, during experiment 3 (the single uncoated cable experiment), the end cover on Penlight fell off late in the exposure. This resulted in fresh, ambient air flooding the exposure chamber and would have delayed the ignition time substantially. Hence, it is not appropriate to compare the ignition time for experiment 3 to that of experiments 7, 11, and 15. In the case of the second set of four experiments, those with two single lengths of cable, in one case (experiment 22), Penlight was shut down early, after electrical failure but before ignition, and the cable did not ignite during the cooldown period.

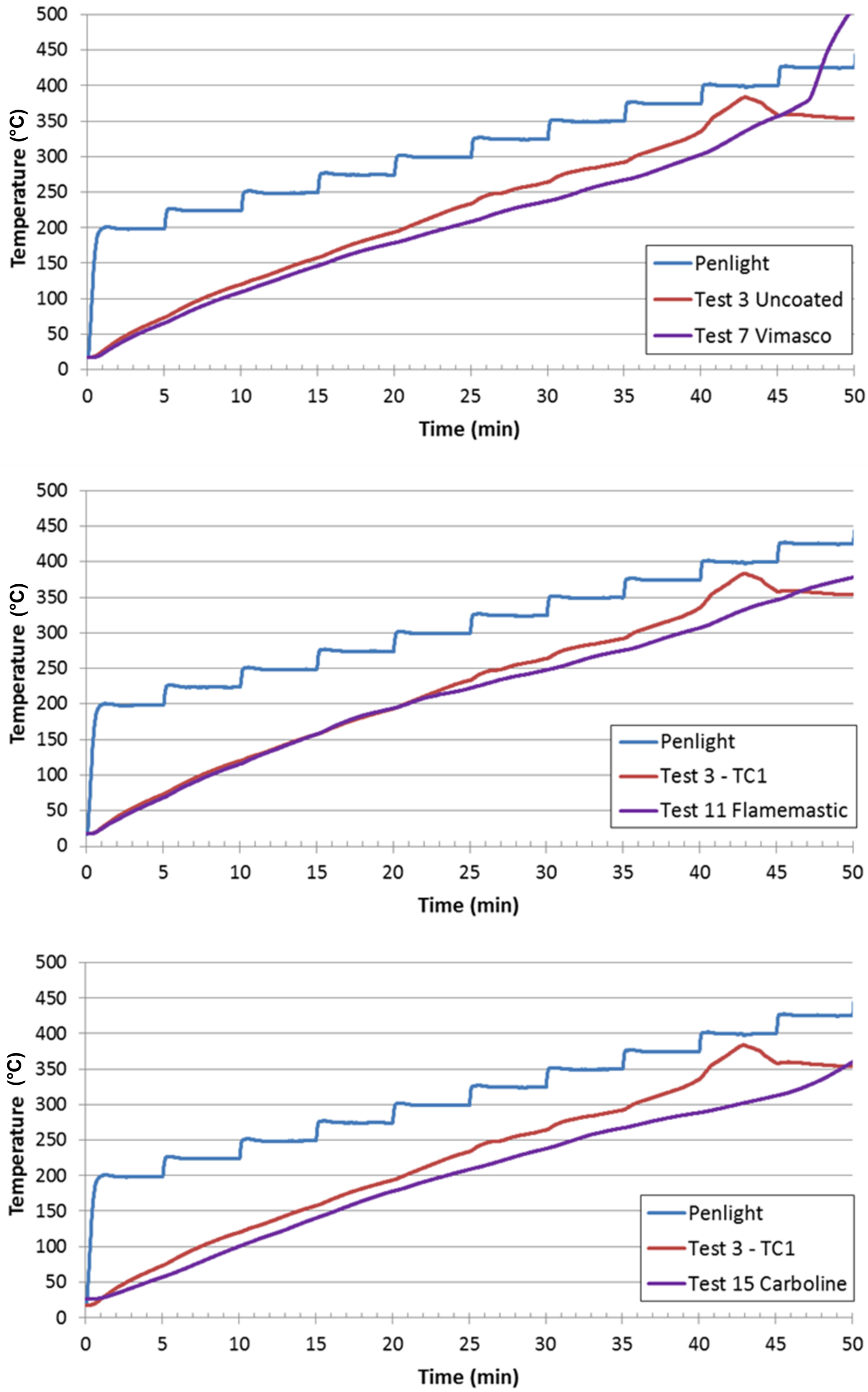


Figure C-13. Comparison plots for the single TP cable experiments for Vimasco (top), Flamemastic (center), and Carboline (bottom).

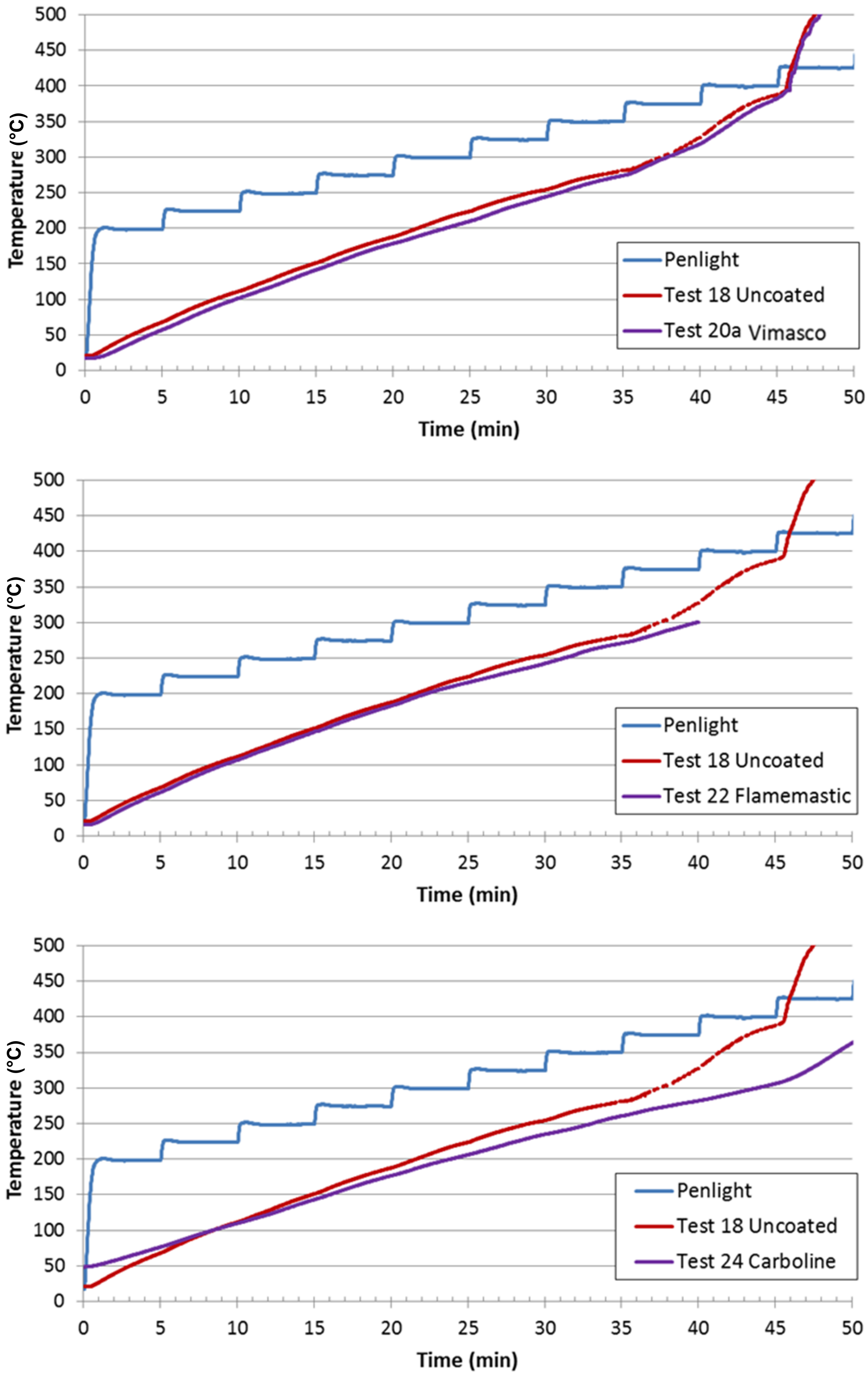


Figure C-14. Comparison plots for the TP cable experiments using two single lengths of cable for Vimasco (top), Flamemastic (center), and Carboline (bottom).

Given these qualifiers, Table C-4 shows the ignition and electrical damage times for experiments R18, R20a, R22, and R24. In all cases, the cables experienced electrical failure before ignition, a behavior that is often seen with TP cables. Beyond that, one unexpected result is apparent—the uncoated cable lasted longer before electrical failure than any of the coated cables. Given only one experiment per configuration, it is difficult to draw strong conclusions from this result; however, this would argue that the coatings had, at most, no appreciable beneficial effect on the time to electrical failure.

Overall, comparison group 4 presents two interesting results. First, for some experiments the coatings seem to have resulted in a perceptible delay in the cable thermal response, while in other experiments, there is no appreciable effect. With respect to electrical damage times, there is only one experiment per coating configuration but, given that limitation, the uncoated cable actually lasted longer before failure than each of the three coated cables. This result is unexpected and was not verified by repeating these experiment configurations because the behavior was not noted until well after the experiments were completed. Therefore, it is not possible to determine if the observed behavior was an anomaly or repeatable behavior. Given these challenges, no strong conclusions have been drawn based on this comparison group.

Table C-4. Ignition and electrical failure times for experiments R18, R20a, R22, and R24.

Experiment #	Coating Material	Time to Cable Ignition (minutes)	Time to Electrical Failure (minutes)
18	No Coat	45.57	32.08
20a	Vimasco	45.85	27.37
22	Flamemastic	(see note)	31.58
24	Carboline	50.83	31.32

C.2 Seven-Cable Bundle Experiments

The second cable experiment configuration involved the seven-cable bundles, with uncoated samples providing a baseline response, and coated samples providing comparison cases. As in the single-cable experiments, both TS and TP cables were used. These experiments were less controlled than the single-cable experiments, so a wider random variability was anticipated. That is, as noted previously, the bundles have a tendency to separate during the experiment, which sharply impacts the subsequent behavior. Because the time of separation is not controlled, the overall thermal response is subject to wider variability compared to the single cable experiments. Also, only one experiment per configuration was performed, so conclusions must be drawn with care, given that experiment-to-experiment variability was not explored.

The bundles represented a significantly more massive thermal system than the single-cable samples described in section 4.2. As a result, the bundles heated more slowly for a given exposure condition. Coatings are applied to the same nominal thickness for the bundles as for the single cables, and as a result, the coating itself represents a lower fraction of the total system mass and volume in the case of the bundles than for the single cables. The reason is that the mass of coating is proportional to the surface area of the coated object, which is proportional to the cable/bundle radius. Volume and mass are proportional to the cross-sectional area, which is proportional to the square of the radius.

The seven-cable bundle experiments have been split into two comparison groups for analysis. Comparison group 4 represents the TS bundles, and group 6 represents the TP bundles.

C.2.1 Comparison Group 4

The fourth comparison group included experiments 2, 6, 10, and 14. These four experiments involved the seven-cable bundles with TS cables. All four experiments used the same step-wise increasing temperature profile seen in comparison group 1.

One behavior important for this comparison group is that, during each experiment, the cable bundle separated. Initially, the cables were arranged in a tight array bound at each end to maintain a consistent shape. During heating, the cables expanded and, as a result, the bundle relaxed, and the cables separated from each other. Figure C-15 shows the cable bundle separation behavior in before and after pictures. Note that the photo showing the cables after the experiments had been concluded reflects severe damage and burning that continued after bundle separation. In the bundle arrangement, even for an uncoated bundle, the individual cables blocked the radiant energy to other cables by limiting the exposed cable surface area. Separation of the bundle exposed more of the cable's surface to direct heating from the Penlight shroud. For coated bundles, the separation was typically delayed, but still occurred. The separation caused large breaches in the coating, as shown in in the closeup photo of a separated bundle (Figure C-16). The coatings tended to stay in place, continuing to shield the cables from radiant heating, but the intimate contact between coating and cables was generally lost.

Figure C-15. Before and after photos of the cable bundle separation behavior.

Figure C-16. Closeup photo of separated cable bundle.

This effect can be seen in the uncoated experiment in particular. The black oval in Figure C-17 highlights the time at which the bundle separated and a sudden departure from the general heating trend becomes apparent for cable D. A corresponding jump in cable temperature rate of rise persisted for 1 to 2 minutes before the cable stabilized on a new heating trend. Note that the jump does not correspond to either cable ignition or to any of the Penlight setpoint changes. The coated cable bundles also separated to varying degrees. The separation caused the coatings to crack open, which appears to have impacted the experiment results. Based at least in part on the bundle separation, comparison group 4 showed inconsistent results. For each of the coating products, a substantive time delay is seen for some of the cables, while other cables see little or no delay at all.

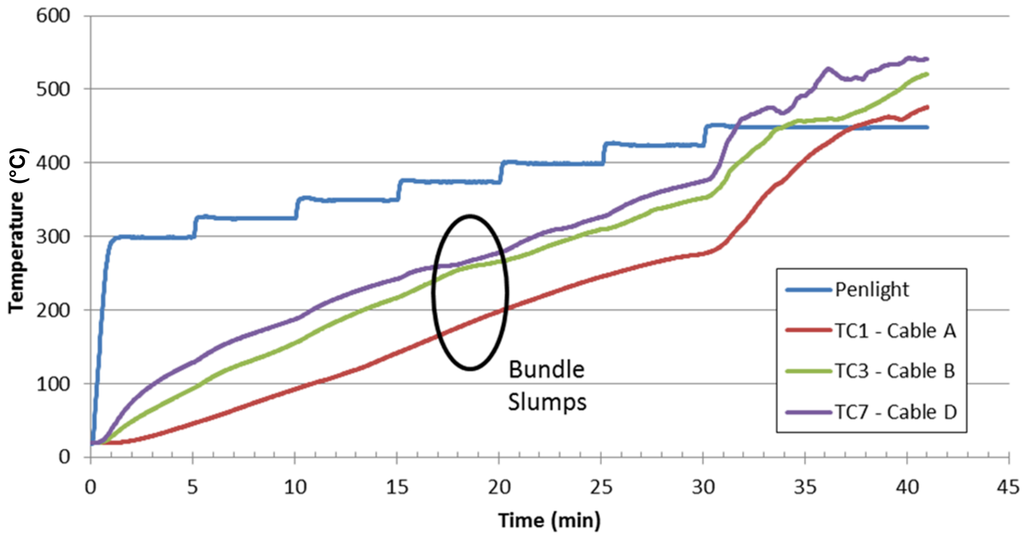


Figure C-17. Cable temperatures for the outer-ring cables in the uncoated, seven-cable bundle (experiment 2).

Figure C-18 compares the uncoated bundle (experiment 2) to the seven-cable bundle coated with Vimasco (experiment 6) comparing each of the thermal response cables, A–D, for each bundle. Note that the response for cable A is largely the same, whereas a significant delay in thermal response is seen for the other three cables. Also note that the central cable (C) sees the most pronounced effect.

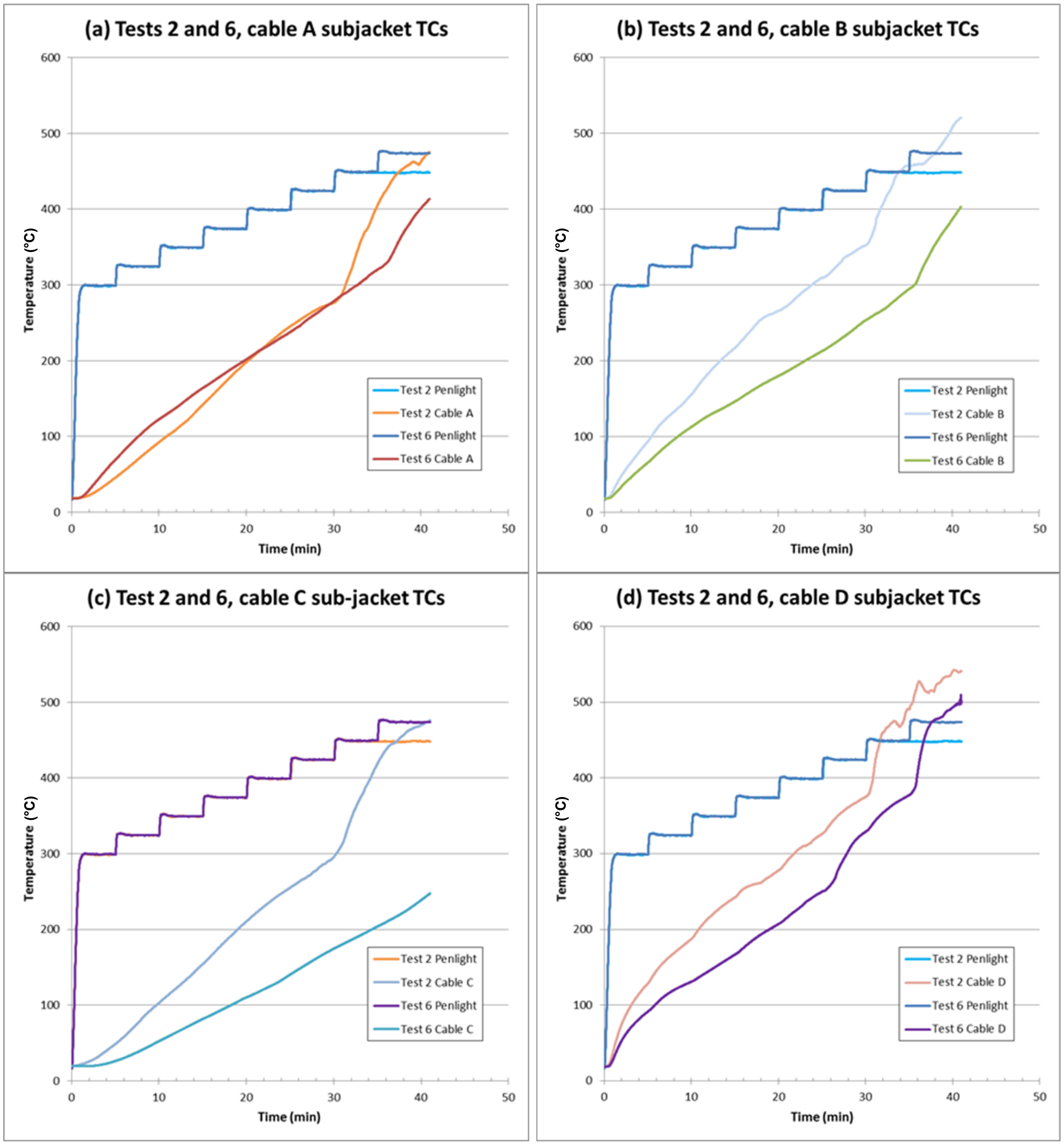


Figure C-18. Cable thermal response comparison for the seven-cable bundle experiments for uncoated (experiment 2) and for Vimasco-coated cables (experiment 6).

Figure C-19 shows a similar plot for the Flamemastic coating. Once again, cables B–D see significant time response delays, while cable A exhibits only a minor net delay.

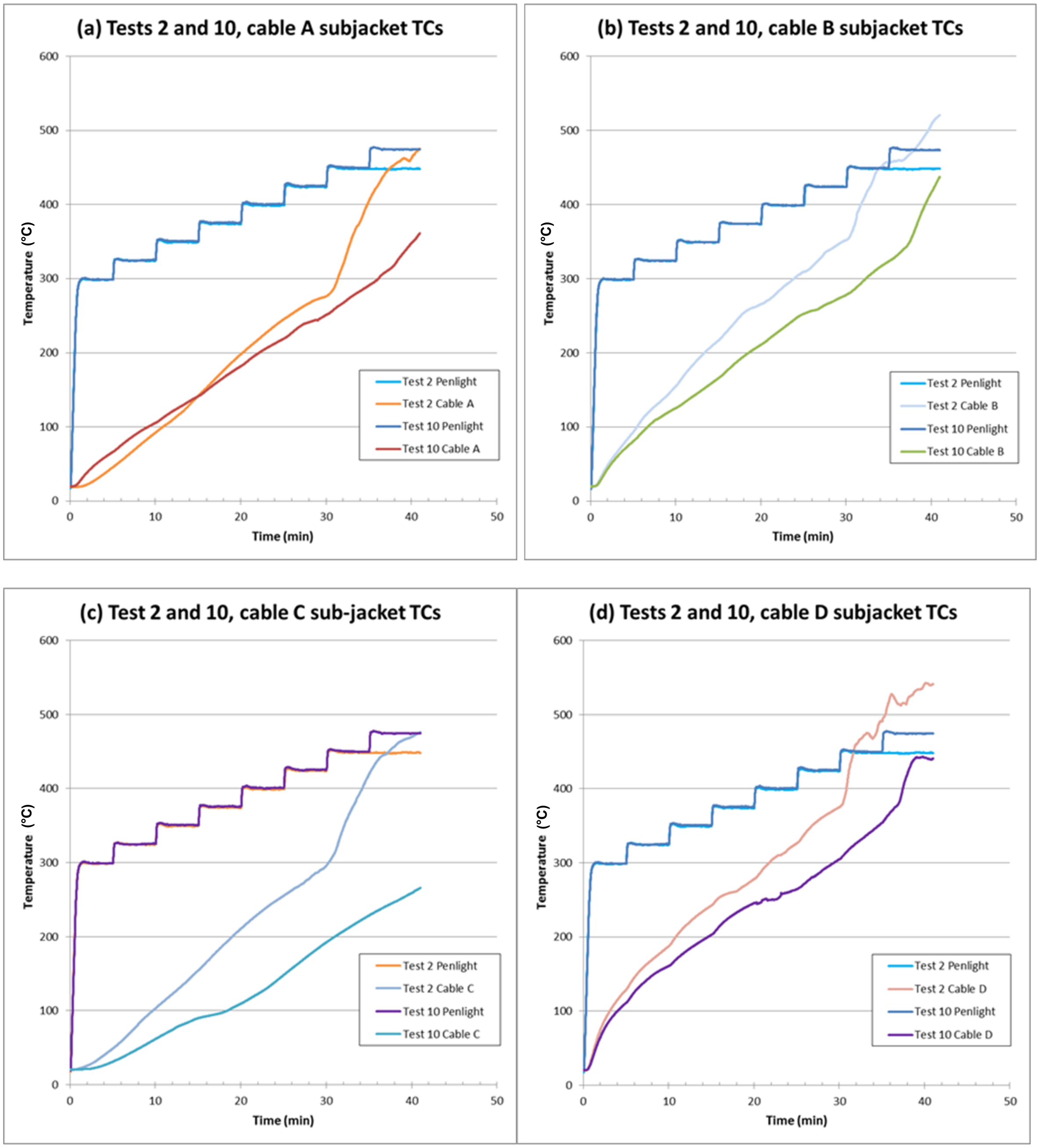


Figure C-19. Cable thermal response comparison for the seven-cable bundle experiments for uncoated cables (experiment 2) and for Flamemastic-coated cables (experiment 10).

Figure C-20 presents a similar plot for the Carboline coating. In this case, all four thermal response cables experienced a substantive delay in thermal response, although the delay for cable A is less pronounced than for the other three cables. Overall, the Carboline-coated cable appears to experience the most significant delays. However, with only one experiment per configuration, it is difficult to draw a strong conclusion based on this comparison group alone.

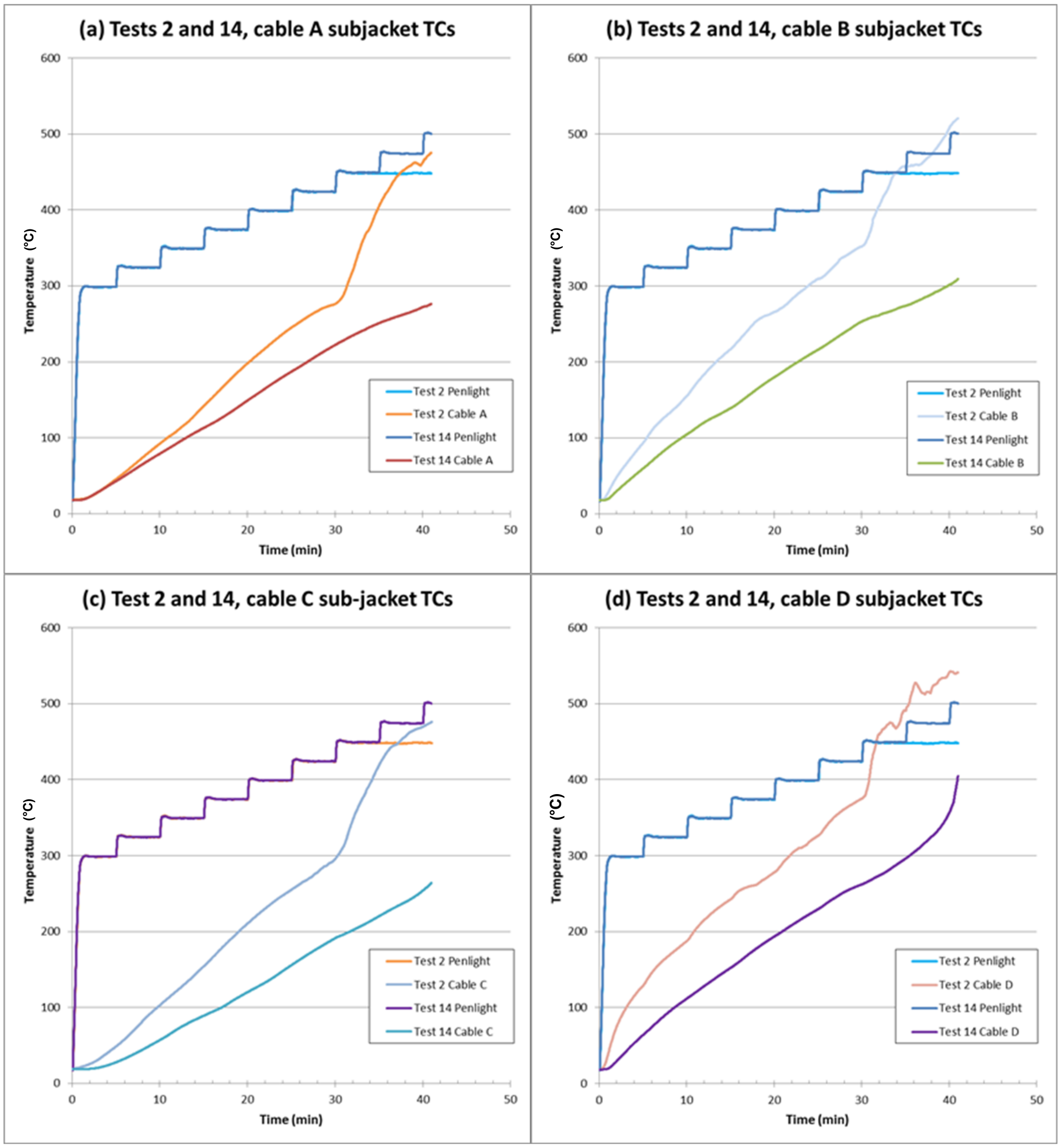


Figure C-20. Cable thermal response comparison for the seven-cable bundle experiments for uncoated cables (experiment 2) and for Carboline-coated cables (experiment 14).

Table C-5 shows the ignition and Surrogate Circuit Diagnostic Unit (SCDU) failure time results for comparison group 4. Note that ignition time delays were similar for the Vimasco and Flamemastic products. The Carboline product showed slightly different delayed ignition.

Table C-5. Summary of ignition and electrical failure times for comparison group 4.

Experiment number	Coating configuration	Time to ignition (min)	Time to electrical failure	
			Cable	Time (min)
2	No Coat	30.45	E1	38.8
			E2	36.0
			E3	34.8
6	Vimasco	35.65	E1	51.6
			E2	43.2
			E3	40.4
10	Flamemastic	37.17	E1	50.5
			E2	43.7
			E3	42.1
14	Carboline	39.87	E1	55.8
			E2	46.2
			E3	n/a

In terms of time to electrical failure, there is consistency in the failure times within a bundle. That is, SCDU circuit E3 consistently failed first, followed by E2 and then E1. This is an artifact of the placement of the electrical circuit cables in the bundle and their relative exposure to the shroud. Circuit E3 was associated with a cable on the top of the bundle and received the most severe exposure, so that it failed first as expected. Circuit E1 was on the bottom of the bundle and remained shielded by the other cables throughout the experiment even when the bundle separated. Hence, E1 failed last. Circuit E2 was in an intermediate condition.

Note that in experiment 14, the Carboline-coated bundle, SCDU circuit E3, failed to function; there was no power to the circuit during the experiment because of failure of the control power transformer fuse during setup. Hence, the time of first failure cannot be stated in a manner consistent with the other coatings.

In summary, the performance of the coatings for comparison group 4 was inconsistent, especially with respect to the thermal response cables. All coatings provided some level of protection relative to time to ignition, and for most cables, a corresponding delay in thermal response was also observed. However, for the Vimasco and Flamemastic products, one thermal response cable

(cable A) that saw little or no benefit from the coating application. It is suspected that separation of the cable bundle caused large openings to form in the coatings, which likely exposed the cables at the top of the bundle to more direct radiant heating. The Carboline-coated bundle did not see the same effect (i.e., all four thermal response cables saw a substantial delay in only one experiment). However, it is difficult to draw firm conclusions as to whether this result is representative. This question will be addressed again in the context of the TP cable experiments and the larger bundle experiments.

C.2.2 Comparison Group 6

Comparison group 6 includes the four TP cable small-bundle experiments, experiments 4, 8, 12, and 16; experiment 4 was an uncoated experiment. Figure C-21 illustrates the results for this group for the Vimasco product, Figure C-22 for the Flamemastic product, and Figure C-23 for the Carboline product. As with comparison group 4, each figure compares the four thermal response cables from the uncoated experiment to the corresponding cables for each coating product.

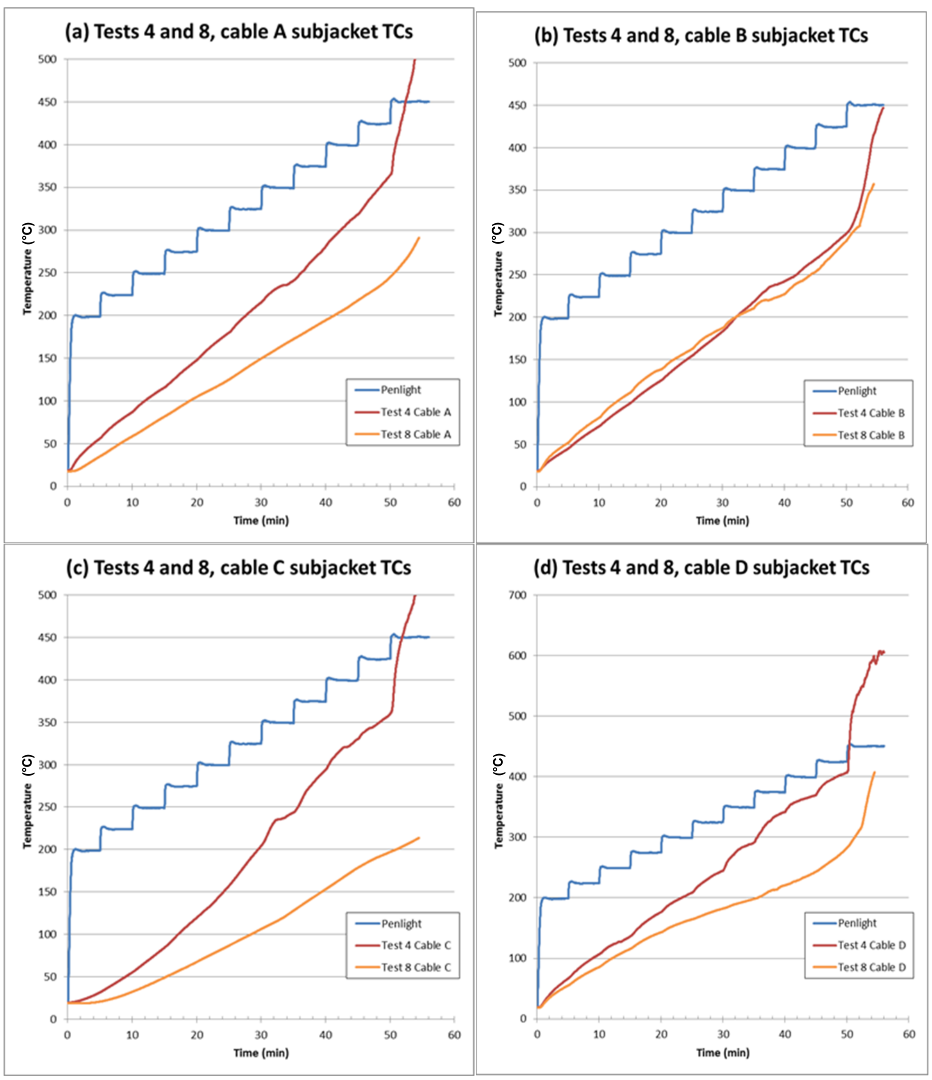


Figure C-21. Comparison of corresponding thermal response cables for the uncoated and Vimasco-coated, small TP cable bundle experiments.

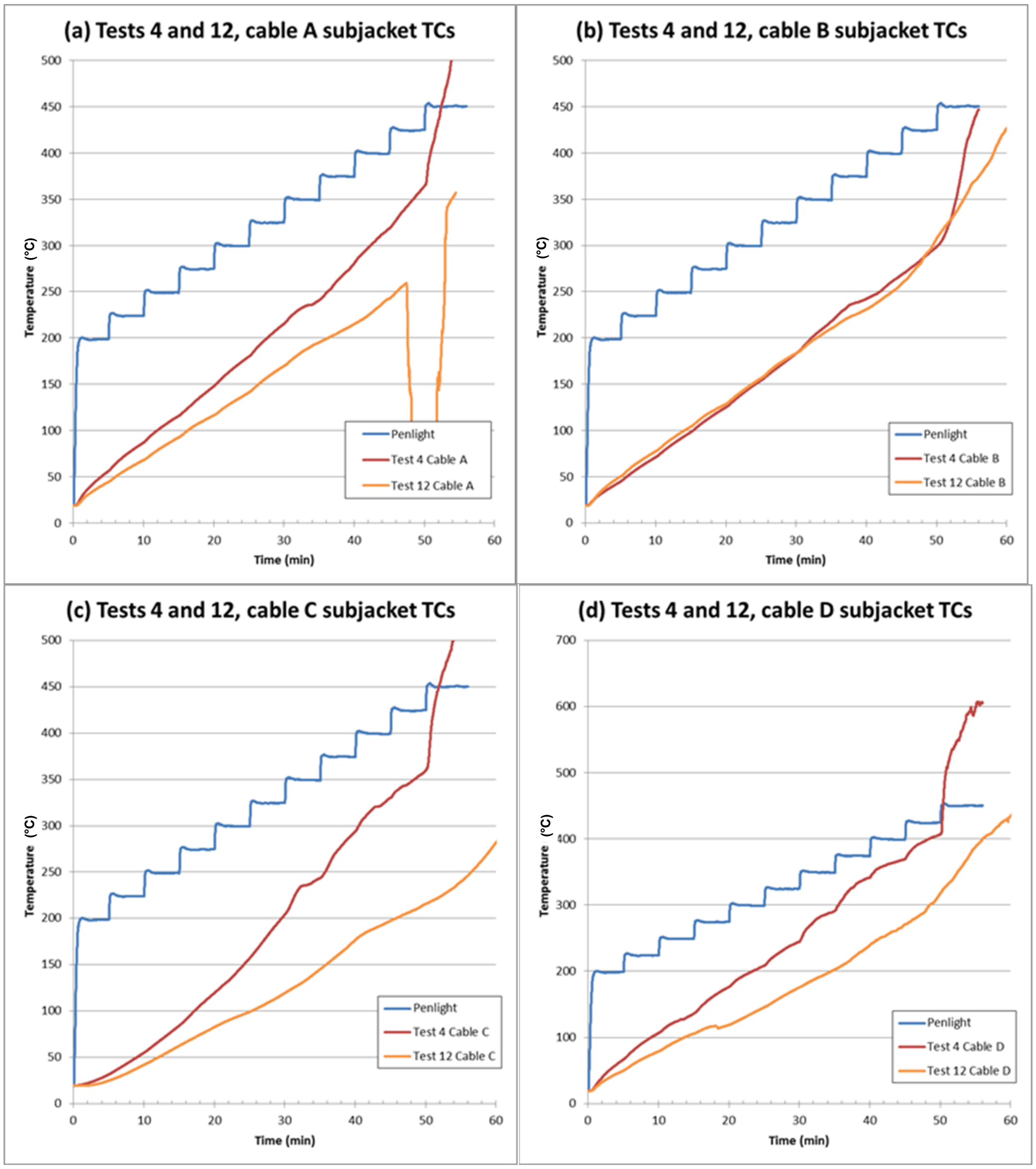


Figure C-22. Comparison of corresponding thermal response cables for the uncoated and Flamemastic-coated, small TP cable bundle experiments.

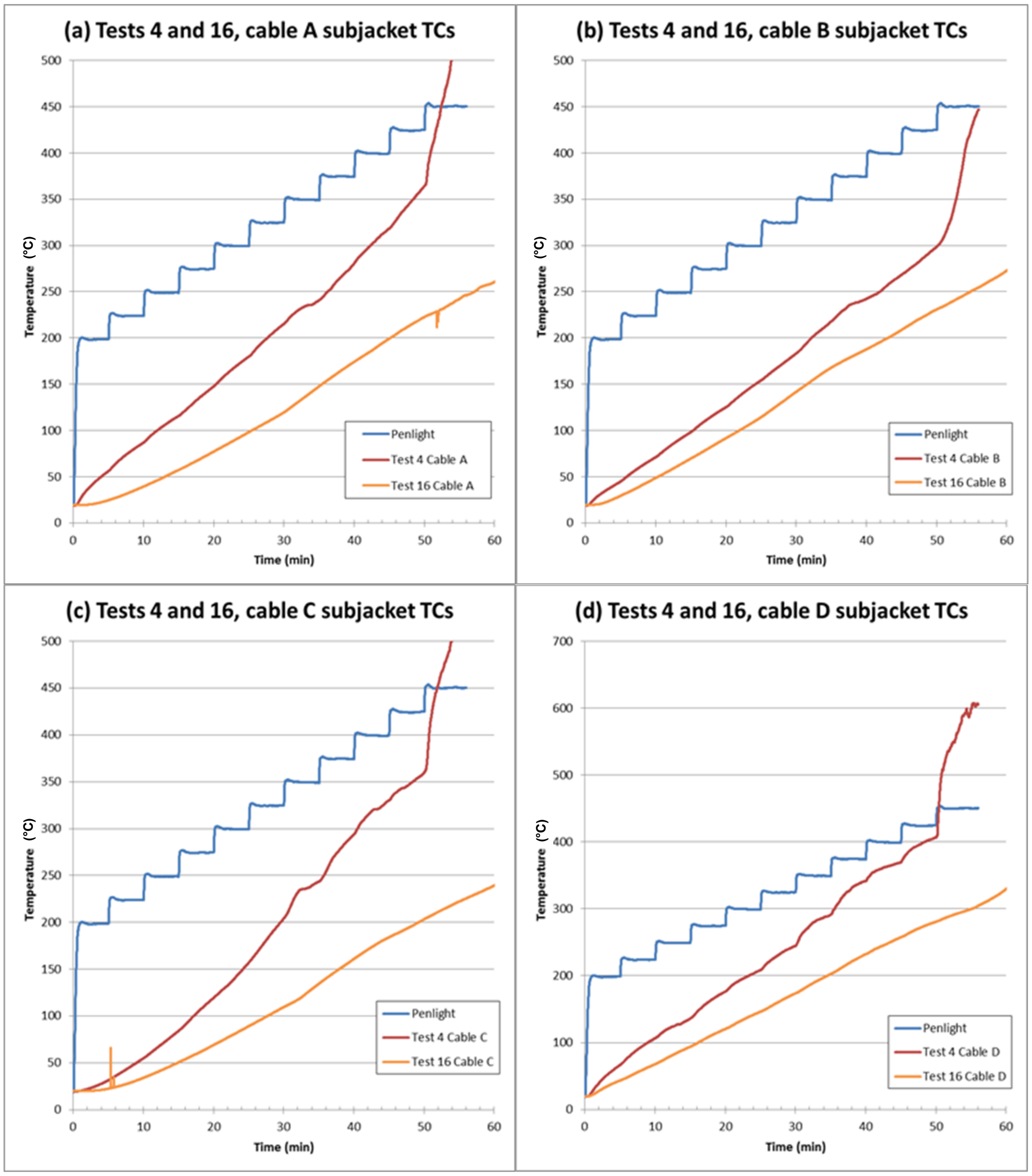


Figure C-23. Comparison of corresponding thermal response cables for the uncoated and Carboline-coated, small TP cable bundle experiments.

The TP cable small-bundle experiments mirror closely the corresponding TS cable small bundles. Both the Vimasco and Flamemastic coating led to a substantial heating delay for three of the four thermal response cables. However, the fourth cable (cable B) saw essentially no heating delay. For the Carboline coating, all four thermal response cables saw a substantive heating delay compared to the uncoated bundle.

Table C-6 shows the corresponding ignition and electrical failure times for comparison group 6. Note that the results are inconsistent. With no repeated experiments, care must be taken in drawing conclusions.

The electrical failure times showed a high level of inconsistency. Note that SCDU circuit E3 failed more quickly for the uncoated bundle compared to any other circuit. All coatings performed well in terms of this particular circuit (E3). However, for the other two circuits, the results vary by a wide margin, and in at least one case for each coating, the coated cable circuit failed more quickly than the uncoated circuit. There is no clear trend in these particular results; the results appear to be driven more by random factors, such as separation of the cable bundle, than any discernible effect that might be attributed to the coatings.

Table C-6. Summary of ignition and electrical failure times for comparison group 6.

Experiment number	Coating configuration	Time to ignition (min)	Time to electrical failure	
			Cable	Time (min)
4	No Coat	50.9	E1	51.7
			E2	55.0
			E3	32.1
8	Vimasco	52.2	E1	41.7
			E2	53.0
			E3	51.2
12	Flamemastic	47.6	E1	55.6
			E2	48.3
			E3	42.7
16	Carboline	63.3	E1	61.6
			E2	51.8
			E3	53.2

C.2.3 General Observations from the Seven-Cable Bundle Experiments

The seven-cable bundles pointed to some interesting results that impacted the design of the final experiment set involving the ten-cable bundles. One notable result is that the seven-cable bundles appear to be above the mass level needed to negate the effect of exothermic burning of the coating materials (see section 5.2). There are some inconsistencies in the thermal responses measured, but those appear to be mainly due to bundle separation rather than the mass effects. The bundle experiments did not display the same sort of impact on thermal response that the single cable samples did. With only one experiment per configuration, strong conclusions cannot be drawn.

The other effect that was clear from the bundle experiments was that separation of the bundled cables caused by heating and expansion directly impacted the response behavior. The effects of cable bundle separation are obvious in the data based on sudden temperature increases among the cables. One factor that appears to have made the Carboline product more effective under these conditions was that Carboline showed a higher degree of structural rigidity during the heating process, which tended to aid in maintaining the integrity of the bundle for a longer time.

By comparison, the Vimasco and Flamemastic products were far more pliable and, when heated, softened and even ran or dripped during the thermal exposures. Hence, these two products likely offered little in the way of structural support to the bundles. The separation behavior was delayed compared to uncoated cable, but the protective effect of the coating on the cable ties was the apparent cause of this delay. For this reason, the Vimasco and Flamemastic products performed similarly and offered somewhat less protection than the Carboline product.

C.3 Ten-Cable Bundle Experiments

Given insights from the initial experiment sets, the final set of 10-cable bundle experiments incorporated three significant design changes. First, the mass of cables was increased. The 10-cable bundle is 43 percent greater in mass than the 7-cable bundle. Second, duplicate experiments were performed for each coating configuration so that the experiment-to-experiment variability could be explored. Third, the bundles were secured more robustly.

With regard to the last point, the seven-cable bundles had been secured using nylon cable ties placed near each end of the bundle and just outside the exposure zone. These cable ties remained intact throughout the experiment, but that arrangement left the cable bundle unbound over the roughly 0.9 m (3 ft) exposure length. During the experiments, as noted in section 5.2 separation of the cable bundle significantly affected the thermal response. For the 10-cable bundles, additional nylon cable ties were used to secure the cable bundle at roughly 46 cm (18 in.) intervals. The cables were secured as in the small-bundle experiments with ties just outside the exposure zone, but two additional ties were placed along the length of each bundle within the exposure zone. The intent was to focus the results more on the coatings and less on the bundle separation behavior. All bundles used the same type of cable tie, the two extra ties were installed between the rungs of the cable tray and about 23 cm (9 in.) outboard from the exposure centerline, and the coatings were applied over the cable ties (i.e., the ties were installed before the bundles were coated and left in place).

This approach delayed separation of the cable bundle to some extent. However, in all experiments, the nylon cable ties melted before cable ignition or electrical failure times, and the cable bundles separated during the experiment. Late in the experiment series, the final uncoated bundle was constructed in order to explore the extent to which melting of the cable ties impacted the behavior of the uncoated bundles. This final experiment is referred to as the “uncoated wire-bound” configuration. The only difference between this experiment article and the other uncoated bundles is that the two extra nylon cable ties were replaced with steel baling wire, which would not melt. The use of baling wire to secure a cable bundle is not a typical industry practice; this exercise was meant only to explore how significant the time that the cable ties melted was to the measurement of event times (ignition and failure). Even for this bundle, the cables separated to some degree, but far less than in other experiments.

To illustrate the thermal response results for the large bundles, the results for cables A and B are shown. Recall that, as shown in Figure 4-10, cable A is at the center of the top row of cables, and cable B is next to cable A at the end of the top row (cable S1 is at the opposite end of the top row).

Figures C-24 through C-27 show the thermal response results over the first 30 minutes (1,800 seconds) of exposure. Figure C-24 shows the thermal response for cable A, as recorded during 13 of the 14 larger bundle experiments, with the experiments grouped by the coating configuration (only the uncoated wire-bound bundle is excluded). For each coating configuration, the results across the available trials (three or four trials per configuration) are also averaged and plotted. That is, the temperatures at each time step across the available trials are averaged for each coating configuration. Figure C-24 is intended mainly to illustrate the relative consistency of the cable response temperatures across the trials within a given coating configuration. Figure C-25 shows the corresponding results for cable B.

Figure C-26 compiles the average response curves for cable A for each coating configuration. That is, in Figure C-26, the average response values are shown for each coating configuration but not the individual trials. Also included in Figure C-26 is the one trial involving the uncoated wire-bound cable bundle. Figure C-27 shows the same results for cable B.

Note that the thermal response results show good consistency across the trials for a given coating configuration. The main inconsistency seen is the bundle separation time for the uncoated cables, which has an obvious impact on the uncoated cable thermal response. For each individual trial, when the cable bundle separated, there is a sudden jump upward in the cable temperature. The separation times for the uncoated bundle ranged from about 9.3 to 15.2 minutes. During this period, there is a divergence among the uncoated trials, but once all the bundles have separated, they largely converge to a relatively consistent response profile.

Also note that, as seen in Figure C-26, the uncoated wire-bound sample also separated with a corresponding temperature jump. The metal ties did not break or melt, but the cables still relaxed and separated as they heated and expanded. Following this point, the uncoated wire-bound bundle follows a very similar response profile to that of the other uncoated (nylon tie) bundles.

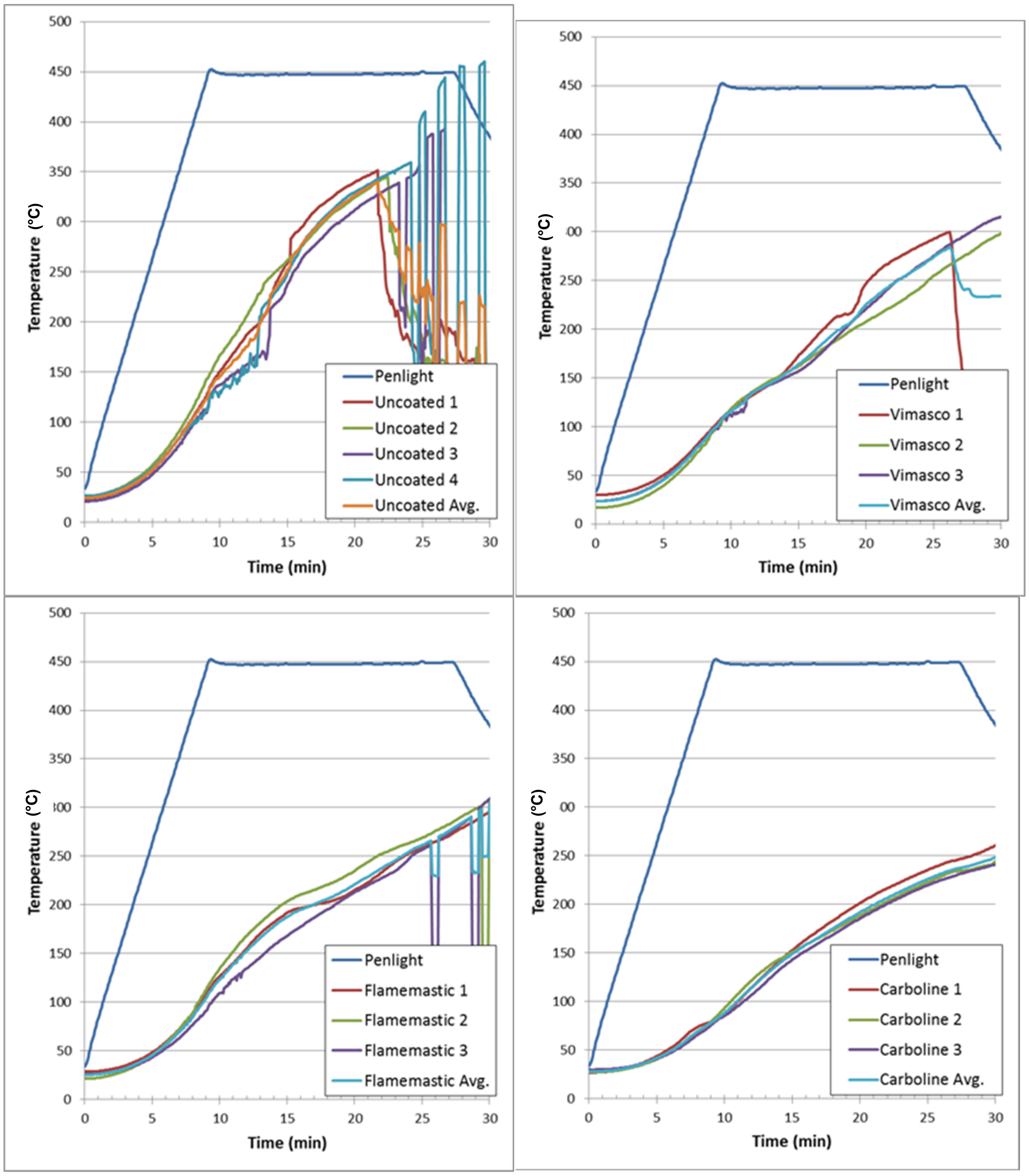


Figure C-24. Thermal response results for cable A from each of the large-bundle experiments grouped by coating configuration; includes the average thermal response across trials for each coating configuration.

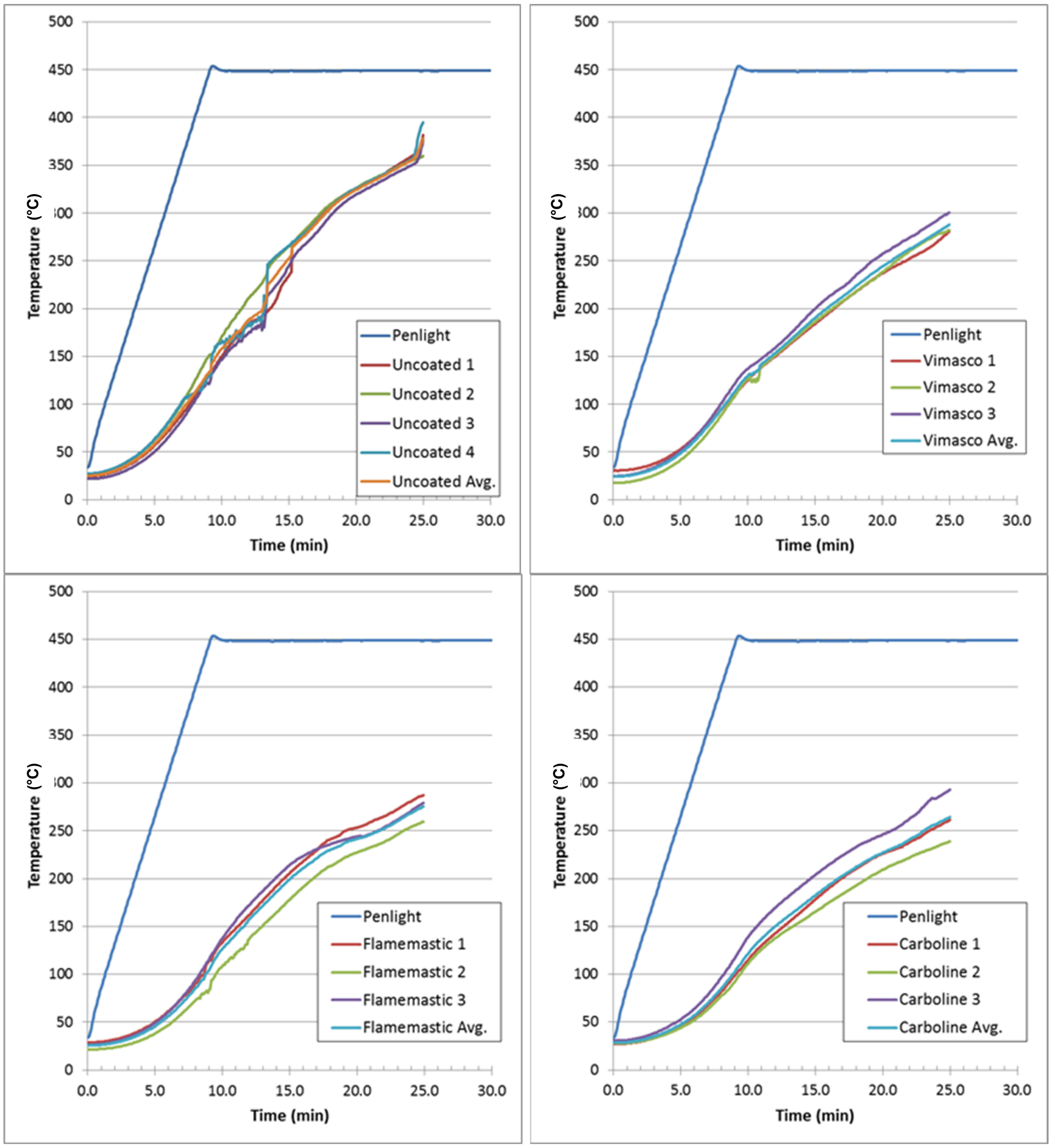


Figure C-25. Thermal response results for cable B from each of the large-bundle experiments grouped by coating configuration; includes the average thermal response across trials for each coating configuration.

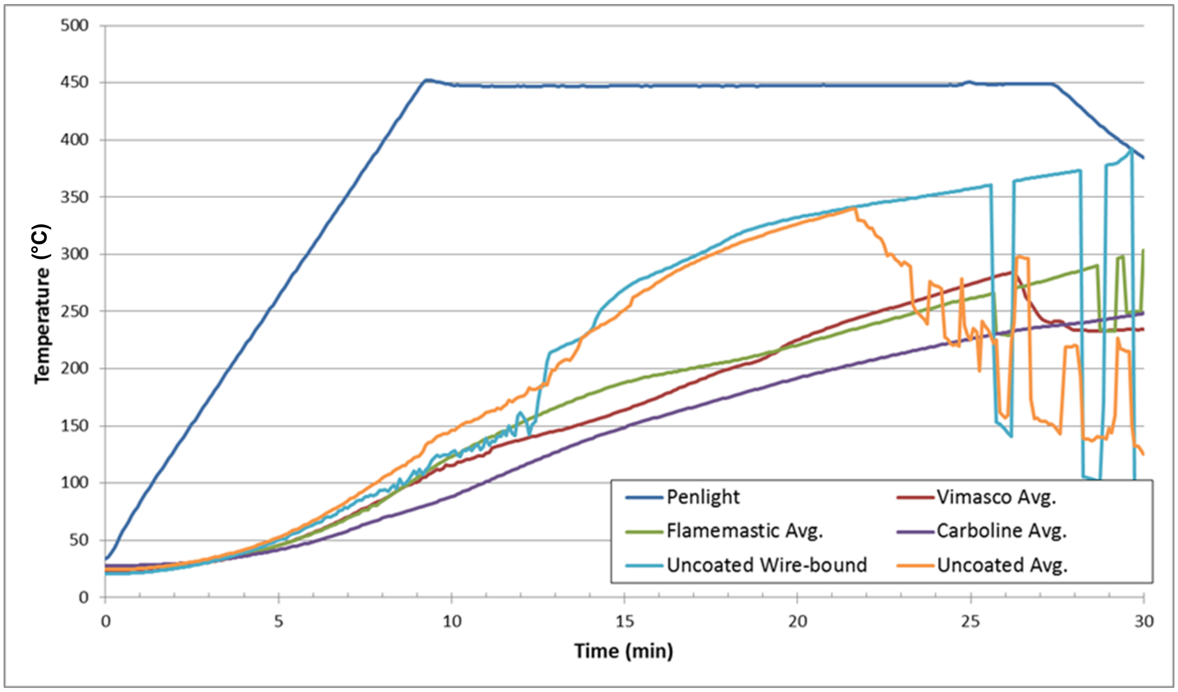


Figure C-26. Average thermal response results for cable A in the 10-cable bundle experiments, including the uncoated wire-bound experiment bundle.

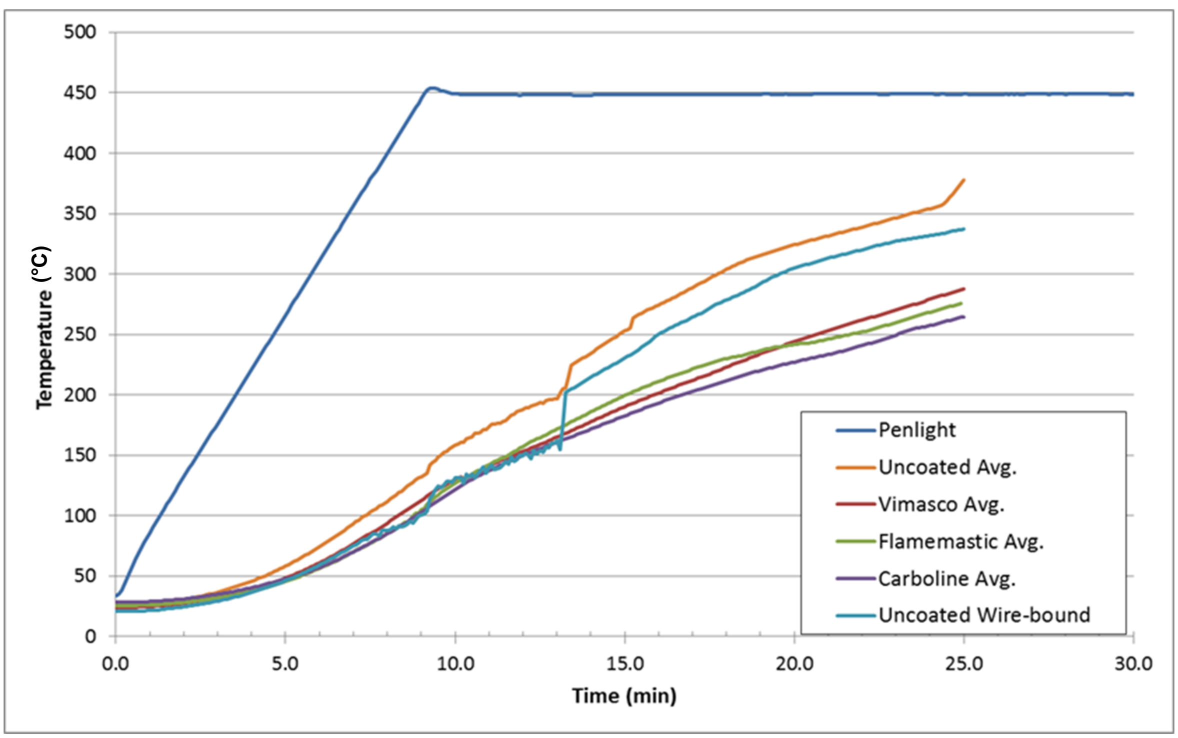


Figure C-27. Average thermal response results for cable B in the 10-cable bundle experiments, including the uncoated wire-bound experiment bundle.

The coated bundles and the uncoated wire-bound bundle follow similar heating profiles through about 13 minutes. At roughly 12 minutes, the uncoated wire-bound bundle also separated, although the steel ties did not break. A corresponding sharp temperature rise is seen in the upper cables, as illustrated in Figure C-26 and Figure C-27. The coated bundles all maintain a substantial time delay throughout the entire period shown and generally throughout the exposure period. Clearly, the bundle-separation behavior is a significant contributor to the thermal response profiles even when the bundles are well secured.