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

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ABSTRACT

This report presents the results of a series of cable fire-retardant coating tests sponsored by the US Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research and performed at Sandia National Laboratories in conjunction with the National Institute of Standards and Technology (NIST). The goal of the tests was to assess the effects of three commercially available fire-retardant cable coating materials on cable thermal and electrical response behavior under fire-exposure conditions. The specific test objectives were to assess, under severe radiant heating conditions, how the coating materials impacted (1) cable thermal response and (2) electrical integrity behavior. The tests were not explicitly designed to assess the impact of the coatings on cable flammability, although some insights relative to the burning behavior of the coating materials themselves and cable ignition times were gained. NIST is currently investigating these attributes under the Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIEFIRE) program (NUREG/CR-7010).

The cables used in construction of the test articles were all seven-conductor 12AWG (American wire gage) control or power type copper conductor electrical cables. Two cable insulation types were represented, a polyethylene thermoplastic material and a cross-linked polyethylene thermoset material. Both cable types used have been tested extensively in recent NRC-sponsored experimental programs involving both circuit failure modes and effects testing and fire growth testing. The test articles included uncoated cables and cables coated with one of three fire-retardant coating materials: Carboline Intumastic 285, Flamemastic F-77, and Vimasco 3i. Test configurations included single lengths of cables, bundles of seven cables, and bundles of ten cables.

The tests show that, under certain conditions, the fire-retardant coatings provide a substantial benefit relative to delays in cable heating, ignition and electrical failure times. However, as has been seen in prior test programs, the performance varied substantially among the coating products. The current tests also show that the benefit gained by the coatings was heavily dependent on the thermal mass of the coated cable system. Low thermal mass systems, such as the single lengths of coated cable, saw essentially no net benefit from application of the coatings. Intermediate mass systems, represented by the seven-cable bundles, saw some benefit from application of the coatings, but the benefit was inconsistent, and some cables in the bundles saw essentially no delay in thermal response or time to failure. For the larger thermal mass systems, represented by the ten-cable bundles, the benefit of the coatings was both more pronounced and more consistent with all coatings providing a measurable benefit.

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EXECUTIVE SUMMARY

Background

Between 1976 and 1978, a series of cable fire-retardant coating tests was performed under US Nuclear Regulatory Commissions (NRC) sponsorship. These tests were intended to assess the effectiveness of various cable fire-retardant coatings, in addition to certain other protection measures, on cable flammability and flame spread. To a very limited extent, the early tests also assessed the impact of the coatings on fire-induced cable electrical failures; however, given the techniques used at the time, these results are not currently seen as reliable.[1]

These early tests found that all of the tested fire-retardant cable coatings offered some measure of protection but that there was wide variation in each coating's ability to retard combustion when exposed to fire and to prevent or delay fire propagation. Extrapolation of these early tests to a specific plant configuration has been a challenge given the nature of the experiments and uncertainty regarding plant application practices compared to the test conditions.

Overview of the Current Test Program

This report covers a series of small-scale fire-retardant cable coating tests sponsored by the NRC Office of Nuclear Regulatory Research (RES) and performed at Sandia National Laboratories (SNL). The tests were designed to assess the impact of intumescent fire-retardant cable coatings on cable thermal response and electrical performance under fire conditions. The assessment of flammability effects (e.g., fire spread rates or burning intensity) was not an explicit goal of the tests, although some insights on cable ignition time were gained.

Cable heating under exposure fire conditions and, ultimately, the time to fire-induced electrical failure are key questions in a modern fire probabilistic risk assessment (PRA). The current tests were also designed as a first step in the development of better fire PRA application guidance.

Two cable types were used during this study, one thermoset and one thermoplastic. Both cables were seven-conductor control or power type cables. Both cables have been used in several prior NRC-sponsored projects, including cable failure modes and effects testing programs at SNL and cable flammability tests performed by the National Institute of Standards and Technology (NIST). As a result, both cables are well characterized relative to their electrical performance limits and flammability.

Three cable configurations were utilized in testing, single lengths of cable, small bundles of seven cables, and larger bundles of 10 cables. The test articles included both uncoated cables and cables coated with one of three commercially available fire-retardant cable coating materials: Carboline Intumastic 285, Flamemastic F-77, and Vimasco 3i.

Once samples were prepared, they were exposed to simulated fire conditions using a small-scale test apparatus known as Penlight. This apparatus creates controlled radiant heating conditions

[1] These early tests used low-voltage (28Vac) power sources not representative of in-plant control circuits and known to yield optimistic cable durability results compared to common control circuit voltages (e.g.., 120Vac).

analogous to fire plume or hot gas layer conditions. The same techniques have also been applied in several recent RES-sponsored programs[2]. While Penlight does not involve direct flame exposures, the cable samples will typically ignite and burn over the course of an experiment.

Instrumentation included thermocouples embedded in some of the sample cables to measure cable internal heating and thermal response. An electrical performance monitoring system was used to monitor other cables in order to determine the time of electrical failure (short circuits). The electrical performance monitoring system is based on 120Vac systems that allow detection of both conductor-to-conductor and conductor-to-ground short circuits. The techniques used are consistent with several recent RES-sponsored cable testing efforts.[2]

A DVD accompanies this report that includes all test data, select videos and photographs of the tests, as well as an electronic version of this report.

Conclusions

The test results showed that coating performance varied based on the specific product, the exposure conditions, and the test sample configuration. The initial results were unexpected and led to important insights. Overall, the tests demonstrated that the potential benefits to be gained by an intumescent fire-retardant coating relative to cable thermal response, ignition, and electrical failure times are heavily dependent on the thermal mass of the protected cable system. Hence, the conclusions from the testing have been framed in terms of the thermal mass of the system.

Low Thermal Mass Cable Systems

For a low thermal mass system, such as the single lengths of cable tested here, none of the three coatings provided a net benefit relative to cable thermal response, time to ignition or time to electrical failure. The response profiles for the coated cables differed from those of an uncoated cable, but the net effect, given an exposure lasting through cable ignition and failure, was negligible.

The key to understanding this unexpected result was an understanding of the coating materials themselves. All three of the coating products tests are an intumescent material, which means that, when heated sufficiently, the coating will expand from the initial dry thickness forming a low-density char layer. This low-density char layer provides an insulating effect intended to delay the transfer of heat from the fire to the coated cables. While the coating materials are of very low flammability, they are, in fact, combustible.

When the coatings ignite, they burn exothermally, which contributes some heat to the thermal system (i.e., the coated cables). Based on these tests, for a low thermal mass system, the heat contributed by burning the coating can overwhelm the initial benefits gained, based on the enhanced insulation provided by the expanded char layer. This was demonstrated by the single cable tests when, during the early stages of the heating process, a delay in cable thermal response

[2] See, for example, CAROLFIRE – NUREG/CR-6931.

was observed. However, following coating ignition, the temperatures of the coated cables caught up to, and in some cases surpassed, the temperatures measured for an uncoated cable. In the end, the ignition times and times to electrical failure were essentially identical (falling within experimental uncertainties and random variability). This behavior would be expected to extend to both individual or small bundles of cables in a cable drop (e.g., cables that drop from a cable tray into an electrical cabinet) and to cable trays with either a light cable loading or maintained spacing arrangements (i.e., where individual cables are secured to the tray rungs, and a gap between adjacent cables is maintained).

The testing suggests that, for low-thermal-mass systems (e.g., for an individually coated cable or for a group of smaller instrument, control, or communications type cables), no delays be assumed given an intumescent fire-retardant coating relative to cable thermal response, cable ignition times, or time to electrical failure. The testing also suggests that, in the analysis of fire scenarios, the ignition and damage time for a low-thermal-mass system assume that intumescent cable coatings will have no net impact. Based on this testing, the cable thermal response leading to ignition and electrical failure performs as if there were no coating present at all.

For Higher Thermal Mass Cable Systems

For the higher-thermal-mass system, as represented here by the seven-cable and ten-cable bundles, some delay in thermal response and time to failures due to the coatings was observed, but the effect was inconsistent. Note that the seven-cable bundles described here weighed about 2.8 Kg/m (1.9 lbs/ft). For these tests, some of the coated cables in the bundle saw substantial delays in thermal response (e.g., on the order of 7-10 minutes compared to an uncoated cable), but other cables in the same bundle saw no time delay at all compared to the corresponding uncoated cable. It does appear that the seven-cable bundles had sufficient mass to absorb the heat produced by burning the coating material without adverse net temperature rises. However, one important behavior that was observed is that the bundles eventually lost continuity, and the individual cables separated, which breached the integrity of the coating. That is, during heating, the cable bundles expanded, causing the cables to separate from each other. Once the cable ties holding the bundles together failed, the entire bundle opened, the cables separated, and the bundle settled into a much more open configuration. This, in turn, caused gaps to open in the coating, which exposed one or more cables in the bundle to effectively direct radiant exposure.

Based mainly on the effects of cable bundle separation, the benefits of the coating relative to thermal response delays were inconsistent. Hence, for a bundle that is not well secured, the beneficial effect cannot be relied upon in a fire scenario analysis.

The ten-cable bundles weighed approximately 4 kg/m (2.75 lbs/ft) and were clearly above the mass threshold needed to avoid the adverse effect of coating combustion. These larger bundles not only increased the thermal mass of the coated cable system but were secured more robustly using additional nylon wire ties along the bundle length. These two changes impacted the response behavior. Under these conditions, the effects of the coatings on thermal response and time to failure were both more pronounced and more consistent. All three of the coatings provided a significant degree of protection for all of the cables in the tested bundles, and both of the design changes noted above appear to have contributed to this result. The rate of temperature rise for the coated cables was substantially reduced compared to the uncoated cables. The time to electrical failure was delayed by 10 to nearly 40 minutes given the exposure protocol used in testing and depending on the coating product.

Again, one important factor in the behavior of the larger bundles is their ability to maintain a higher degree of physical integrity than the smaller bundles. That is, while the cable bundles separated to some degree, the added wire ties delayed this process by a few minutes compared to the smaller bundles, which were more loosely bound. Under these conditions, the coatings were generally able to maintain a higher degree of coverage and protection, even though separation of the expanded coating from the cables during the heating process was observed. The beneficial effects observed for the larger bundles are expected to extend to other higher-mass cable systems that are relatively well secured, including random-fill cable trays with a substantial cable loading such that the coated cables form a single, common mass.

For a well-restrained or well-bound cable system of sufficient mass (e.g., 4 Kg/m (2.75 lbs/ft) or more), benefits were observed from the application of the coating products tested in the analysis of cable thermal response and time to damage. The current practice of assuming a 10- 12-minute delay period under these conditions would be conservative.

Specific details of the recommended practice are provided in the body of this report but vary by coating type and include a recommendation that the application should establish some basis for the assumption that the coating (1) matches one of the three products tested here, (2) has been applied consistent with manufacturer recommendations, (3) has been maintained over time, and (4) has not degraded over time. Further, the recommendations include verification that the coated cables are both of sufficient mass to overcome combustion of the coating itself, and that the grouping is sufficient, restrained or bound, to prevent early shifting of the cables and breach of the coating.

Unanswered Questions and Recommendations for Follow-on Work

Several areas are identified that would be of interest if follow-on tests were performed. These areas are summarized as follows:

- Assess the potential impact of coatings applied significantly in excess of the manufacturer recommended thicknesses.
- Assess the effect of coatings on the ampacity ratings. Previous work was conducted in this area.[3] Generally, when the coatings are applied in the recommended thickness, they appear to have no adverse impact on cable ampacity, but thicker applications may increase the effects.

[3] Black, W.Z., Brown, K.W., and Harshe, B.L., "Ampacity of Cables in Trays Surrounded with Fire Barrier Material," *IEEE Transactions on Power Delivery,* Vol. 14, No. 1, January 1999, pp. 8-17

- Determine the thermal mass threshold beyond which the heat contributed by combustion of the coating itself will not negate the benefits of the added insulation, including the testing of higher-mass individual cables (e.g., larger power cables).
- Assess the performance of the coatings on various, likely cable-tray configurations, including random fill trays. Include an assessment of how cable-fill depth impacts coating performance.
- Assess direct flame impingement conditions and their impact on coating performance.
- Assess the effects of the coatings on flammability, including fire spread and burning intensity.

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ACRONYMS AND ABBREVIATIONS

7/C	seven conductor
ac	alternating current
AOV	air operated valve
AWG	American wire gage
CAROLFIRE	the Cable Response to Live Fire project
CFR	Code of Federal Regulation
CPT	control power transformer
CSPE	chlorosulfanated polyethylene
dc	direct current
DCSim Panel	direct current simulation panels
DESIREE-Fire	the Direct Current Electrical Shorting in Response to Exposure Fire project
EPR	ethylene propylene rubber
EPRI	Electric Power Research Institute
FB	fuse blow
HS	hot short
IEEE	Institute of Electrical and Electronics Engineers
IR	insulation resistance
IRMS	insulation resistance measurement system
KATE-Fire	Kerite Analysis in Thermal Environment of Fire project
MOU	memorandum of understanding
MOV	motor operated valve
NA	not applicable
NEI	Nuclear Energy Institute
NFPA	National Fire Protection Agency
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
NRR	Nuclear Reactor Regulation
PE	polyethylene
PORV	power operated valve
PRA	probabilistic risk assessment
PVC	polyvinyl chloride
RES	NRC Office of Nuclear Regulatory Research
SA	spurious actuation
SCDU	surrogate circuit diagnostic units
SNL	Sandia National Laboratories
SOV	solenoid operated valve
SWGR-C/T	switchgear close/trip circuit
TC	thermocouple

XLPE	cross-linked polyethylene
XLPO	cross-linked polyolefin

1 OBJECTIVES, TECHNICAL BACKGROUND AND APPROACH

1.1 Objectives

This report describes a series of small- and intermediate-scale fire tests to assess the impact of three commercially available fire-retardant cable coatings materials on cable thermal response and electrical failure times. The objective of the tests was to provide data that could be used to confirm and, in certain instances, update the current guidance relative to fire-retardant coatings and their credit in a risk-informed application.

The efforts described in this report were sponsored by the US Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research (RES) Fire Research Branch, and the tests were performed primarily by Sandia National Laboratories (SNL) in Albuquerque, NM. The report also includes the results of cone calorimeter tests provided by the National Institute of Standards and Technology (NIST).

1.2 Technical Background

After the 1975 Browns Ferry fire, nuclear power plant (NPP) operators and the NRC staff sought solutions to improve fire safety. Included among the possible options was the application of fire-retardant cable coatings. In the latter half of the 1970s, the NRC-sponsored fire safety research program investigated seven Factory Mutual approved fire-retardant coating materials (NUREG/CR-5384). These early efforts focused on flammability effects, including whether the coatings could prevent or delay flame spread along lengths of cables, delay cable ignition, and prevent or delay tray-to-tray fire spread of fire. The tests also explored cable electrical failure behaviors but only using low-voltage (28Vac) power sources. The use of low-voltage sources is now known to be suspect because the use of a low-voltage source is not representative of in-plant performance and generally understates cable damageability; these results are considered suspect.

The 1970's testing included gas chromatography and emission spectroscopy to determine outgassing at temperatures below 300°C (572°F). Coated-cable performance tests were then conducted in small- and full-scale experiments. Small-scale tests were conducted using the Ohio State University Release Rate Apparatus to measure relative ignition time, smoke release rates, and heat release rates for coated single- and three-conductor light power cable samples. These small-scale tests used a thermoset XLPE insulated cable. A comprehensive literature search conducted by RES on research related to the use of fire retardant coatings in cable trays is presented in Appendix A.

A set of full-scale tests was then 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 of tests involved the piloted ignition of a stack of two random-fill horizontal trays using the same gas burner. In these two phases, one- or three-conductor cables were placed in the tray(s) in a relatively open (low density) weave that left significant air gaps in and among the cables. A set of two propane-air burners was located beneath the trays. The exposures for each test would cycle the burner on for five minutes then off for five minutes until sustained ignition was observed or through a maximum of six cycles. In the two-tray tests, a noncombustible barrier was placed between the first and second trays whenever the burner was ignited. The barrier was removed when the burner was extinguished (i.e., after each 5-minute burn cycle). The intent here was to create a fire in the lower tray using the burner, but to then expose the second tray only to the burning first tray, not the gas burner. The third phase investigated the effect of a spilled hydrocarbon (diesel fuel) pan fire on a two-tray stacked similarly 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- and large-scale tests showed that all coatings offered some measure of additional protection. However, there was a wide range of effectiveness among the coatings in both their ability to retard combustion when exposed to a fire and in their ability to prevent fire propagation from one tray to another. While electrical measurements were made during full-scale testing, very little discussion and interpretation was provided on the electrical data, and, as noted above, the techniques used are no longer considered reliable. The diesel fire provided a more realistic fire exposure to the test assemblies than the propane burner tests. Delays on the order of several minutes were typical for most of the coating products.

As noted above, these early tests 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 could be gained on the electrical performance of these cables. The data indicate some relative differences both with and without coatings and from coating to coating, but are not considered reliable indicators in comparison to current practice. Also, while temperature measurements were made during the tests, the measurements cannot be correlated back to the actual cable conditions. Hence, one cannot correlate cable temperature and electrical failure behaviors, which is typical in current practice. Overall, these early tests provided important insights but do not provide the type of information of most interest to current applications, such as risk-informed applications and fire probabilistic risk assessment (PRA). That is, risk-informed and PRA applications seek to predict the temperature response and failure time behavior for cables under fire-condition exposure.

1.3 General Approach

The tests described in this report represent the first significant follow-up on cable coating performance sponsored by the NRC since the 1970s. The tests described here focus on the thermal response of coated versus uncoated cables when exposed to a severe radiant heating environment designed to simulate fire exposure conditions in either a plume or hot gas layer type condition (i.e., not including direct flame impingement). The tests were designed to measure thermal response in two ways, direct measurement of the cable temperature response and electrical short-circuit times, which have been shown in prior efforts to correlate well to insulation temperature.

The cable's temperature response was measured using thermocouples inserted below the cable's outer jacket. This technique has been used in several prior test programs and has been shown to provide good correlation between cable temperature and electrical failure behaviors (e.g., see NUREG/CR-6931). That is, prior testing has shown that the cable insulation temperature is well correlated to electrical failure, and the subjacket thermocouples provide a reasonable measure of the cable insulation temperature. Insertion of a thermocouple does potentially compromise a cable's electrical integrity, so temperature response cables are not monitored for electrical performance.

Electrical response and short-circuit behavior were monitored using two different electrical integrity measurement systems. The first system is called the Insulation Resistance Measurement System (IRMS) and measures actual insulation resistance between the conductors of a multiconductor cable and between conductors and ground. The second system is the Surrogate Circuit Diagnostic Unit (SCDU), which simulates a motor-operated valve (MOV), 120Vac control circuit including the motor starter contactor sets as active short-circuit targets.

All tests were performed in an apparatus known as Penlight, a test facility also used in the previously performed tests. Testing involved the exposure of coated and uncoated cable sampled to like exposure conditions; test comparisons were conducted between tests. Penlight is especially well suited to this type of comparative investigation because it provides a highly repeatable exposure environment.

All tests utilized seven-conductor (7/C) 12AWG control or power type cables. Two cable types were used. The first is a thermoplastic-type cable with polyethylene (PE) insulation and polyvinyl chloride (PVC) jacket. The second cable is a thermoset type cable with cross-linked polyethylene (XLPE) insulation and a chlorosulfanated polyethylene (CSPE) jacket. Cables were tested in three configurations, single lengths, a bundle of seven cables, and, in the case of the thermoset cables only, a bundle of ten cables. Additional details are provided in Section 2.

2 CABLE AND COATING SAMPLES

2.1 Overview

The cables used in testing were one thermoset (e.g., XLPE/CSPE) and one thermoplastic (e.g., PE/PVC) cable, both being of a control or light-power 7/C configuration. Both cable products have been used extensively in other recent fire testing programs (NUREG/CR-6931, NUREG/CR-7100, and NUREG/CR-7010).

Test articles included both single lengths of cable and bundled configuration of seven or ten cables each. Three different coating materials were used during this test program, Carboline Intumastic 285, Flamemastic F-77, and Vimasco 3i. Subsections 2.2 and 2.3 describe the cables and the coatings used in testing in greater detail.

2.2 Cable Descriptions

The Cable Response to Live Fire (CAROLFIRE) project (NUREG/CR-6931) explored a rather wide range of cable types in part to provide damage data for use in the fire modeling work and in part to assess whether or not the cable type had an impact on the failure modes and effects. The results indicate that, while thermoset- (TS) and thermoplastic- (TP) insulated cables behaved differently, the various thermoset cable types behaved similarly, as did the various thermoplastic cable types. For the purposes of this study, the testing focused on two of the most common available cables. The following two cables were used for this study:

- Rockbestos Firewall III XLPE insulated, CSPE (also known as Hypalon) jacketed cable,[1] (the TS cable) and
- General Cable PE insulated, PVC jacketed cable[2] (the TP cable).

These two cable types are considered representative of thermoset- and thermoplastic-insulated cables that are used most often at US NPPs. The emphasis for testing has been placed on 7/C, 12 AWG cables, which is a very common configuration in ac control circuits. Prior to the application of any coating material, the cables were cleaned and freed of any debris that could have impacted adhesion. The two cables are very similar in size and weight.

The CAROLFIRE reports (NUREG/CR-6931) provide extensive descriptions and detailed characterizations for these two cables. One characteristic of interest to this project is the cable mass per unit length. The TS cable has a net weight of 0.393 kg/m (0.275 lb/ft). The TP cable has a net weight of 0.364 kg/m (0.255 lb/ft).

[1] This cable is identified as Cable #10 in the CAROLFIRE reports.

[2] This cable is identified as Cable #15 in the CAROLFIRE reports. Note that Table 3.3 of NUREG/CR-6931 contains a typographical error relative to the cable weight in the Kg/m units. The numbers cited here are correct.

2.3 Coating Descriptions

Three different coatings were selected based on both their availability and their use in existing NPPs. These coatings were found to be a representative selection of those commonly used in industry. Note that all three of the coatings used intumescent materials, which play into the data analysis presented later in this report. Appendix B provides vendor information for each of the coatings, including material safety data sheets.

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. It should be noted that each coating had a relative shelf life between 12 and 18 months, after opening, and all samples were prepared within, at most, one month of the containers being initially opened. Subsections 2.3.1 through 2.3.3 provide a description of each material used for this study.

2.3.1 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 coated electrical cables. The wet film thickness is specified at 3.2 mm (1/8 inch), which will dry to approximately 1.6 mm (1/16 inch). Recommended cure time is 15 days, and, once dried, the coating meets code and insurance requirements for interior and exterior use.

Common application procedures for this product include palming, troweling, and spraying the material onto cables. The manufacturer stated that, if spraying, an airless sprayer should be used to apply the coating and that the product could be thinned with clean, potable water, up to 5% by volume. Given the limited number of samples to be tested and the desire to achieve uniform coverage, it was decided that palming the material would provide the most consistent and even coverage. Troweling was also attempted but did not yield the uniform results achieved with the palming technique; the material was rather stiff and thick having the consistency much like an adobe-type material or a heavy, fibrous clay. The material required considerable manipulation to achieve a uniform thickness consistent with the manufacturer recommendations. Typically the material was initially applied by the handful to the cables 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 (butyl-rubber chemical protective gloves were required for personnel safety). 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.

When the product fully cured on the samples, it was gray, and evidence of cracking along the length of the cable was observed in many of the samples (see Figure 1). It is important to note that the cracks never appeared to extend to the jacketing material. In addition, along the length of the cable, fibers were observed extending out of the coating, as shown in Figure 2. The fibers were firmly imbedded within the coating and varied in length, ranging from approximately 3.18

to 6.36 mm (1/8 to1/4 in.). Also visible in both Figure 1 and Figure 2 are small, light-brown, textured spots in the coating material.

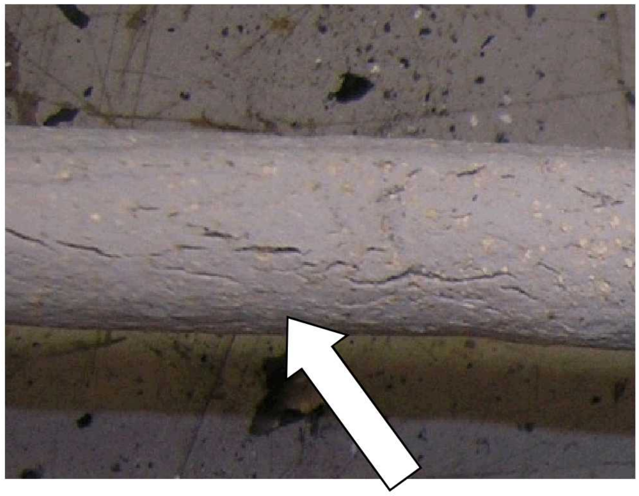

Figure 1. Cracking in the Carboline Intumastic 285 coating along cables

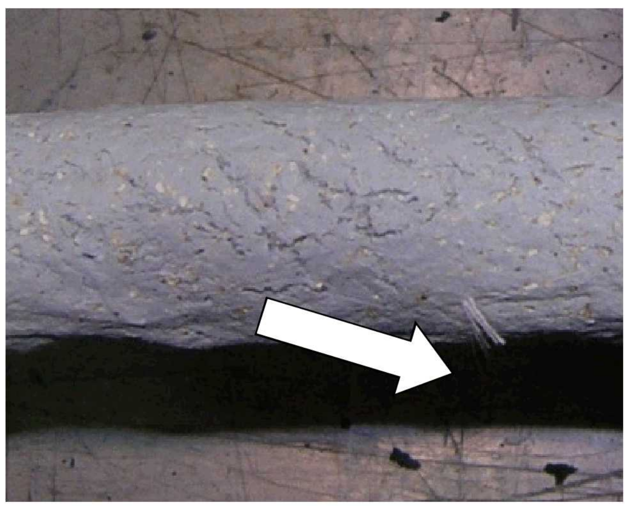

Figure 2. Fibers in the Carboline Intumastic 285 coating along cables

2.3.2 Flamemastic F-77

Flamemastic F-77 is a registered product of the Flamemaster Corporation. According to manufacturer literature, the coating material is a water-based thermoplastic resin, flame-retardant chemical, and inorganic, incombustible-fiber compound. It is further described as nonintumescent, thixotropic compound with no asbestos. There are two available product variations; one is sprayable, and the other is mastic, the latter of which was used for this test 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 two days, but the product is dry to the touch after four hours. In all cases, the tested samples cured for 14 days or longer.

Spraying is the most common application method for this coating; however, unlike the Carboline product, material thinning is not recommended since it could impact the thixotropic properties. Based on facility constraints, spraying the coating material was not attempted. The product could be applied by brushing; however, the manufacturer specified that attention needed to be given to ensure appropriate adhesion to the cable jacket. Attempts to brush the coating material onto cables proved unsuccessful because uniform coverage was difficult to obtain. It was decided that palming would be the most effective method to achieve even coverage and ensure appropriate adhesion to the cables. The Flamemastic material is much thinner than the Carboline product, having the consistency of a somewhat overly wet plaster. The material was easily applied with relatively good uniformity using the palming technique, spreading easily with minimal dripping or sagging.

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 a 9 cm (3.5 in.) bend radius was exceeded.[3] When cracking occurred, it was observed to be circumferential at the point of bending and axial along the length of the cable. Figure 3 displays a cable sample with cured Flamemastic coating. The peaks created during the application process were not uncommon and did not smooth out over the curing period. This was not deemed to affect the quality of the tests.

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

2.3.3 Vimasco 3i

Vimasco 3i, also known as Cable Coating 3i, is a registered trademark product of the Vimasco Corporation. The material is described by the manufacturer as a "a heavy-bodied, water-based intumescent coating that is designed to prevent flame spread along the jacketing of electrical (or

[3] Note that none of the samples subjected to bending was used in the thermal exposure tests.

other) cables and to provide a thermal barrier for protection against heat damage." (Vimasco 2006). 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 2006)

In terms of flammability, the manufacture states that the product "passes IEEE-383 flame propagation test …" and "will not support combustion in wet or dry state." The manufacturer also indicates an ASTM E84 flame spread index of 15, and an ASTM E162 Flammability index of 15 (Vimasco 2006). These ratings are relatively low (roughly equivalent to an epoxy resin or treated plywood). These values indicate that the material is *not* noncombustible but will burn to a limited extent, and some limited quantify of heat is produced in the burning process. This attribute turned out to be important to the interpretation of some of the test results discussed in Section 4.

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 2006) Expansion by 600% would imply an expanded thickness of 9.5 mm (3/8 in.). Recommended cure time is two days, but the product is dry to the touch after two 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. Application by palming was messy process because the material flowed and sagged far more than the other products. 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, for some samples, a thin secondary coat was applied to ensure an even coating and complete coverage. This is an acceptable practice per the manufacturer instructions.

In the last two test sets, which used the seven-cable and the ten-cable bundles, the cables were coated in the tray and in a horizontal configuration. 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. No attempts were made to remove excess material from such locations, although 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 test samples because the locations were away from the tray central point where the most severe exposure occurs. During testing it was noted that some of this excess material would soften and drip from the trays prior to ignition.

Peaks in the coating that were created during application 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 the most flexible of the three tested. Although it was dry to the touch after the recommended curing time, the material still felt tacky. This tackiness would cause samples to adhere to adjacent cables if not completely separated. The adhesion was sufficiently strong to prevent the samples from being separated without damaging the cured coating. When this occurred, these damaged samples were not used. A photo of a cable coated with the Vimasco product is shown in Figure 4.

Figure 4. Fully cured Vimasco 3i on a cable sample

3 TEST ARTICLE CONSTRUCTION AND THE TEST APPARATUS

This section describes the test articles, instrumentation, and the test apparatus used. Section 3.1 describes how the various test articles, including both the single cables and bundles, were prepared and instrumented. Section 3.2 describes the Penlight apparatus used to create the exposure environment. Section 3.3 describes the two electrical performance-monitoring systems used in testing.

3.1 Sample Preparation

The goal of this study was to investigate the effect cable coatings have on cable thermal response. In particular, the goals were to determine if, under fire-exposure conditions, the coatings would delay cable heat-up and/or the time to electrical failure. Times to cable ignition were also noted although flammability effects were not a primary objective in these tests.

To achieve these goals, cable samples were prepared for one of two measurements. Some cables were instrumented using thermocouples (TCs) that measured directly the heating effects and thermal response timing. Other cables were monitored for electrical performance. These techniques mirror those developed for the CAROLFIRE project (NUREG/CR-6931) and other, more recent programs.

The first test 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 mid-length (center)[7] and two located 23 cm (9 in.) off center, west of Penlight. For these early tests, TCs were also placed on the outer surface of the cable jacket material, opposite each subjacket TC prior to application of the cable coating. Figure 5 shows a sketch of a typical thermal response cable as used in the single- and small-bundle tests. The brown outer color represents the coating material, and the red dots represent TC positioning. Figure 6 shows the location of the thermocouples 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.

The TCs placed below the outer cable jacket were installed using a technique where a small slit was cut in the jacket allowing insertion of the TC bead. The bead itself was typically inserted to 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).

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[7] Note that the cable mid-point or center position corresponds to the axial and radial center of the cylindrical Penlight heating shroud when the samples are installed for testing. This is the location where the most severe thermal exposures occur (based on shroud-to-target geometry).

After being instrumented, the cables were suspended vertically using an A-frame drying rack as shown in Figure 7Figure 7. The heads (or connector end) of the thermocouples were covered with plastic bags to prevent inadvertent contact with the coating material. The thermocouple lead wires were secured to the cables with fiberglass tape and coated along with the cables. As noted in Section 2, all three coatings were applied by palming, using the unused, as-shipped coating materials rather than thinning the material.

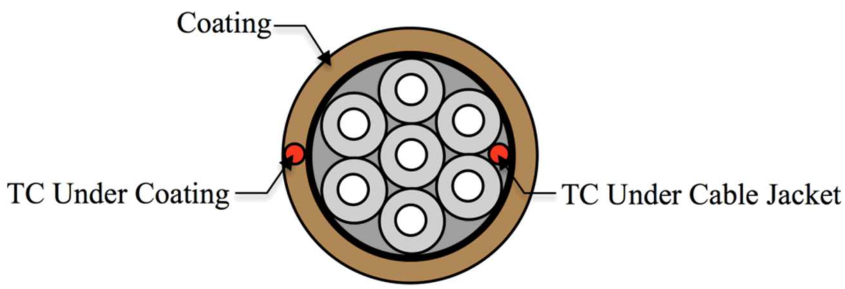

Figure 5. Cross-sectional view of a 7/C cable with thermocouple locations

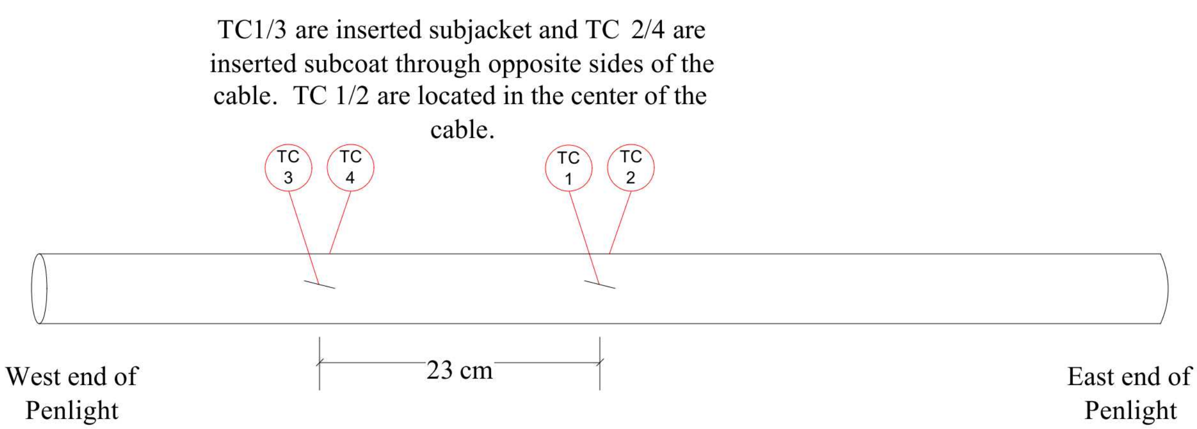

Figure 6. Longitudinal view electrical cable instrumented with thermocouples

Figure 7. Welded A-frame used to suspend single lengths of cable for the coating process

For the second set of tests, two individual lengths of cable were tested simultaneously; one was instrumented for thermal response (a TC cable), and one was instrumented for electrical performance. In these tests, the two cables were placed in symmetric positions on either side of the cable tray centerline. Figure 8 illustrates this dual-cable setup, including the separation distance, 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 thermocouple on or within a cable could impact the electrical failure behavior.

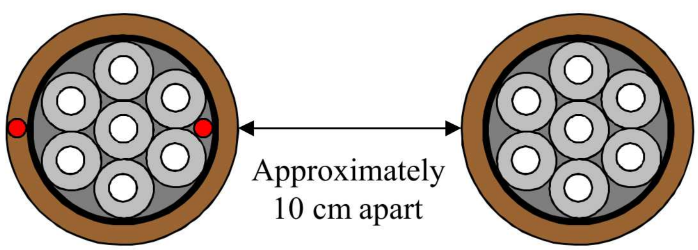

Figure 8. Example thermocouple arrangement for temperature monitoring (left) of 7/C cable located near the electrically monitored (right) cable in tray

The third test set involved small cable bundles. Each bundle consisted of seven similar cables, 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 9. 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 10 shows some of the seven-cable bundles curing within their respective trays.

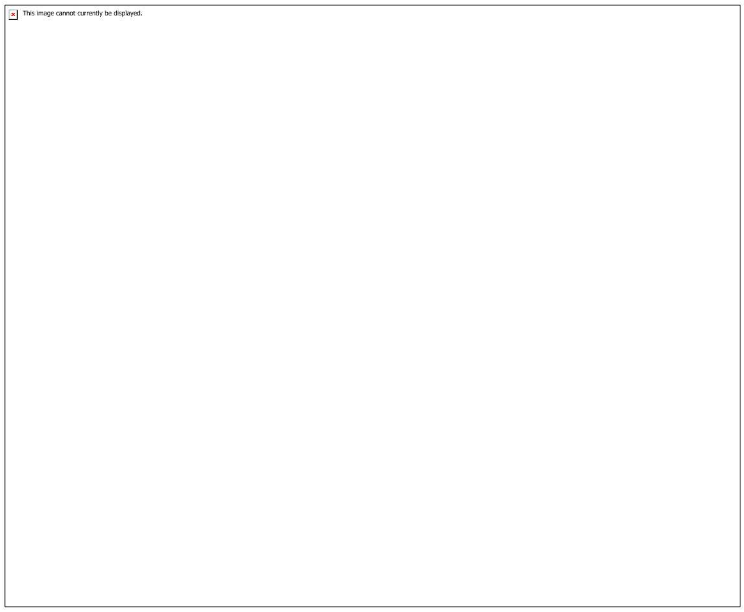

Figure 9. Arrangement of thermal response and electrical performance cables in the seven-cable bundles.

Figure 10. The curing of bundled and single lengths of cables.

The last test set involved the ten-cable bundles. These bundles were similar in configuration to the small bundles, but three additional thermal response cables were added. The physical arrangement is shown in Figure 11. 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, although the ten-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 12 in. outboard to each side of the central location (between tray rungs), and these ties remained in place during testing. As noted above, the seven-cable bundles only used cable ties at the remote ends of the bundles, and separation of the cable bundles was seen to affect the thermal response. The ten-cable bundles used two additional cable ties each in order to determine how this would affect behavior (discussed further in Section 5).

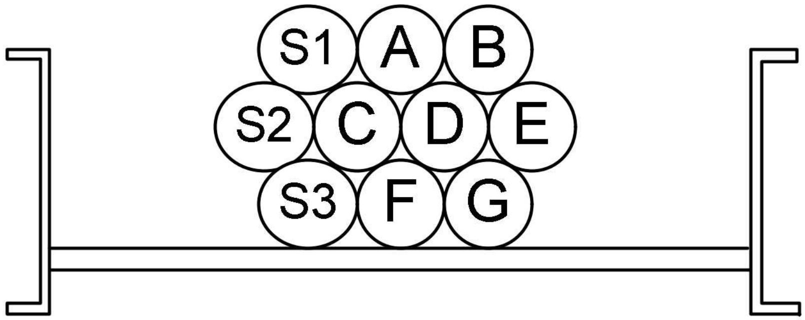

Figure 11. Ten-cable bundles

All of the ten-cable bundles were constructed using the TS cable only. No tests were performed using the TP cables in this configuration. The thermal-response results for the TS cables should extrapolate well to a similar bundle of TP cables up to the failure temperature of the TP cables. The reason is that the 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 to the point of electrical failure. The two cables are also similar in mass and physical size. Hence, the predegradation thermal responses to the same exposure environment would be very similar through the point of TP cable failure. Eliminating the TP cables from this test configuration allowed more repetition of the TS bundle configurations (i.e., three or more repeats for each configuration).

Per the manufacturer's specification, the coating materials required between 2 and 15 days to fully cure. After the curing process, the prepared samples were re-inspected to ensure that there were no gaps in the coverage and that thermocouples were still in place beneath the fire-retardant material. No cables were found with gaps in the coating coverage, but a few cases were found where the TC bead had become exposed during curing. For the samples that had an exposed TC bead, such as the case as shown in Figure 12, additional coating material was applied in the area around the bead and allowed to cure for the recommended period. This was not necessary for the ten-cable bundles since these cable-surface TCs were not used.

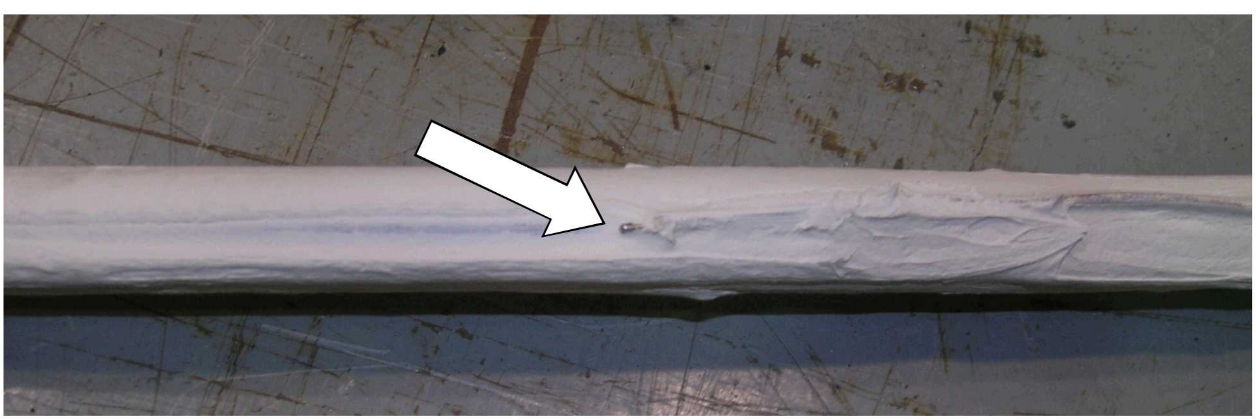

Figure 12. Example of an exposed thermocouple bead, shown on a single cable specimen. The TCs in these cases were re-coated prior to testing.

3.2 Penlight Heating Apparatus

3.2.1 General Description of Penlight

The equipment and physical test configurations used for these tests are essentially identical to the small-scale tests performed during CAROLFIRE (NUREG/CR-6931). Volume 2 of that report provides a detailed description of the small-scale tests facilities and the general test protocols.

Penlight is a radiant heating apparatus, shown in Figure 13. Penlight 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, reradiating heat to a test sample located within the shroud. The exposure temperature is monitored and computer controlled based on thermocouples mounted on the inner surface of the shroud. 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. That is, the hot-gas layer, thermal-exposure environment is dominated by radiant heat exchange between the hot, smoke-filled, gases and any immersed objects. The hot, smoke-filled gases act largely as a gray-body radiator. Penlight simulates these conditions with the shroud temperature being analogous to the hot-gas layer or smoke temperature. The relationship between shroud temperature and shroud heat flux, assuming an emissivity of 0.815, is shown in Table 1.

Figure 13. The Penlight apparatus

All of the tests in this study were conducted on a 30-cm-wide (12 in.), ladder-back style cable tray suspended through the center of the Penlight shroud. The cable trays and other physical test conditions are effectively identical to those used in CAROLFIRE (NUREG/CR-6931).

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

Temperature (°C)	Heat Flux (kW/m²)
200	2.32
225	2.85
250	3.46
275	4.17
300	4.99
325	5.92
350	6.97
375	8.16
400	9.49
425	10.98
450	12.64
475	14.48
500	16.51
525	18.75

3.2.2 Penlight Heating Profiles

The experimental exposure profile is defined by the Penlight shroud time-temperature history and varied by test set. In most of the early tests (Tests 1-24, including repeat tests 1a, 19a and 20a) and test 32, Penlight was initially set to a moderate temperature set point given the cable type. For the TP cable samples the initial temperature was set to 200ºC (392ºF), while for the thermoset cable samples, the initial temperature was set to 300ºC (572ºF). These temperatures are well below the anticipated cable failure thresholds. For the balance of the test, the Penlight set point would be increased by 25ºC (77ºF) every 5 minutes until either failure or ignition was observed.[8] The cable ignition time varied from test to test. Once ignition occurred, the power to the Penlight lamps was be cut, and a cool-down period began. The stepwise increase profiles are illustrated in Figure 14. Note that, in data plotting, for tests using these profiles, time=0 is defined as that time when the first step increase from ambient to either 200 or 300ºC (392 or 572ºF) is input into the Penlight controller. Penlight typically reached the new set point within 1 minute.

[8] The one exception to this profile among the first two test sets is Test #1, during which the temperature was increased in 10°C (50°F) increments every 5 minutes rather than 25°C (77ºF).

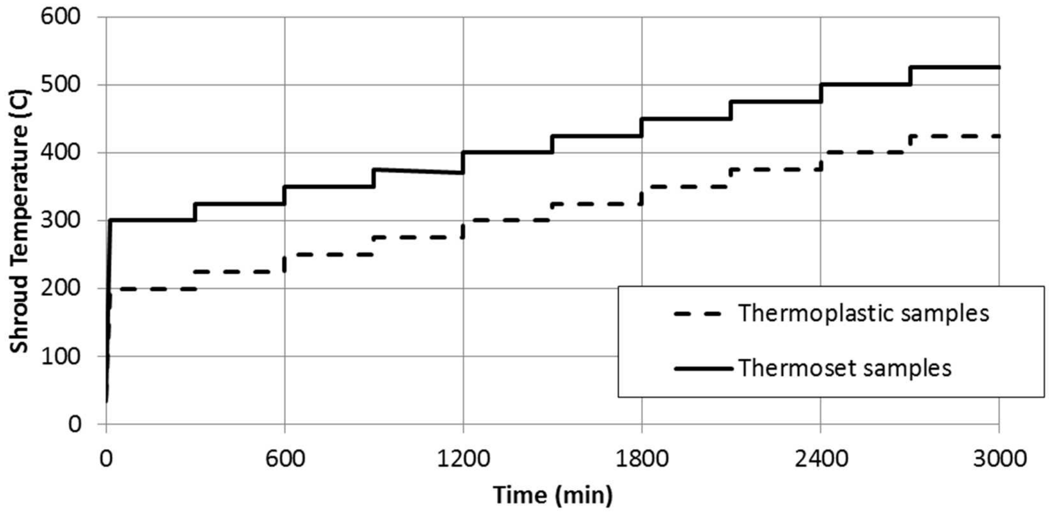

Figure 14. Heating profiles using stepwise 25°C (77ºF). increases

Note that, relative to the Penlight exposure profiles, the exposure conditions are highly reproducible. The data analysis presented in Section 5 will use comparison groups to illustrate the test results and insights gained. Comparison group 1 includes the single cable thermoset cable tests, using the stepwise increasing exposure profile illustrated in Figure 14. This comparison group can also be used to illustrate the consistency and reproducibility of the Penlight exposure conditions.

Comparison group 1 includes eight tests each, beginning with an initial set point of 300°C (572ºF), with subsequent 25°C (77ºF) increases every 5 minutes. Figure 15 shows the measured Penlight shroud temperature for all eight tests in this comparison group. The exposure profiles are virtually indistinguishable with two minor exceptions, both associated with test 9. In test 9, the step from 375°C to 400°C (707 to 752ºF) was delayed by approximately 20 seconds, compared to the other seven tests in the group. Test 9 also made a final step from 475°C to 500°C (887 to 932ºF), at approximately 2400 seconds (40 minutes), that the other tests did not make. Overall, the test-to-test differences in the exposure conditions are quite trivial, and the test-to-test differences within the other comparison groups described in Section 5 below are even less significant. As a general practice, in analyzing and presenting comparative test results within a comparison group, plots will show the Penlight temperatures recorded during the first test in the group as indicative of the group's exposure condition. For example, the Penlight shroud temperature measured during test 1a will be used in all data plots as typical of the exposure conditions for comparison group 1.

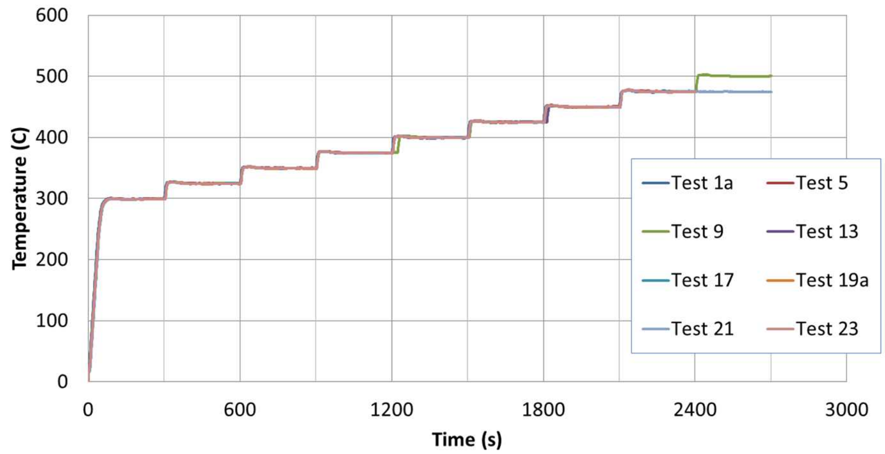

Figure 15. Penlight shroud temperatures for the tests in comparison Group 1

The second exposure profile used in testing was that used in tests 25-31, all of which involved single lengths of the thermoset cable. For these tests, Penlight was raised to a set-point temperature and held constant for the duration of the test. The set-point temperatures used ranged from 300°C (572ºF), which is well below the anticipated damage threshold for the thermoset cables, and 450°C (842ºF), which typically results in rapid ignition of an uncoated cable. In tests 29, 30 and 31, the test was intentionally ended prior to ignition so that the condition of the coatings after heating could be observed.

The third and final exposure profile was used for all of the ten-cable bundle tests (tests 33-46). The step-wise profile shown in Figure 14 was designed to nominally represent a transient fire development profile; however, the step-wise temperature increases complicated the analysis. As described subsequently, data analysis ultimately included consideration of the rate of temperature rise for coated and uncoated cables. Each of the step increases resulted in a spike in the cable temperature rate-of-rise data stream; that is, each step increase is reflected in the thermal-response data as a short-term doubling or tripling of the rate of temperature rise. These spikes tended to mask other behaviors of potential interest.

For the larger ten-cable bundle tests, a ramp-and-hold profile was used instead of the stepwise increases. To establish a common starting point, Penlight was initially raised to 35°C (95ºF) and held there for 10 minutes. The primary exposure profile then began with a ramp from 35°C (95ºF) to 450°C (842ºF) at a rate of 45°C (113ºF), per minute. Note that 450°C (842ºF) is well above the damage threshold for the thermoset cables used in testing. The temperature was then held constant at 450°C (842ºF), generally, until failures were observed on two of the three surrogate circuit diagnostic units (SCDU) modules, typically S1 and S2. In all cases, this was after the time of ignition. This heating profile is illustrated in Figure 16. 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 noted, that time=0 is defined for these tests as the time when the primary ramp (i.e., from 35 °C to 450°C (95 to 842ºF)) was initiated. All of the data plots for this test set use this same time convention.

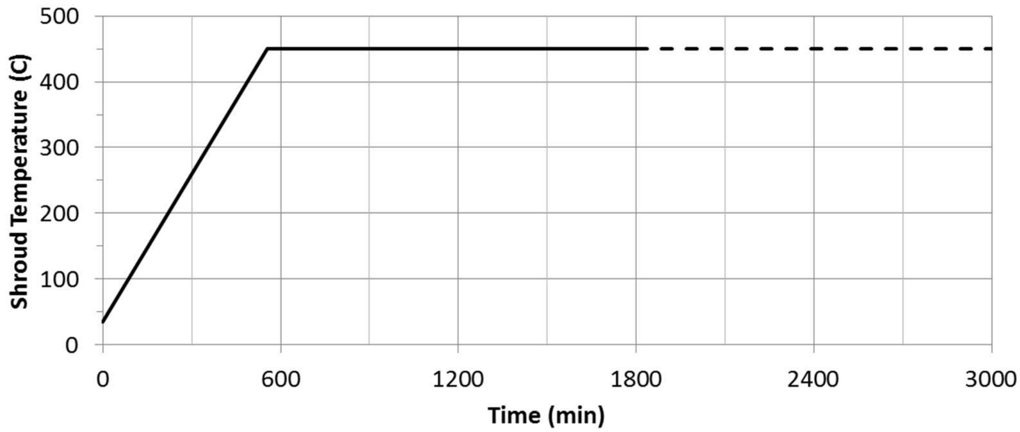

Figure 16. Shroud temperature profile used in the final test set involving the ten-cable bundles

3.3 Cable Electrical Performance Monitoring Units

Two diagnostic systems were used to measure cable electrical performance and failures. Both systems are based on 120Vac-powered electrical sources, and both systems have been used in multiple test programs to analyze the failure modes and effects of cables subjected to adverse thermal environments. The characteristics of these two diagnostic systems are described briefly in the following subsections.

3.3.1 Surrogate Circuit Diagnostic Unit

The SCDU was developed for CAROLFIRE, and an extensive description of the system is provided in Appendix C of NUREG/CR6931-V1. The SCDU system includes four separate modules, each providing the ability to simulate one 120Vac control circuit. The typical test configuration simulates a motor-operated valve (MOV) control circuit with a pair of interlocked motor starter contactor units, although other configurations are possible. Figure 17 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 this test series. 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-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 test cable and this path is marked "G").

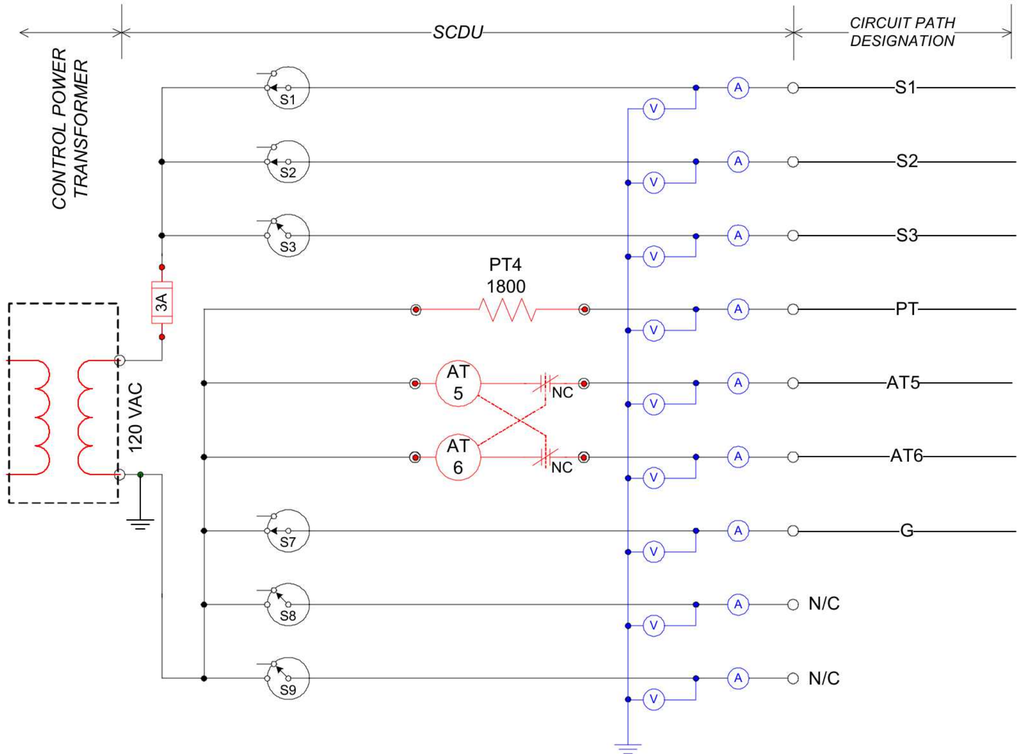

Figure 17. Circuit diagram for a generic SCDU including an active electrical interlock on the contactor pair

The motor starter sets used as active targets are Joslyn-Clark[9] motor starters of the same type used in the original Electric Power Research Institute (EPRI) / Nuclear Energy Institute (NEI) Fire Test Program (EPRI TR 1003326). The pickup and dropout voltages and holding current for each contactor in the three SCDU (SCDU1-3) modules used in this program are presented in Table 2.

For the tests in this study, the SCDUs were connected in a simple, first-failure detection configuration rather than the standard MOV wiring configuration typically used in CAROLFIRE (NUREG/CR-6931). The main goal relative to performance monitoring for this test 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 also will detect a short between an energized conductor and an external ground (e.g., the cable tray).

[9] Catalog number 30U031.

Table 2. SCDU motor contactor characteristics.

	MOV ID	Pickup voltage (Vac)	Holding current (A)	Dropout voltage (Vac)
SCDU1	AT5	93.9	0.07	71.7
	AT6	80.5	0.08	67.1
SCDU2	AT5	81.1	0.08	60.1
	AT6	79.7	0.08	69.5
SCDU3	AT5	82.3	0.09	64.6
	AT6	83.2	0.08	57.5

For the coatings tests, the energized 7/C cables were connected using a combination of energized sources, S1 and/or S2, and active targets, AT5 and/or AT6 (see Figure 17.). The sources and targets were connected to alternate cable conductors in the outer ring of six cable conductors. The central conductor was not connected or monitored during testing because prior testing has shown that the central conductor is always the last conductor in the cable to fail because it is thermally protected by the outer ring of conductors. The SCDU test configuration is illustrated in Figure 18, where "S" represents an energized source conductor, and "T" represents an active target. Note that use of the active targets yields a realistic and representative cable failure condition because activation of an active target caused by a conductor-to-conductor hot short is a realistic representation of cable failure conditions in real applications.

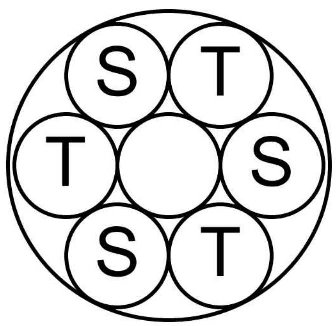

Figure 18. Typical configuration for the SCDU modules as connected to a single, 7/C electrical performance cable.

Given this configuration, any conductor-to-conductor short between adjacent conductors would activate the associated target device (one of the motor contactors). Conductor-to-ground shorting for any of the energized conductors would result in a blown-fuse failure. Note that, in the analysis of the SCDU test data, the only values of interest 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). The voltage and current on all circuit paths are routinely monitored by the data-logging software and are included in the data file, but the values for other circuit paths have no relevance given the test configuration used here.

3.3.2 The Insulation Resistance Measurement System

The Insulation Resistance Measurement System (IRMS) was originally developed as a part of the NRC Office of Nuclear Regulatory Research (RES) collaboration on the 2001 EPRI/NEI Fire Test Program (EPRI TR 1003326). A detailed description of IRMS is available in NUREG/CR-6776. The system was also deployed during CAROLFIRE (NUREG/CR-6931) where the design, operation, and data analysis associated with the IRMS remain are described.

IRMS uses 120Vac (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 (IR) values between conductor pairs (conductor-to-conductor or c-c resistance) and between conductors and ground (c-g resistance) can be calculated.

The graphs for each IRMS test presented in the appendices depict the electrical response of the test cable based on either c-c minimum or c-g minimum. In these graphs, c-c minimum is the lowest conductor-to-conductor IR value measured among the various conductor pairs within a cable sample at each time step. Similarly, c-g minimum is the lowest conductor-to-ground IR value among the various conductors within a cable sample at each time step. These data highlight the first failure to occur which is the primary measure of interest to the current tests. IRMS was used in only 10 of the current tests (see Section 4 for test configurations).

3.3.3 Thermocouple – SCDU Interference Issues

Potential interference issues between the electrical performance monitoring systems and the thermocouples exist when used in the same test. This has been observed as a minor issue in past tests but became a more significant issue here, in particular, during the final set of ten-cable bundle test.

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

Specifically, given three SCDU modules energized, as the test article cables heated beyond approximately 300°C (572°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 test in the set (test 34, uncoated #2) made no difference at all, and the formation of false junctions in multiple TCs concurrently is highly unlikely. During the third test performed in this series (test 38, Vimasco #1), the undeniable correlation between the SCDU and the TC faults was identified. As soon as the SCDU modules were powered down, the thermocouple 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 test 38 pointed to a simple strategy to mitigate the effect. For the remainder of the tests, the SCDU system was left de-energized until well into the exposure and was then cycled on/off to optimize gathering of both temperature and electrical data. As the cable temperatures approached damaging levels (e.g., around 370°C (698°F), for this particular cable), the SCDU modules were cycled on for short times (roughly 30 seconds per cycle) and then turned back off. Cycles were repeated at one-to-two 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 one to two minutes at a time and then cycled off for 30 seconds until electrical failures were observed when the modules were turned off and left off.

In the end, the interference problems compromised to some degree the first three ten-cable bundle tests performed. In particular, the temperature data for tests 33, 34 and 38 (uncoated #1 & #2 and Vimasco #1) were compromised during the later stages of each test.[10] 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. The remainder of the tests used the SCDU cycling strategy and will show gaps in the temperature data during later stages of the test; these tests, however, provide essentially intact pre-ignition temperature data and periodic post-ignition temperature data.

The data from all tests are reported and have been included in the analysis because the effect is quite obvious and can easily be accounted for. Further, the temperature data are primarily of interest prior to cable ignition. Beyond the point of ignition, temperature data become unreliable because the measurement bead may pop out from under the cable jacket, making that which is actually being measured uncertain. Finally, the SCDU electrical performance data are not of any interest until the time that cable degradation becomes significant and when shorting actually occurs. As demonstrated in prior tests, cable electrical performance tends to remain nominal (good) until a threshold is reached at which time electrical degradation progresses quickly to full shorting (typically over a matter of 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.

[10] Note that one extra uncoated sample was constructed to make up for data losses during the first two uncoated sample tests. Time and materials were not available to allow for construction of a fourth Vimasco test article.

4 TEST MATRIX

The test matrices are shown in Table 3 and Table 4. Table 3 defines those tests involving single lengths of cable and those involving the seven-cable bundles. These tests are characterized by the following parameters where an "X" in a given column indicates the active choice for each experimental variable:

- Cable type. Either thermoplastic or thermoset, as described in Section 2.2.
- Single cable or bundle. Specifies whether the test samples were single lengths of cable or a seven-cable bundle. Note that, in some of the single length test, there was more than one length of cable present (e.g., both temperature response and an electrical response cable). For these tests, the cables are coated individually and maintain spatial separation in the tray. The typical practice is to place two cables in symmetric locations 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 perform system. Specifies either IRMS or SCDU for those cases in which an electrical performance monitoring cable was present.
- Starting exposure temperature. Defines the initial set-point temperature of Penlight. In the case of the stepwise increase profiles (see Section 3.2.2), the initial set point is either 200ºC or 300ºC (392 ºF or 572ºF), for the TP and TS samples, respectively.
- Final exposure temperature. Defines the final set-point temperature of Penlight. For the stepwise increase cases, this differs from the initial temperature, but for the single-step increase cases, the initial and final temperatures are the same. The final temperature is also driven by test duration – longer-duration tests end at a higher temperature, and duration is dependent on time to ignition.

Note that the last three tests shown in Table 3 (1a, 19a and 20a) represent tests that were repeated for various reasons. Test 1 was the only test where the Penlight shroud was initially set to 300ºC (572ºF), and increased by 10ºC (50ºF) every 5 minutes. Test 1a was performed using the modified stepwise profile using 25°C (77ºF) jumps every 5 minutes. Tests 19a and 20a are repeated tests for tests 19 and 20, respectively. Test 19 was repeated because the subjacket TC was found to be between the tray rung and the cable, which could affect the data. Test 20 was repeated because two TCs were installed subjacket, but the subcoat TCs had been omitted.

Table 4 provides the matrix for the final test set, all involving the ten-cable bundles. The matrix here is much simpler because all tests in this set used the same cables (i.e., TS type), the same general test configuration (the ten-cable bundle), the same SCDU setup, and the same heating profile (the ramp and hold profile described in Section 3.2.2). Hence, this matrix simply distinguishes the test article identifiers and the coating, if any, applied. Note that there is one test (37) identified as "uncoated – wire bound." The purpose and configuration of this test is described in Section 5.4.

Table 3. Test matrix for the single- and seven-cable-bundle, cable coatings tests.

Test #	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		
1[1]	X		X		X				X			300	470
2	X			X	X				X		X	300	450
3		X	X		X				X			200	525
4		X		X	X				X		X	200	450
5	X		X			X			X			300	475
6	X			X		X			X		X	300	475
7		X	X			X			X			200	425
8		X		X		X			X		X	200	450
9	X		X				X		X			300	500
10	X			X			X		X		X	300	475
11		X	X				X		X			200	450
12		X		X			X		X		X	200	425
13	X		X					X	X			300	475
14	X			X				X	X		X	300	500
15		X	X					X	X			200	450
16		X		X				X	X		X	200	500
17	X		X		X				X	X		300	475
18		X	X		X				X	X		200	425
19[1]	X		X			X			X	X		300	475
20[1]		X	X			X			X	X		200	400
21	X		X				X		X	X		300	475
22		X	X				X		X	X		200	375
23	X		X					X	X	X		300	475
24		X	X					X	X	X		200	450
25	X		X		X				X		X	450	450
26	X		X			X			X		X	450	450
27	X		X				X		X		X	450	450
28	X		X					X	X		X	450	450
29	X		X			X	X	X	X			300	300
30	X		X			X	X	X	X			350	350
31	X		X			X	X	X	X			400	400
32[2]	X		X			X	X	X	X			300	525
1a[1]	X		X		X				X			300	475
19a[1]	X		X			X			X	X		300	475
20a[1]		X	X			X			X	X		200	425

Notes:
1. Tests 1, 19, and 20 were repeated as tests 1a, 19a, and 20a, respectively.
2. Test 32 was run with the ends of the Penlight shroud open to allow videotaping. All other tests were run with the ends covered. The open ends change the exposure environment, so this test should not be compared to other similar tests run in the closed-end configuration.

Table 4: Matrix of ten-cable bundle tests.

Test Number	Test article identifier and coating configuration	Notes:
33	Uncoated #1	TC failures observed
34	Uncoated #2	TC failures observed
35	Uncoated #3	SCDU cycling strategy
36	Uncoated #4	SCDU cycling strategy
37	Uncoated – wire bound	Special test using baling wire for cable ties
38	Vimasco #1	TC failures observed
39	Vimasco #2	SCDU cycling strategy
40	Vimasco #3	SCDU cycling strategy
41	Flamemastic #1	SCDU cycling strategy
42	Flamemastic #2	SCDU cycling strategy
43	Flamemastic #3	SCDU cycling strategy
44	Carboline #1	SCDU cycling strategy
45	Carboline #2	SCDU cycling strategy
46	Carboline #3	SCDU cycling strategy

5 SUMMARY OF TESTING RESULTS AND OBSERVATIONS

5.1 Organization and Content

A summary of the test results is presented in this section with specific plots chosen to illustrate key aspects of the testing. Section organization is as follows:

- Section 5.2 includes the single cable tests for both thermoplastic and thermoset cables.
- Section 5.3 includes the seven-cable bundle tests.
- Section 5.4 includes the final test set involving the ten-cable bundle test.

In addition to the summary information presented here, a full set of data plots for all of the tests is presented in the appendices as follows:

- Appendix C includes the temperature profiles for the single cable and seven-cable bundle tests.
- Appendix D includes the SCDU data for the single cable and seven-cable bundle tests.
- Appendix E includes the IRMS data for the single cable and seven-cable bundle tests.
- Appendix F includes all data for the ten-cable bundle tests.

Unless otherwise noted, the cable temperature-response plots and data analysis presented in this section are based on the centrally located cable subjacket thermocouples. For example, with the single cable tests data, presentation and analysis are based on TC-1. For the seven-cable bundle tests, the TC numbers are specific to each cable. For the ten-cable bundle tests, the only TCs used are central, subjacket cable TCs. The central subjacket TCs have been shown in prior studies to provide the most reliable and indicative measure of cable response behavior. For Penlight, the central point relative to the shroud is always the hottest location given the shroud geometry. Electrical cable failures will also occur at or very near the hottest point along a fire-exposed cable because the insulation resistance of polymeric insulators degrades exponentially with increasing temperature (NUREG/CR-6681) and electrical breakdown will occur where the insulation resistance is lowest.

Also note that, while the early single cable and small-bundle tests 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 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 during the exposure, but the exact time cannot be determined. Based on the early data analysis, the final test set involving the ten-cable bundles eliminated these thermocouples.

For the purposes of analysis and discussion, an alternate organization of the single cable and seven-cable bundle tests is convenient when compared to the raw test matrix presented in Table 4. Table 5 presents the alternate organization, where the tests are grouped into cohorts, called "comparison groups," for analysis.[11]

[11] Note that tests 1, 19, and 20, which were repeated as 1a, 19a, and 20a, respectively, are not explicitly included in the data analysis, although the results of these tests are included in the appendices. That is, the analysis presented here focuses on the results for the repeat tests rather than the compromised originals.

Table 5. Alternate organization of the single and seven-cable bundle tests into comparison groups for analysis.

Cable Type	Comparison Group	Test	Seven-Cable Bundle or Single Cable	Coating	Electrical Performance System	Test Temperature Range (°C)	
						Initial	Final
Thermoset	1	1a	Single	No Coat	Temperature Only	300	475
		5		Vimasco		300	475
		9		Flamemastic		300	500
		13		Carboline		300	475
		17	Single	No Coat	IRMS & Temperature	300	475
		19a		Vimasco		300	475
		21		Flamemastic		300	475
		23		Carboline		300	475
	2	25	Single	No Coat	SCDU & Temperature	450	
		26		Vimasco		450	
		27		Flamemastic		450	
		28		Carboline		450	
	3	29	Single (3 cables tested side by side)	Vim., Flam., & Carb.	Temperature Only	300	
		30		Vim., Flam., & Carb.		350	
		31		Vim., Flam., & Carb.		400	
		32		Vim., Flam., & Carb.		300	525
	4	2	Bundle	No Coat	SCDU & Temperature	300	450
		6		Vimasco		300	475
		10		Flamemastic		300	475
		14		Carboline		300	500
Thermoplastic	5	3	Single	No Coat	Temperature Only	200	525
		7		Vimasco		200	425
		11		Flamemastic		200	450
		15		Carboline		200	450
		18	Single	No Coat	IRMS & Temperature	200	425
		20a		Vimasco		200	425
		22		Flamemastic		200	375
		24		Carboline		200	450
	6	4	Bundle	No Coat	SCDU & Temperature	200	450
		8		Vimasco		200	450
		12		Flamemastic		200	425
		16		Carboline		200	500

This report contains an accompanying DVD that includes the following:

- An electronic copy of this report
- Representative videos from each of the three coatings tested as well as an uncoated test
- Select photographs of the tests
- Complete data files from all tests

5.2 Single Cable Tests

The first test sets to consider are those with single lengths of cable and include uncoated samples and samples coated with each of the three coatings used in testing and using both TS and TP cables. The single-length cable tests are the most closely controlled and most repeatable of the tests performed and were intended to explore fundamental behaviors of the various coating materials. In practice, the single-cable tests represent a low-mass thermal system that heats quickly. The single-cable tests include comparison groups 1, 2, 3, and 5. These four comparison groups will be discussed in this subsection.

5.2.1 Comparison Group 1

The first comparison group includes tests 1a, 5, 9, 13, 17, 19a, 21, and 23, which all were performed using single lengths of TS cables and the same Penlight heating profile (the stepwise increasing profile). These tests 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 test 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 6 summarizes these results for comparison group 1. Note that while there are minor variations, all of the ignition times fall within a roughly +/-2 minute timeframe with a similar variance on the failure times. Also note that the coatings do not consistently produce the longer ignition/failure times. Instead, the uncoated samples fall in the center of the range. Overall, the differences are small and generally fall within anticipated test-to-test variability.

Again, this was an unexpected result because it had been anticipated 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 6. Times to cable ignition and electrical failure for comparison group 1 – the single thermoset cable, stepwise profile tests.

Test #	Coating Material	Time to Cable Ignition min (s)	Time to Electrical Failure
1a	No Coating	37.80 (2268)	-
17	No Coating	37.65 (2259)	38.00 min (2280)
9	Flamemastic	40.33 (2420)	-
21	Flamemastic	38.80 (2328)	39.78 min (2387)
5	Vimasco	36.10 (2166)	-
19a	Vimasco	37.13 (2228)	39.15 min (2349)
13	Carboline	35.28 (2117)	-
23	Carboline	35.22 (2113)	36.28 min (2117)

Figure 19 illustrates the typical subjacket cable-temperature response behavior observed for all three coating products in the comparison group 1 tests. This particular figure shows tests 17 (uncoated) and 19a (Vimasco coated).

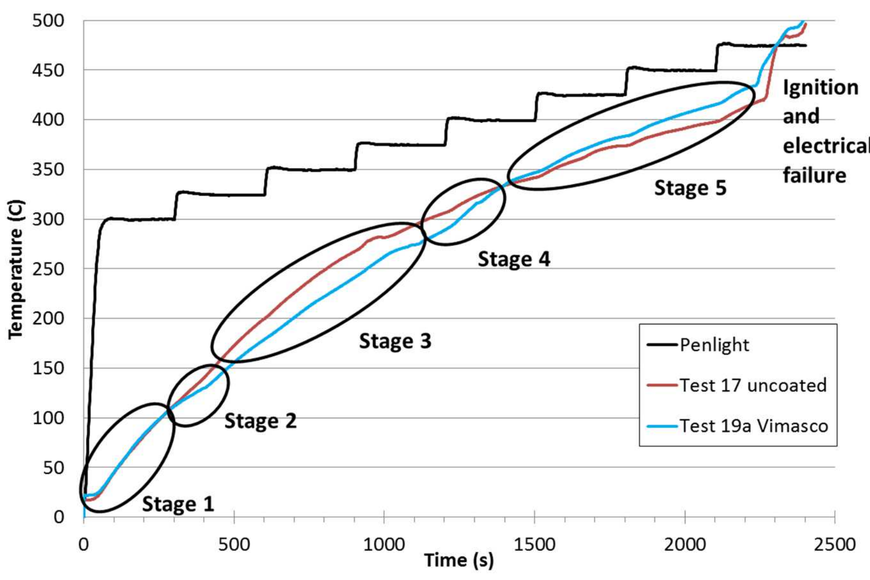

Figure 19. Temperature response for a single thermoset cable comparing an uncoated cable to a cable coated with Vimasco

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 19. That derivative information is illustrated in Figure 20. 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 19, the uncoated cable (the red line) follows a fairly consistent and steady heating behavior that tracks but lags the Penlight shroud temperature. In Figure 20, 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, tests show follows 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.

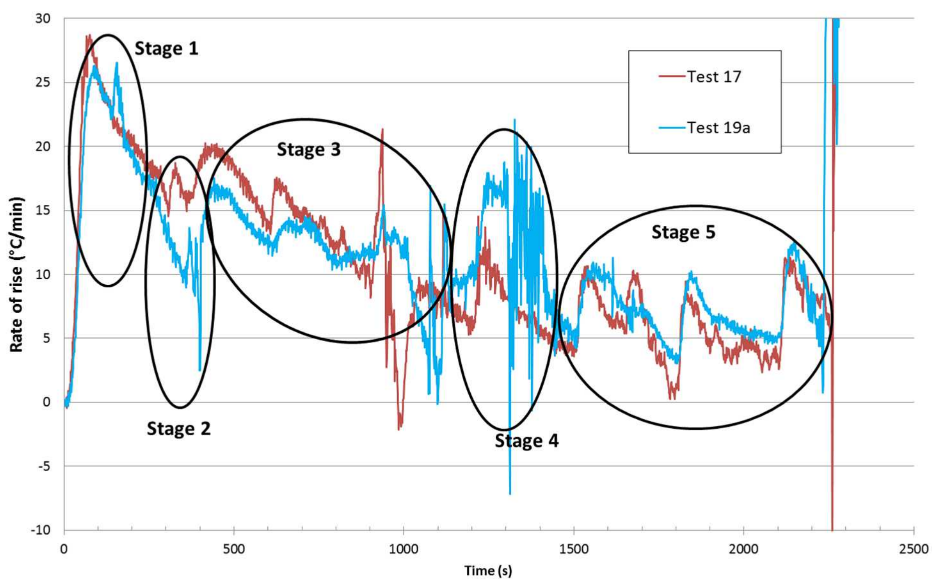

Figure 20. Rate-of-rise plot corresponding to temperature response shown in Figure 19

For the coated cable, the temperature response reflects, in effect, a five-stage heating process. The stages are highlighted in both Figure 19 and Figure 20. The interpretation of the temperature response for the coated cables is tied to the nature of the coating products, that is, all three products tested 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°C (392°F) but product specific), the coating material undergoes a chemical/physical change and expands many times in thickness (as much as 600 to 700% based on manufacturer 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 test data:

- Stage 1. During the first 5 minutes approximately, 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. (Note that these coatings have little or no impact on cable self-heating and ampacity limits, which reflects the minimal insulating

effect associated with the unexpanded material.) The match between the response of the coated and uncoated cables is also reflected (Figure 20), 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 does that of the uncoated cable. Figure 20 shows this clearly as a period where 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 20) similar to, but slightly lower than, that seen for the uncoated cable. Figure 19 shows the temperature response for the coated cable roughly parallels the uncoated cable during this time, but with a time delay of on the order of 5 to 8 minutes.
- Stage 4. During the fourth stage, a rather unexpected behavior is noted. At a certain point, in this case at about 1200 seconds, the rate of temperature rise for the coated cable increases sharply and clearly exceeds that of the uncoated cable (Figure 20). 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 test (Figure 19). An explanation for this behavior has been developed as described further 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 test-to-test 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 test 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 <u>not</u> an anomaly, it is seen consistently across all of the coated single-cable tests, and it is <u>not</u> associated with a change in the exposure environment. An explanation for this behavior was postulated and confirmed by results of cone calorimeter tests.

Product literature from each manufacture provides ASTM flammability test ratings for their products. All three products provide an ASTE E84 flame spread rating, and the Vimasco 3i product also cited an ASTM E162 ratings. The E162 test is of particular interest to this discussion because it is a combined test that measures both flame spread and heat release. For Vimasco 3i, the E84 and E162 rating are 15 and 16, respectively. These ratings indicate low flammability and that the material is combustible. 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 zero).

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, that all behave in a similar manner implies that all three coatings will burn and will contribute some limited heat to the system.

For confirmation, the NIST cone calorimeter tests performed for the same coating materials and for the same cables used in the SNL tests were reviewed. Those results confirm that the coatings burn and contribute a limited amount of heat to the thermal system. These results have not yet been published by NIST, but Figure 21 shows a typical result for the Vimasco coating. In these tests, the cured coating itself is the only material present in the test; 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 also were obtained from the cone calorimeter for the other two coating materials and are shown in Figure 22 for Flamemastic and in Figure 23 for Carboline, where only the cured coating is present.

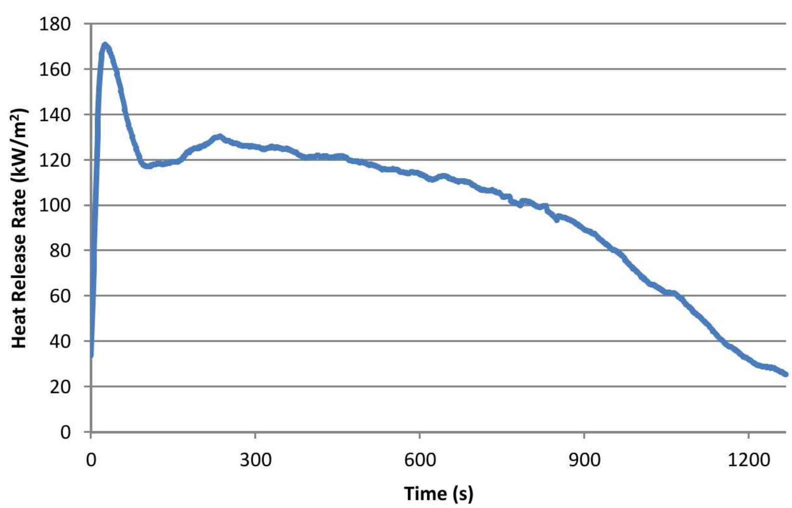

Figure 21. Cone Calorimeter test results for the Vimasco coating (cured coating only)

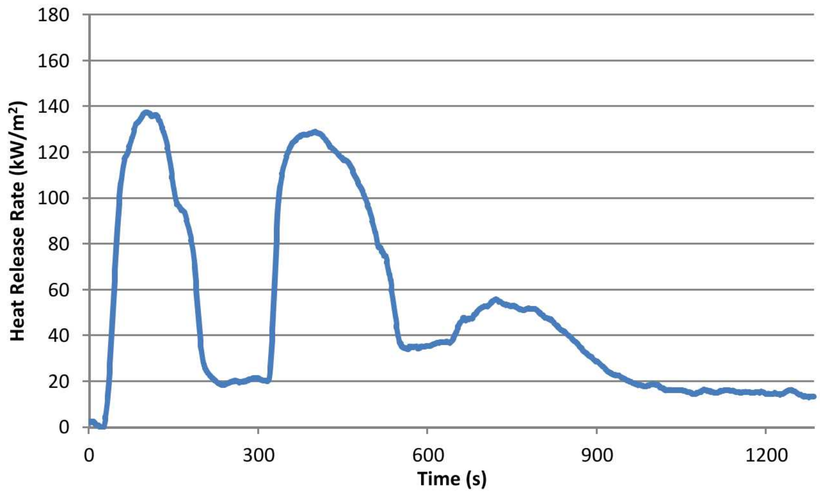

Figure 22. Cone Calorimeter test results for the Flamemastic coating (cured coating only)

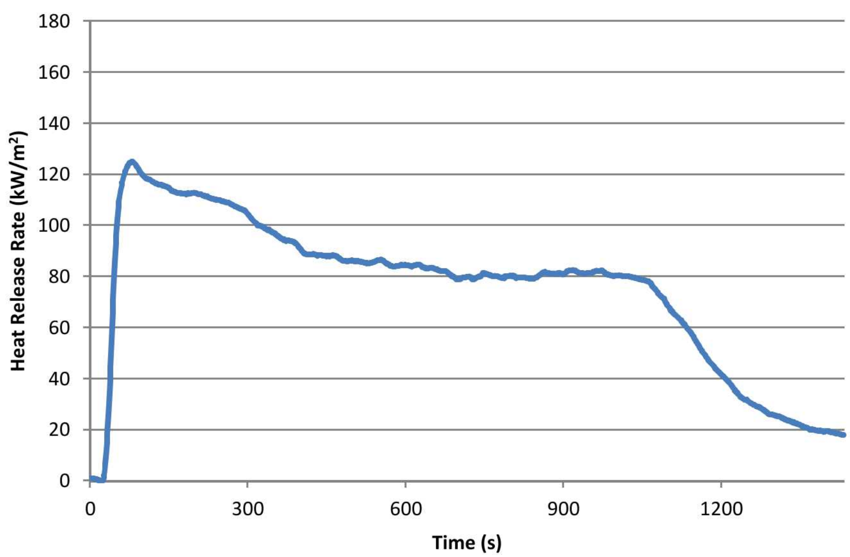

Figure 23. Cone Calorimeter test results for the Carboline coating (cured coating only).

Similar results were obtained in the single cable tests. Figure 24 shows a comparison between the uncoated cable in test 17 to the Flamemastic coated cable in test 9. Figure 25 shows a similar comparison for the Carboline coated cable in test 23. In both figures, the same general five-stage heating process is evident and highlighted.

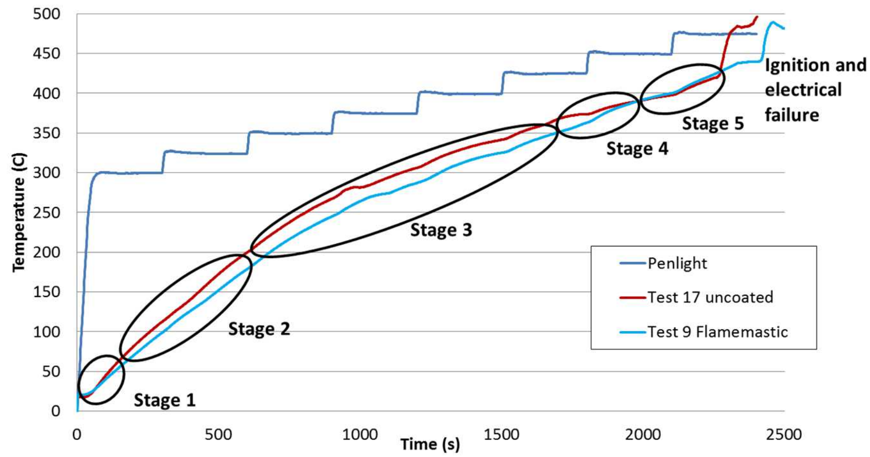

Figure 24. Comparison of single cable uncoated versus Flamemastic coated

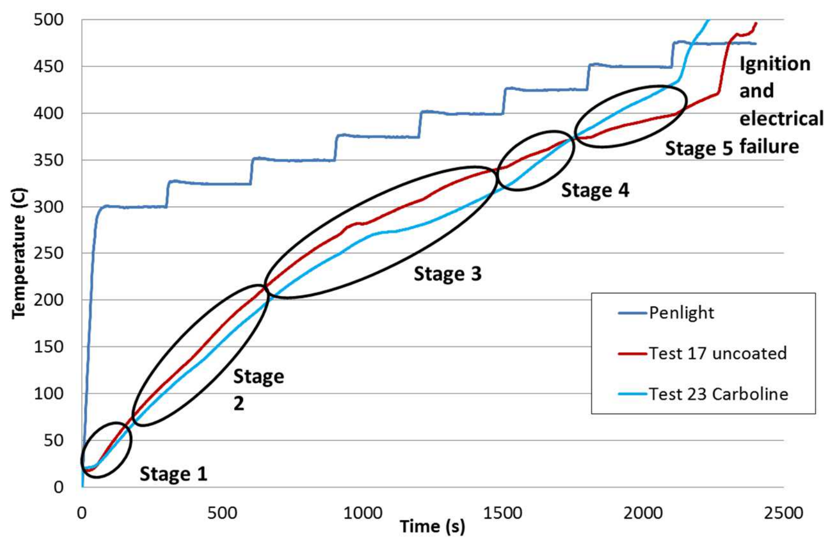

Figure 25. Comparison of for single cable uncoated versus Carboline coated

The calorimetry tests provided by NIST 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 tests are summarized in Figure 26 for the Vimasco tests, Figure 27 for Flamemastic and Figure 28 for Carboline. In each case, the figures compare tests with the uncoated cables (tests 1a and 17) to the tests of the corresponding coated cables.

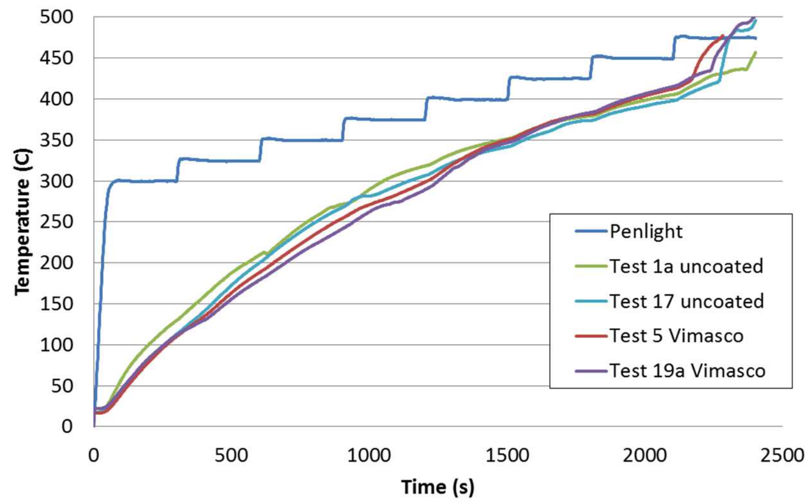

Figure 26. Temperature history of single thermoset cables, comparing the uncoated tests (1a and 17) to cables coated with Vimasco (5 and 19a)

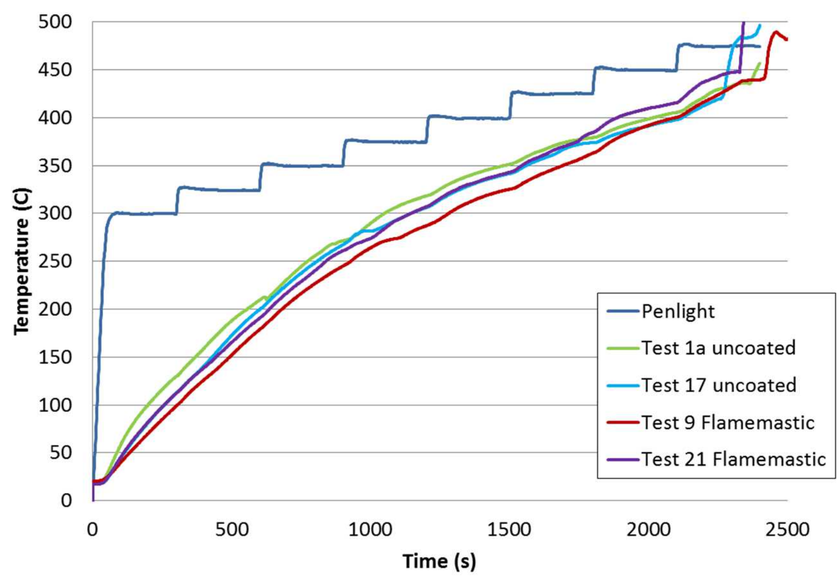

Figure 27. Temperature history of single thermoset cables comparing the uncoated tests (1a and 17) to cables coated with Flamemastic (tests 9 and 21).

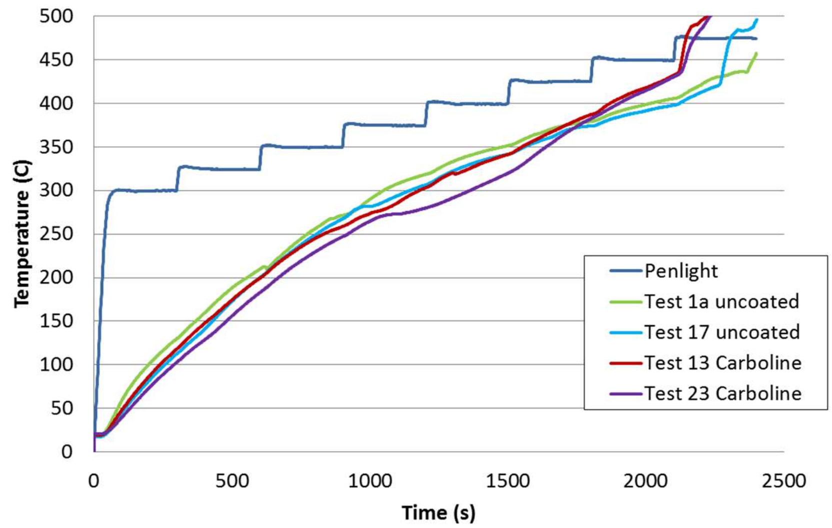

Figure 28. Temperature history of single thermoset cables comparing the uncoated tests (1a and 17) to cables coated with Carboline (tests 13 and 23).

5.2.2 Comparison Group 2

The second comparison group is made up of tests 25-28. These four tests all used single lengths of thermoset cable and a heating profile during which Penlight was raised from ambient to 450°C (842°F) within 2 minutes and held constant for the duration of the test. Note that the shroud temperature of 450°C (842°F) corresponds to a heat flux of 12.64 kW/m^2 (1.11 Btu/ft^2). This is a far more harsh exposure condition than that associated with comparison group 1, so the resulting cable temperature rise is much faster.

The results for the four tests in comparison group 2 are shown in Figure 29. Note that the coated cables all show a more consistent and pronounced delay in the heating profile. Note also that that the uncoated cable ignited in fewer than 7 minutes, which is a shorter time than the 5 minutes after the temperature hold point of 450°C (842°F) was reached.

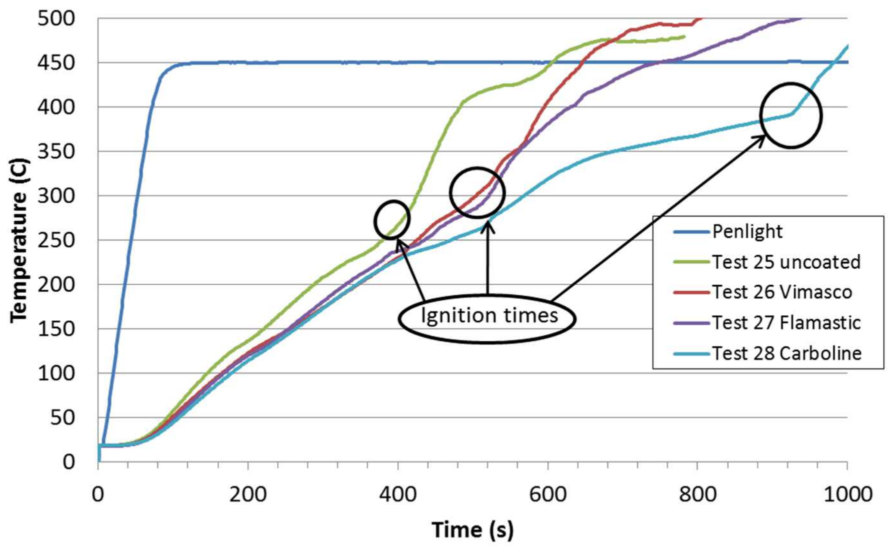

Figure 29. Temperature response data for the four tests in comparison group 2.

There are no repeats for this comparison group; however, there is one test 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. The results relative to ignition and electrical failure for this test group are given in Table 7.

Table 7. Times to cable ignition and electrical failure for comparison group 2.

Test #	Coating Material	Time to Cable Ignition min (s)	Time to Electrical Failure min (s)
1a	No Coating	6.4 (384)	11.6 (696)
9	Flamemastic	8.3 (498)	15.1 (906)
5	Vimasco	8.6 (516)	14.3 (858)
23	Carboline	15.3 (918)	19.0 (1140)

Under these harsh heating conditions, the uncoated cable ignites at 6.4 minutes. The coated cables see ignition delays ranging from 1.9 to 8.9 minutes. Similarly, the uncoated cable failed electrically in 11.6 minutes, and the coated cables saw comparative failure time delays from 2.7 to 7.4 minutes.

Two effects account for this comparison group 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 test (within the first 1 to 3 minutes) so that the protection was present for a greater percentage of the test time, potentially amplifying the beneficial effect. Second, the uncoated cable ignited quickly under these conditions, while the coatings clearly provided an ignition delay. Since the thermoset 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 PRA 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.

5.2.3 Comparison Group 3

Comparison group 3 includes tests 29 through 31. In these tests, three single lengths of the thermoset 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 test, although no uncoated cable was present.

The tests varied in their exposure conditions. The first three tests, 29 through 30, used a single-step change condition in which Penlight 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 thermoset cable used in testing. The last test in this set used a stepwise increasing temperature profile that started at 300°C (662°F) and ended at 525°C (977°F).

These tests were run because a number of coated single-cable samples remained after the other single cable tests in the series had been completed. The tests were intended to provide side-by side comparisons between 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. The details of these tests are included in Appendix A.

5.2.4 Comparison Group 5

The fifth comparison group includes tests 3, 7, 11, 15, 18, 20a, 22, and 24. These are the corresponding single cable TP tests and represent a complement to the tests in comparison group 1. The exposure conditions involved the stepwise increasing temperature profile starting from an initial set point of 200°C (392°C). The various tests in this comparison group end at different set points depending on total test duration, but all are consistent through a minimum of 375°C (707°F); all but one test, 22, are consistent through 425°C (797°F) (test 22 ended at a set point of 375°C (707°F)).

The results for this test set mirror those seen for the thermoset cable tests. 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 to 300°C (500 to 572°F), compared to the TS cable, which is expected to fail at cable temperatures of 370 to 400°C (698 to 752 °F). Figure 30 shows the results for the two uncoated tests that will be used as a basis for comparison against the coated cases. Note that the two tests are quite consistent.

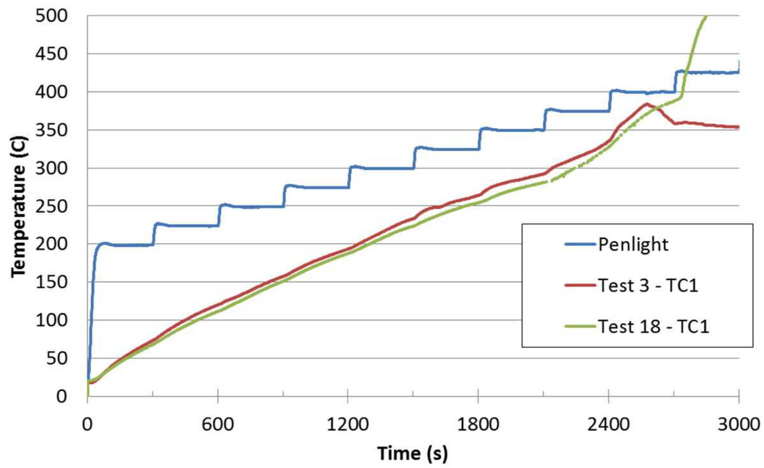

Figure 30. Test results for the uncoated thermoplastic single cable tests 3 and 18

Figure 31 compares the results of the uncoated cable from test 3 to the Vimasco, Flamemastic and Carboline coated cables from tests 6, 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 test. The Flamemastic product shows a different response behavior compared to the other coatings. In particular, the Flamemastic coated cable initially started out 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 test, the Flamemastic cable was closer to the uncoated cable temperature. For example, at 2300 seconds (38.3 minutes), prior to 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 seen among these four tests are not profound and, with only one test per configuration, no strong conclusions can be made.

The corresponding results for the two-cable (single length) tests, 18, 20a, 22 and 24, were similar, as shown in Figure 32. 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 test, a more pronounced difference in thermal response was apparent. However, It should be noted that test 24 began normally, but, soon after the Penlight controller was set to the first temperature rise set point, 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 test restarted. However, because the initial Penlight heating cycle had preheated the Carboline cable to about 48°C (118°F), some care must be taken in the interpretation of this test because the other cables generally started each test 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 relative to cable ignition and damage times. First, during test 3 (the single uncoated cable test) 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 test 3 to that of tests 7, 11 and 15. In the case of the second set of four tests, those with two single lengths of cable, in one case, test 22, Penlight was shut down early, after electrical failure but before ignition, and the cable did not ignite during the cool-down period.

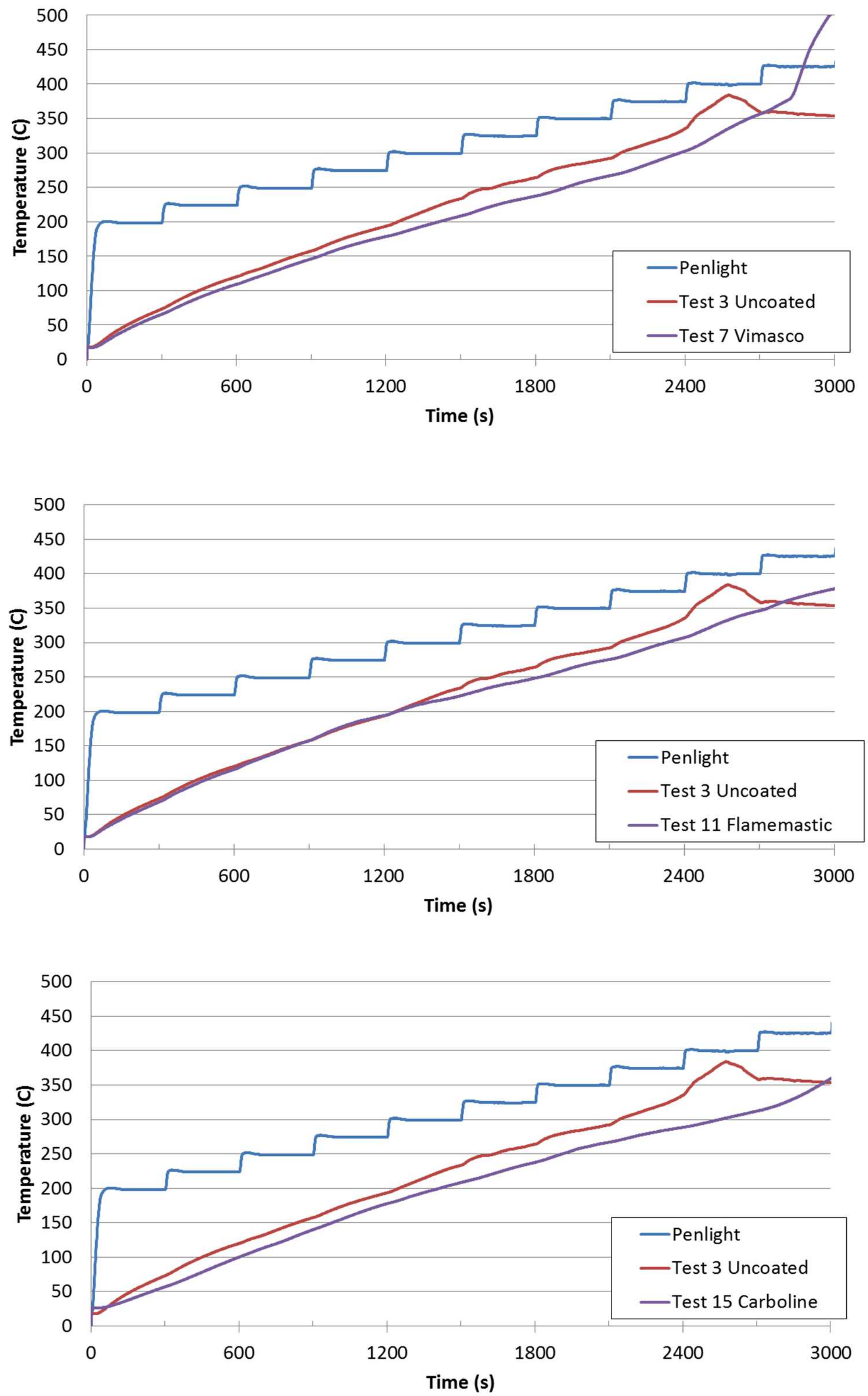

Figure 31. Comparison plots for the single thermoplastic cables tests for Vimasco (top), Flamemastic (center) and Carboline (bottom)

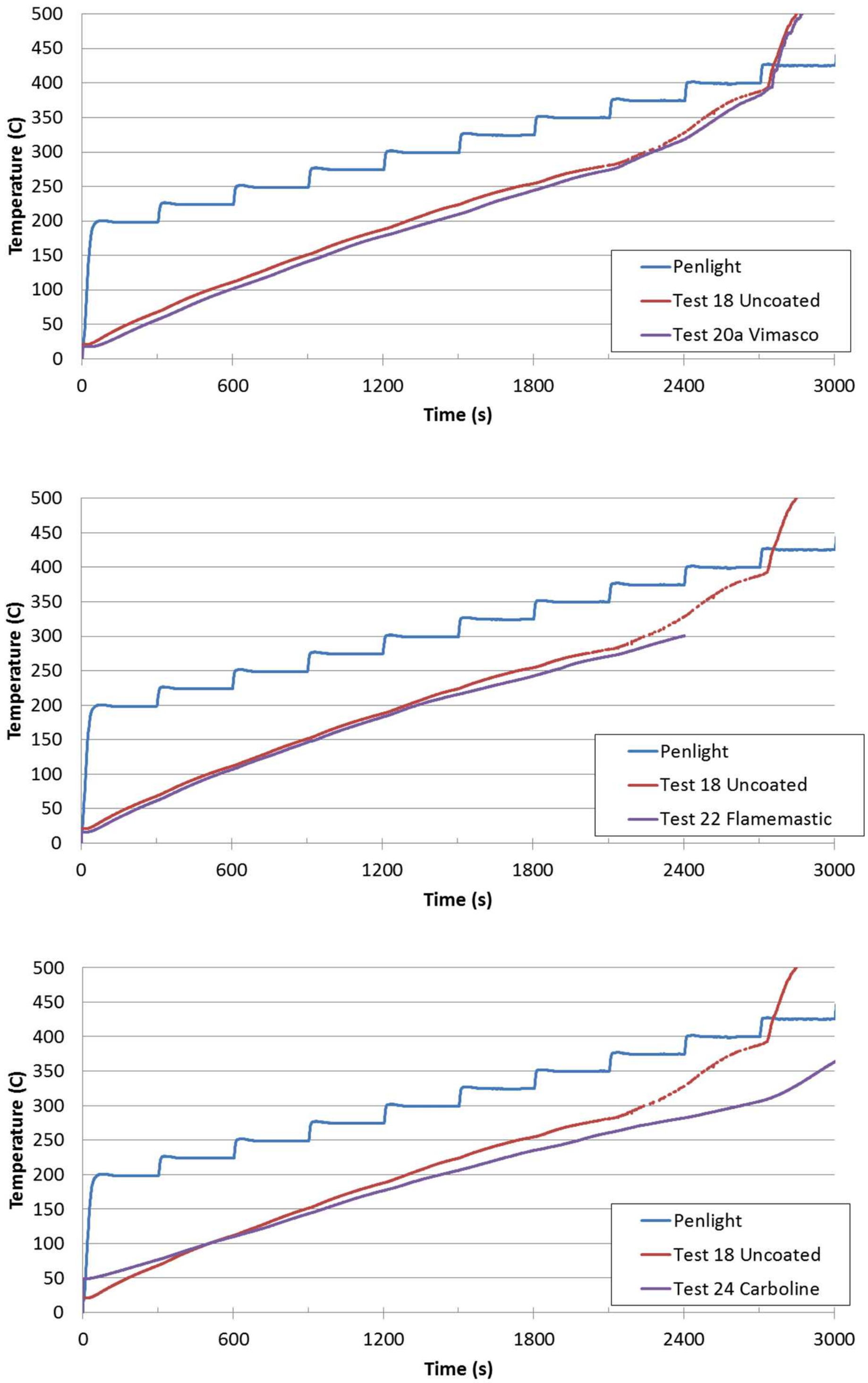

Figure 32. Comparison plots for the thermoplastic cables tests using two single lengths of cable for Vimasco (top), Flamemastic (center) and Carboline (bottom)

Given these qualifiers, the ignition and electrical damage times for test 18, 20a, 22, and 24 are shown in Table 8. In all cases, the cables experienced electrical failure prior to ignition, a behavior that is often seen with TP cables. Beyond that, one unexpected result is apparent, and that is the uncoated cable lasted longer before electrical failure than any of the coated cables. Given only one test 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 tests the coatings seem to have resulted in a perceptible delay in the cable thermal response, while in other tests there is no appreciable effect. With respect to electrical damage times, there is only one test 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 test configurations because the behavior was not noted until well after the tests 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 8. Ignition and electrical failure times for tests 18, 20a, 22 and 24.

Test number	Coating configuration	Time to ignition min (s)	Time to failure min (s)
18	No Coat	45.57 (2734)	32.08 (1925)
20a	Vimasco	45.85 (2571)	27.37 (1642)
22	Flamemastic	(see note)	31.58 (1895)
24	Carboline	50.83 (3050)	31.32 (1879)

Note: In test 22, Penlight was shut down when electrical failure occurred but ignition had not yet occurred. The cable did not ignite during the cool-down period.

5.3 The Seven-Cable Bundle Tests

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

The bundles represented a significantly more massive thermal system than the single cable samples described in Section 5.2. 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 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 tests have been split into two comparison groups for analysis. Comparison group 4 represents the TS bundles, and Group 6 represents the TP bundles.

5.3.1 Comparison Group 4

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

One behavior important for this comparison group is that, in each test, the cable bundle separated during the test. 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. The cable bundle separation behavior is shown as before-and-after pictures shown in Figure 33. Note that the photo showing the cables after the tests had been concluded reflect 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 occurred. The separation caused large breaches in the coating, as shown in in the close-up photo of a separated bundle (Figure 34). The coatings tended to stay in place, providing continued shielding of the cables from radiant heating, but the intimate contact between coating and cables was generally lost.

Figure 33. Before-and-after photos of the cable bundle separation behavior

Figure 34. Close-up photo of separated cable bundle

This effect can be seen in the uncoated test in particular. The black oval in Figure 35 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 set point changes. The coated cable bundles also separated to varying degrees. The separation caused the coatings to crack open, which appears to have impacted the test 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.

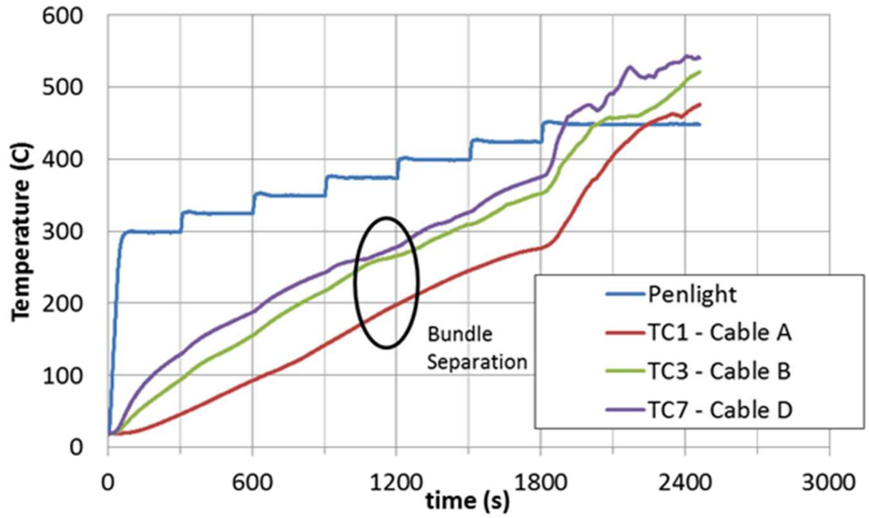

Figure 35. Cable temperatures for the outer-ring cables in the uncoated, seven-cable bundle (test 2)

Figure 36 compares the uncoated bundle (test 2) to the seven-cable bundle coated with Vimasco (test 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 3 cables. Also note that the central cable (C) sees the most pronounced effect.

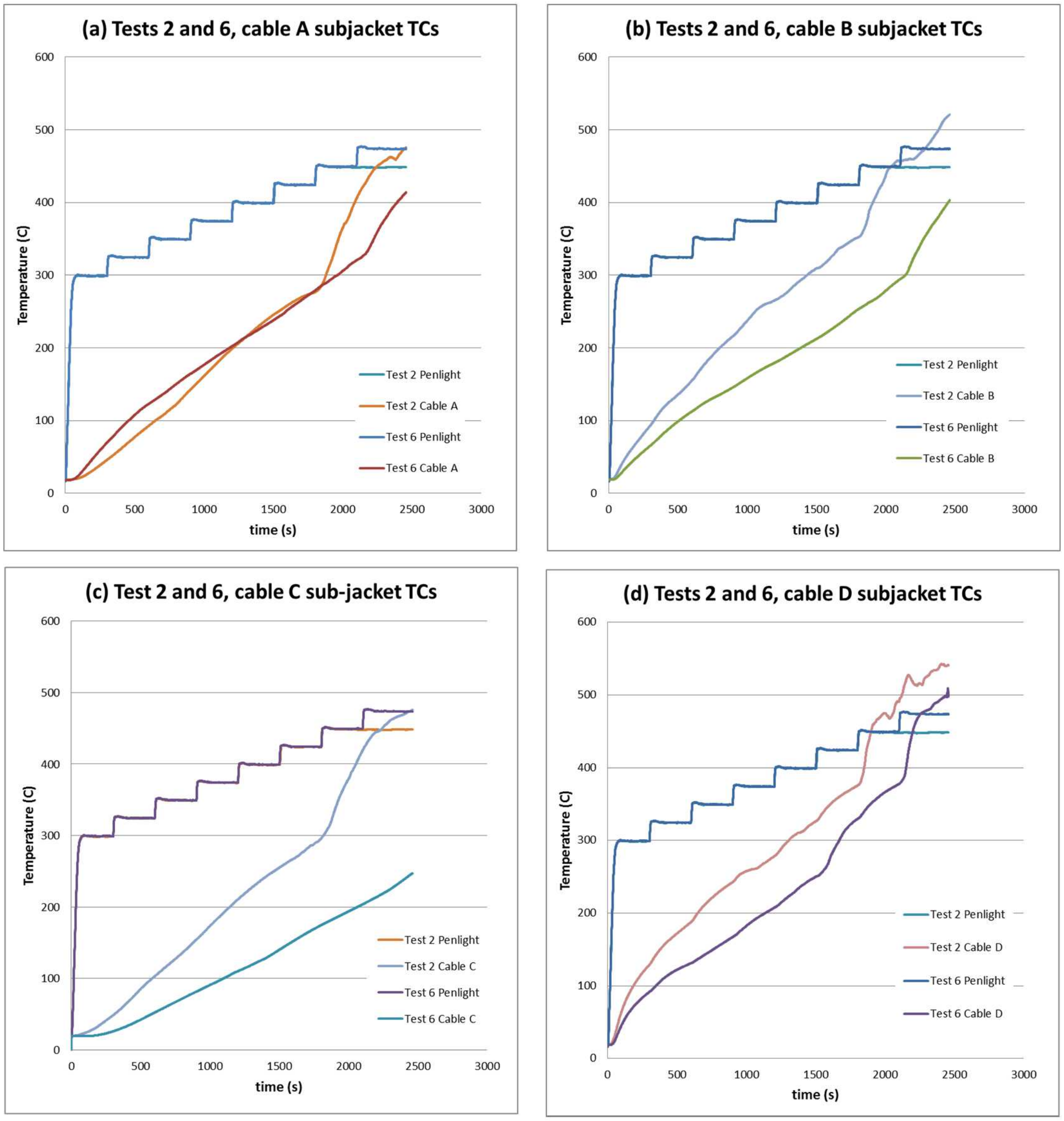

Figure 36. Cable thermal response comparison for the seven-cable bundle tests for uncoated (test 2) and for Vimasco coated cables (test 6).

A similar plot for the Flamemastic coating is shown in Figure 37. Once again, cables B-D see significant time response delays while cable A sees only a minor net delay.

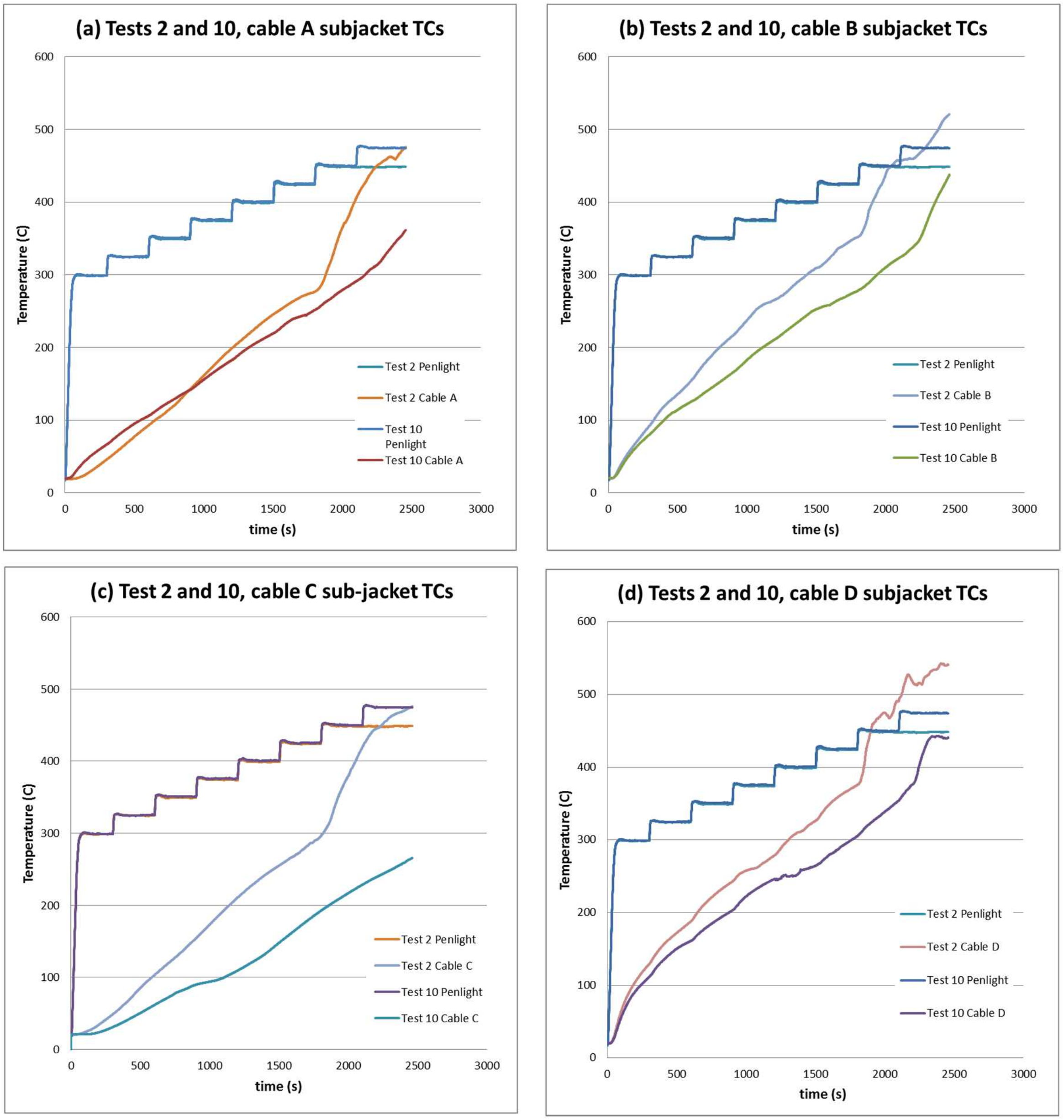

Figure 37. Cable thermal response comparison for the seven-cable bundle tests for uncoated (test 2) and for the Flamemastic coated cables (test 10)

Figure 38 presents a similar plot for the Carboline coating. In this case, all four thermal response cables had seen a substantive delay in thermal response, although the delay for Cable A is less pronounced than the other three cables. Overall the Carboline coated cable appears to experience the most significant delays. However, with only one test per configuration, it is difficult to draw a strong conclusion based on this comparison group alone.

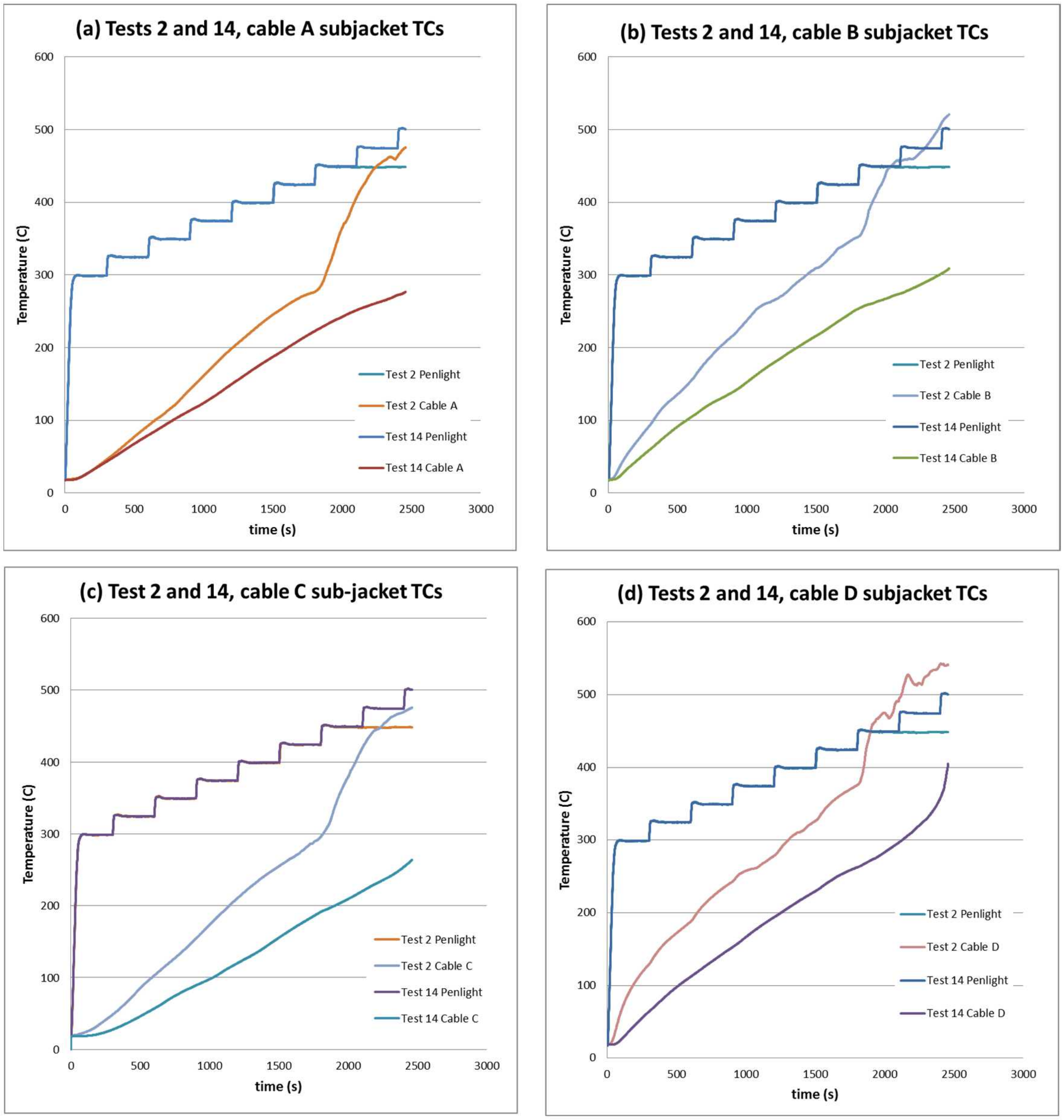

Figure 38. Cable thermal response comparison for the seven-cable bundle tests for uncoated (test 2) and for the Carboline coated cables (test 14)

The ignition and SCDU failure time results for comparison group 4 are shown in. Note that ignition time delays were similar for the Vimasco and Flamemastic products at 5.2 and 6.7 minutes, respectively. The Carboline product delayed ignition by approximately 9.4 minutes.

Table 9. Summary of ignition and electrical failure times for comparison group 4.

Test number	Coating configuration	Time to ignition		Time to electrical failure		
		Time (min)	Delay Time (min)	Cable	Time (min)	Delay time (min)
2	No Coat	30.45	n/a	E1	38.8	n/a
				E2	36.0	n/a
				E3	34.8	n/a
6	Vimasco	35.65	5.2	E1	51.6	12.8
				E2	43.2	7.2
				E3	40.4	5.6
10	Flamemastic	37.17	6.7	E1	50.5	11.7
				E2	43.7	7.7
				E3	42.1	7.3
14	Carboline	39.87	9.4	E1	55.8	17.0
				E2	46.2	10.2
				E3*	n/a	n/a

*See text for discussion.

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 is expected. Circuit E1 was on the bottom of the bundle and remained shielded, throughout the test, by the other cables, even when the bundle separated. Hence, E1 failed last. Circuit E2 was in an intermediate condition.

Note that, in test 14, the Carboline coated bundle, SCDU circuit E3, failed to function; there was no power to the circuit during the test 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.

Given the qualifier for test 14, and comparing circuit to circuit, the Vimasco coating delayed the first electrical failure by 4.6 minutes, and the Flamemastic coating delayed the first failure by 7.3 minutes. The Carboline coating saw more significant time delays, but the lack of data for SCDU circuit E3 makes direct comparison of the first failure difficult. However, we can look at circuit E2 across the four tests. In comparison to circuit E2 in the uncoated test, a delay of about 10.2 minutes was seen in the Carboline test compared to 7.2 for Vimasco and 7.7 for Flamemastic. It is likely that circuit E3 would have failed prior to E2 had it been energized.

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, there was one thermal response 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 with only one test). However, it is difficult to draw firm conclusions as to whether this result is representative. This will be taken up again in the context of the TP cable tests and the larger bundle tests.

5.3.2 Comparison Group 6

Comparison group 6 includes the four TP cables small-bundle tests, tests 4, 7, 12, and 16; test 4 was an uncoated test. Results for this group are illustrated in Figure 39 for the Vimasco product, Figure 40 for the Flamemastic product, and Figure 41 for the Carboline product. As with comparison Group 4, each figure compares the four thermal response cables from the uncoated test to the corresponding cables for each coating product.

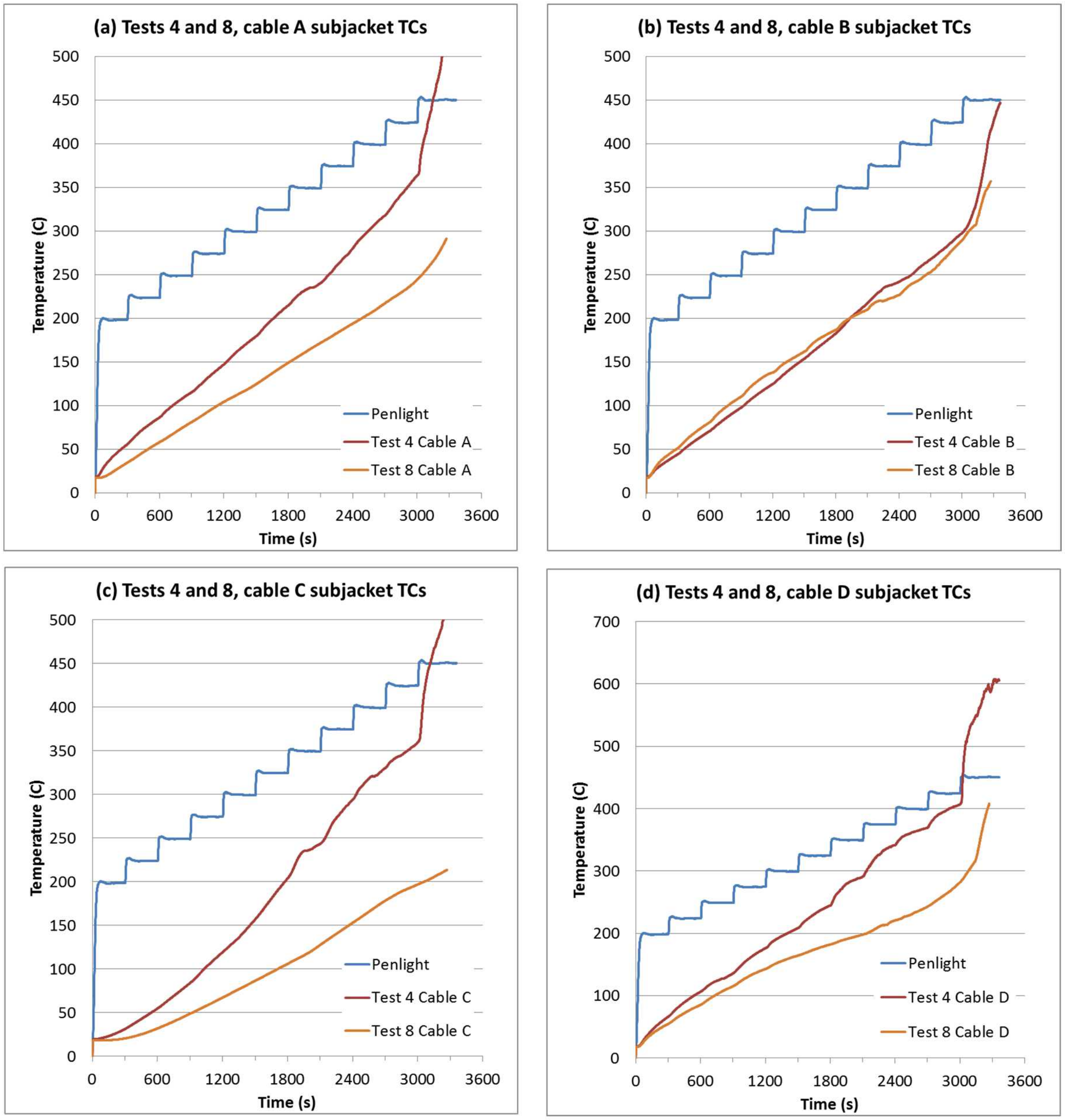

Figure 39. Comparison of corresponding thermal response cables for the uncoated and Vimasco-coated, small TP cable bundle tests.

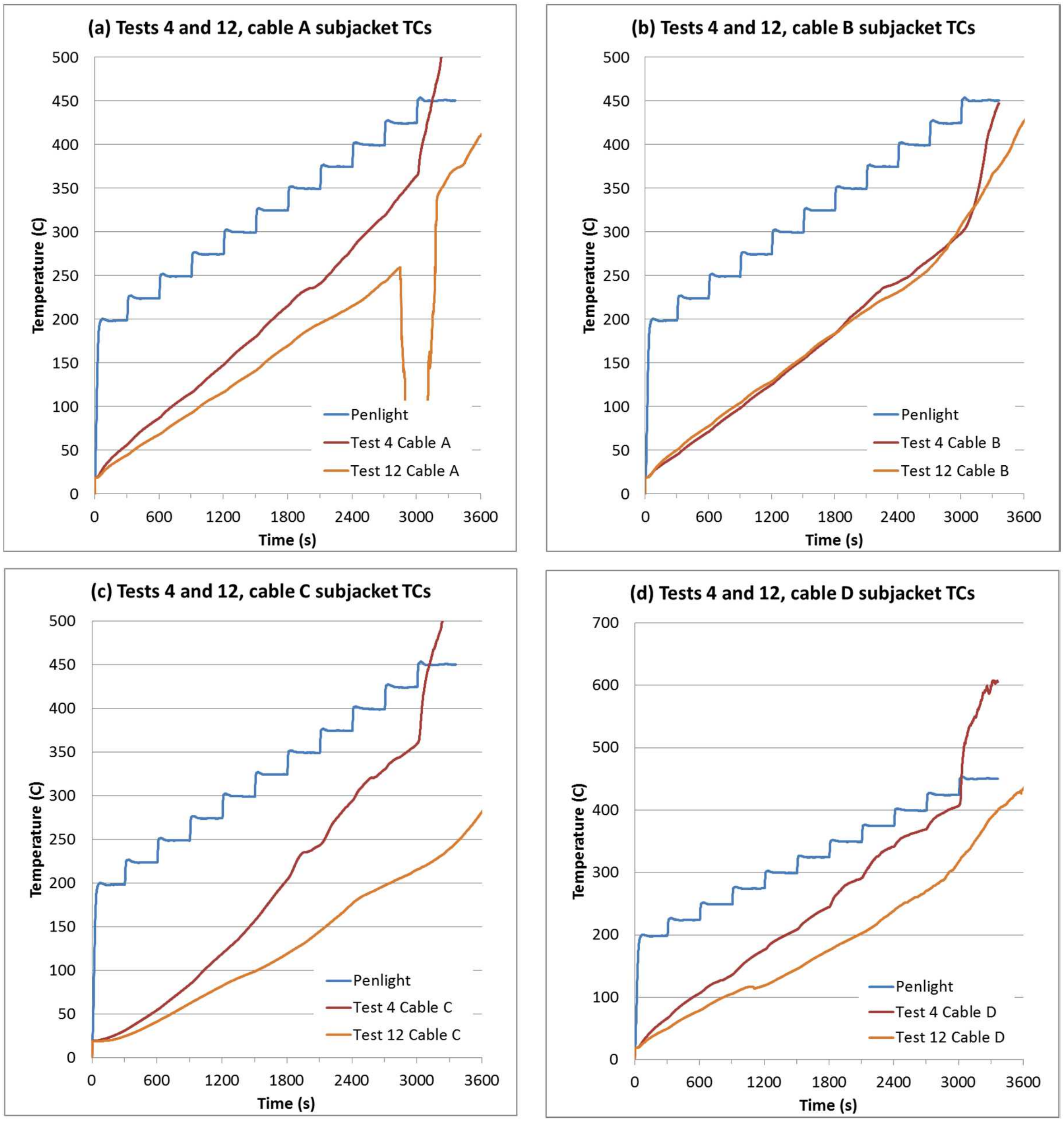

Figure 40. Comparison of corresponding thermal response cables for the uncoated and Flamemastic-coated, small TP cable bundle tests

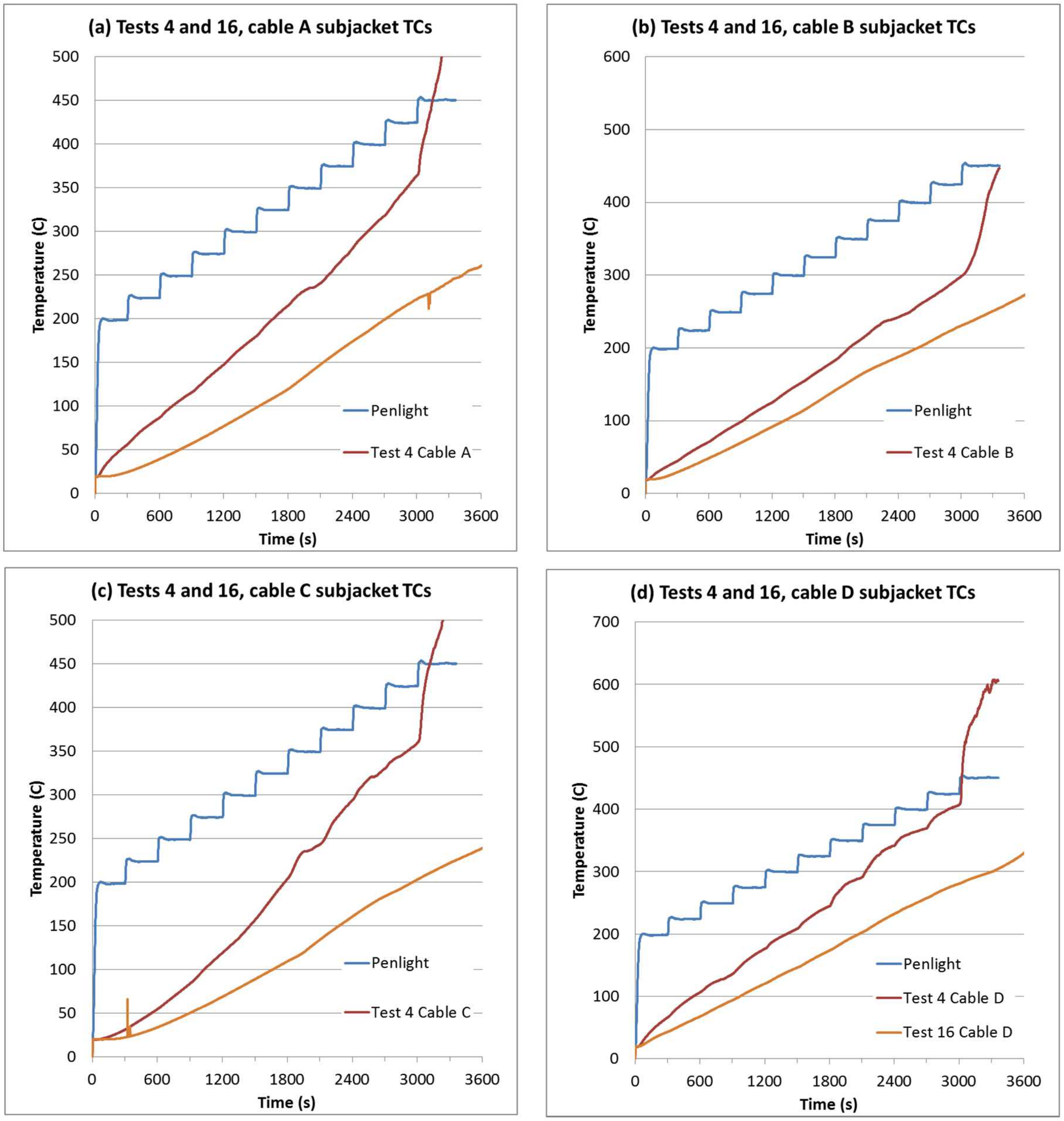

Figure 41. Comparison of corresponding thermal response cables for the uncoated and Carboline-coated, small TP cable bundle tests

The TP cable small bundle tests 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.

The corresponding ignition and electrical failure times for comparison group 6 are shown in Table 10. Note that the results are inconsistent. For ignition, Vimasco delayed ignition time by only 1.3 minutes, while the Carboline coatings delayed ignition by over 12 minutes. The Flamemastic coated bundle ignited in less time than the uncoated bundle, over 3 minutes faster. With no repeated tests, care must be taken in drawing firm conclusions.

With respect to electrical failure times, there was a high level of inconsistency. Note that SCDU circuit E3 failed quickly for the uncoated bundle compared to any other circuit. All of the 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 discernable effect that might be attributed to the coatings.

Table 10: Summary of ignition and electrical failure times for comparison group 6.

Test number	Coating configuration	Time to ignition		Time to electrical failure		
		Time (min)	Delay Time (min)	Cable	Time (min)	Delay time (min)
4	No Coat	50.9	n/a	E1	51.7	n/a
				E2	55.0	n/a
				E3	32.1	n/a
8	Vimasco	52.2	1.3	E1	41.7	-10.0
				E2	53.0	-2.0
				E3	51.2	19.1
12	Flamemastic	47.6	-3.3	E1	55.6	3.9
				E2	48.3	-6.7
				E3	42.7	10.6
16	Carboline	63.3	12.4	E1	61.6	9.9
				E2	51.8	-3.2
				E3	53.2	21.1

5.3.3 General Observations from the Seven-Cable Bundle Tests

The seven-cable bundles pointed to some interesting results that impacted the design of final test set involving the ten-cable bundles. One point to note 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 discussion in Section 5.2.1). 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 tests did not display the same sort of impact on thermal response that the single cable samples did. With only one test per configuration, strong conclusions cannot be drawn.

The other effect that was clear for the bundle tests 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 it would appear this was caused by the protective effect of the coating on the cable ties. For this reason, the Vimasco and Flamemastic products performed similarly and offered somewhat less protection than the Carboline product.

5.4 The Ten-Cable Bundle Tests

Given insights from the initial test sets, the final set of ten-cable bundle tests incorporated three significant design changes. First, the mass of cables was increased. The ten-cable bundle is 43% greater higher mass than the seven-cable bundles. Second, duplicate tests were performed for each coating configuration so that the test-to-test 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 through testing, but that arrangement left the cable bundle unbound over the roughly 0.9-m (3-ft) exposure length. During the tests, as noted in Section 5.3, separation of the cable bundle had a significant impact on the thermal response. For the ten-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 tests 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 tests the nylon cable ties melted prior to cable ignition or electrical failure times, and the cable bundles separated during testing. Late in the test 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 test article is referred to as the "uncoated wire-bound" configuration. The only difference between this test 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 measure event times (ignition and failure). Even for this bundle, the cables separated to some degree, but far less than for other tests.

To illustrate the thermal response results for the large bundles, the results for cables A and B will be shown. Recall that, as shown in Figure 11, cable A is at the center of the top row of cables, and cable B is next to A at the end of the top row (cable S1 is at the opposite end of the top row).

Figure 42 through Figure 45 show the thermal response results[12] over the first 30 minutes (1800 seconds) of exposure. In Figure 42, the thermal response for cable A as recorded during 13 of the 14 larger bundle tests is shown with the tests 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. The purpose of Figure 42 is mainly to illustrate the relative consistency of the cable response temperatures across the trials within a given coating configuration. Figure 43 shows the corresponding results for cable B.

Figure 44 compiles the average response curves for cable A for each coating configurations. That is, in Figure 44, the average response values are shown for each coating configuration but not the individual trials. Also included on Figure 44 is the one trial involving the uncoated wire-bound cable bundle. Figure 45 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 relative to 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 (560 to 910 seconds). 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 44, 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 as do the other uncoated (nylon tie) bundles.

[12] Recall that, as described in Section 3.3.3, at higher cable temperatures, interference issues arose between the thermocouples and the SCDU. This behavior is clearly evident in these plots.

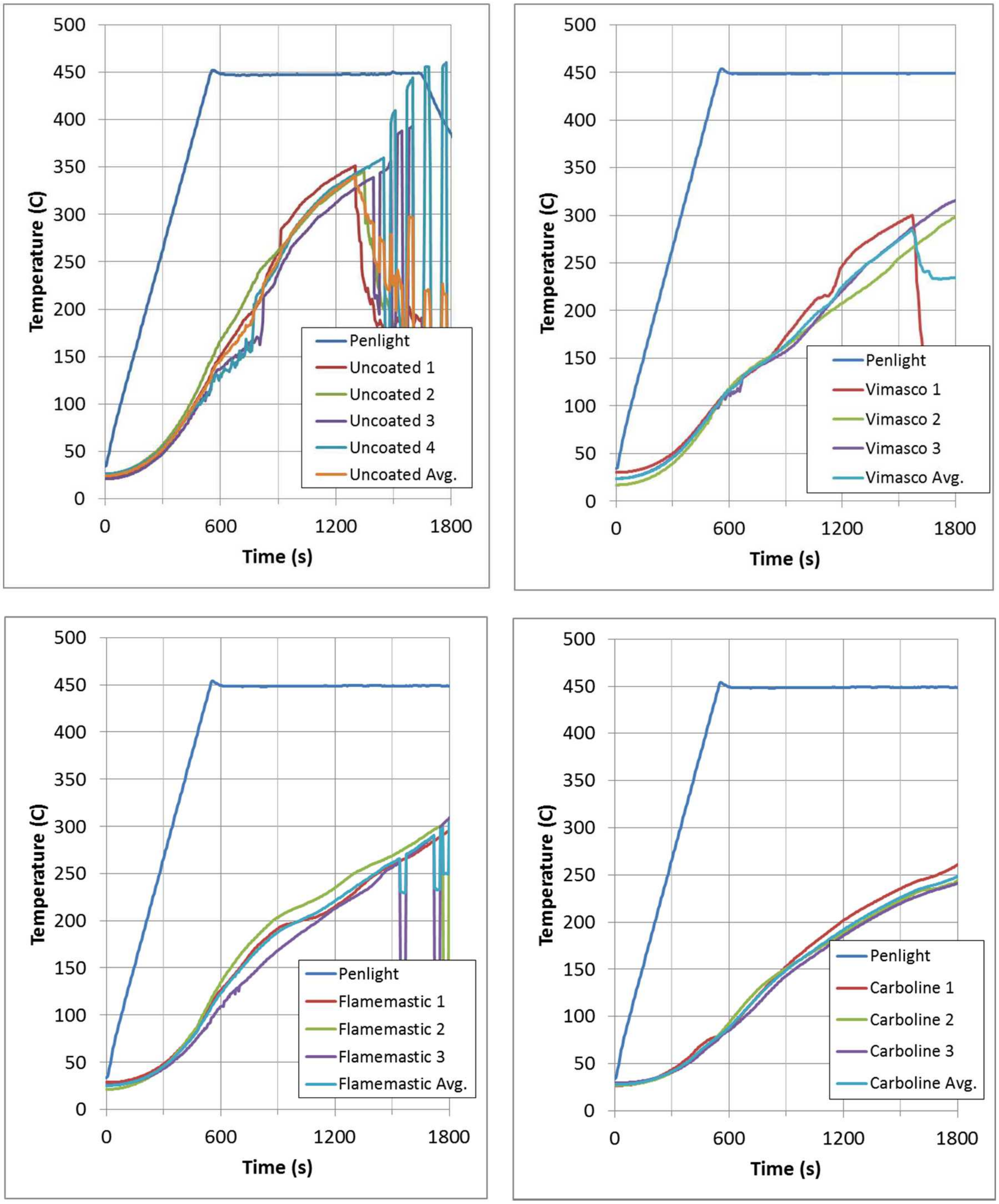

Figure 42. Thermal response results for cable A from each of the large-bundle tests grouped by coating configuration; includes the average thermal response across trials for each coating configurations

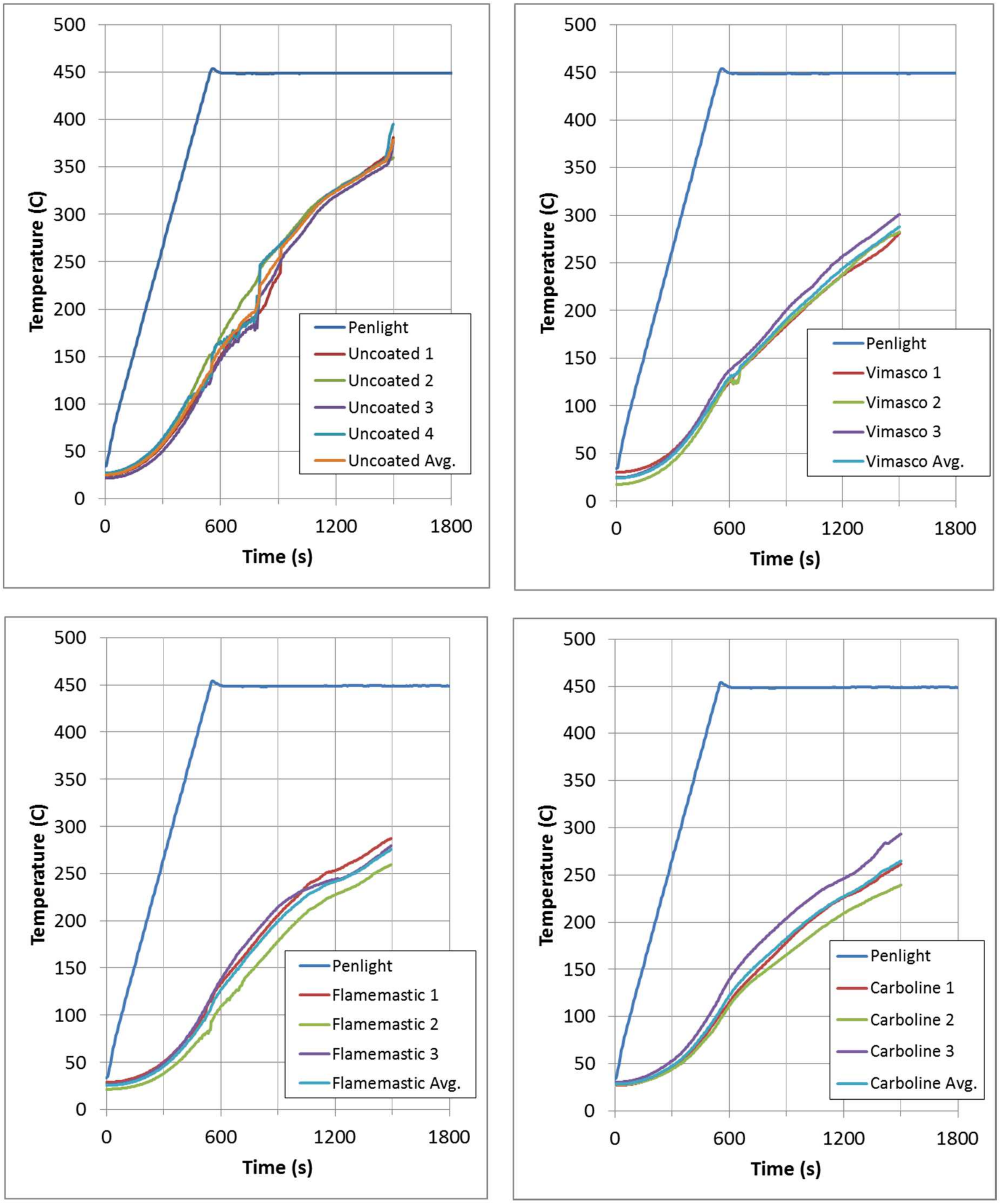

Figure 43. Thermal response results for cable B from each of the large-bundle tests grouped by coating configuration; includes the average thermal response across trials for each coating configurations.

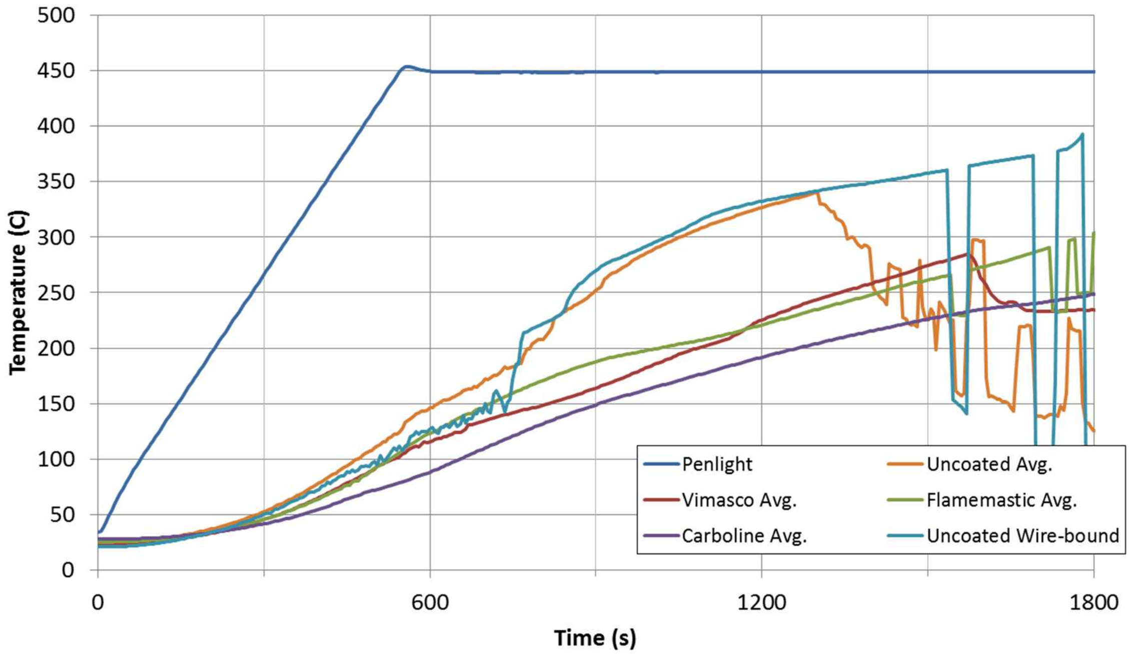

Figure 44. Average thermal response results for Cable A in the ten-cable bundle tests, including the uncoated wire-bound test bundle.

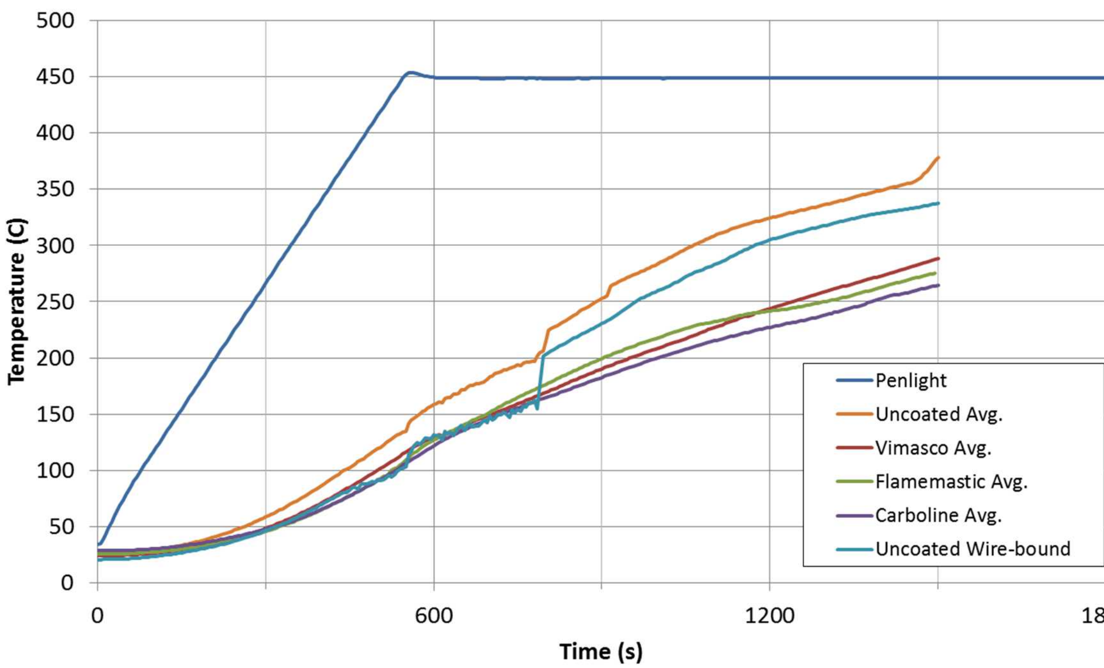

Figure 45. Average thermal response results for Cable B in the ten-cable bundle tests, including the uncoated wire-bound test bundle.

The coated bundles and the uncoated wire bound bundle follow similar heating profiles through about 780 seconds (13 minutes). At roughly 780 seconds, 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 44 and Figure 45. The coated bundles all maintain a substantial time delay through 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.

The ignition and damage time results for the large-bundle tests are summarized in Table 11 and are especially telling. The table summarizes the individual SCDU module failure times for each test (each experimental trial) and provides the time to ignition. Note that, in the case of ignition, the time given is the time to continuous flaming. In many cases, brief ignition flashes were seen, lasting only as long as it took for accumulated combustible gasses within the test chamber to be consumed. These typically were seen within 2 to 3 minutes prior to continuous ignition and these flash events were not included when reporting the ignition times.

Note that, in some cases, the third SCDU module did not experience failures. As a general test protocol, Penlight heating was terminated once two of the three SCDU modules had experienced failure, typically SCDU modules 1 and 2. Hence, for all tests, if SCDU 3 experienced failures, the failures occurred during the cool-down period. Also note that Vimasco Trial 1 was terminated early due to the problems with SCDU-thermocouple interference (discussed in detail in Section 3.3.3).

In addition to the raw test results, Table 11 also provides the numerical average and standard deviation across the available trials for both the electrical failure times and ignition times. Finally, the table includes a time delay associated with the average time for each coating product, compared to the average time for the uncoated bundles. Time-delay results are also presented for the uncoated, wire-bound test bundle as compared to the other uncoated bundles, although there was only one trial for the wire-bound configuration. Several points are worth noting relative to these results.

First, note that the variability in both ignition time and the electrical failure times is relatively small; that is, the standard deviations are all small compared to the average event times. For example, SCDU module 1 failure times across four trials of the uncoated bundle varied from 29.9 minutes to 32.9 minutes for a standard deviation of just 1.36 minutes. The coated bundles also show good test-to-test repeatability, and the failure and ignition times are quite consistent within each trial set. The highest variability in these results is seen for the Carboline product, but the Carboline product has consistently higher time delays than the other coatings. Given the higher failure and ignition times, a somewhat higher variability would be anticipated. Overall, the tests showed less test-to-test variability than was nominally anticipated.

Table 11. Cable ignition and electrical failure times for the large-bundle tests, including time delays (relative to uncoated bundles).

Uncoated (nylon ties)							
	Trial 1 (min)	Trial 2 (min)	Trial 3 (min)	Trial 4 (min)	Average time (min)	Standard Deviation	Delay (min)
SCDU1	29.9	29.3	30.3	32.9	30.6	1.36	n/a
SCDU2	29.2	29.8	29.7	30.2	29.7	0.36	n/a
SCDU3	DNF	34.2	33.8	36.4	34.8	1.14	n/a
Ignition	24.2	25.0	24.1	24.0	24.3	0.40	n/a
Uncoated Wire Bound							
	Trial 1 (min)				Average time (min)		Delay (min)
SCDU1	35.2				35.2		4.6
SCDU2	36.6				36.6		6.8
SCDU3	38.3				38.3		3.5
Ignition	28.9				28.9		4.6
Vimasco							
	Trial 1 (min)	Trial 2 (min)	Trial 3 (min)		Average time (min)	Standard Deviation	Delay (min)
SCDU1	n/a	47.8	43.5		45.7	2.16	15.1
SCDU2	n/a	47.1	44.3		45.7	1.41	16.0
SCDU3	n/a	50.3	DNF		50.3	n/a	15.5
Ignition	n/a	40.3	37.5		38.9	1.42	14.6
Flamemastic							
	Trial 1 (min)	Trial 2 (min)	Trial 3 (min)		Average time (min)	Standard Deviation	Delay (min)
SCDU1	42.5	41.5	39.7		41.2	1.14	10.6
SCDU2	41.9	42.9	41.7		42.2	0.50	12.4
SCDU3	DNF	47.1	48.7		47.9	0.77	13.1
Ignition	35.6	36.6	35.7		36.0	0.45	11.6
Carboline							
	Trial 1 (min)	Trial 2 (min)	Trial 3 (min)		Average time (min)	Standard Deviation	Delay (min)
SCDU1	69.5	59.0	60.1		62.8	4.71	32.2
SCDU2	70.5	62.0	66.0		66.2	3.49	36.4
SCDU3	DNF	76.2	DNF		76.2	n/a	41.4
Ignition	69.3	57.2	53.2		59.9	6.84	35.6

Second, the uncoated, wire-bound case presents an interesting result. Simply binding the cables with a wire tie, compared to a nylon cable tie, resulted in 3.5- to 6.8-minute delay in ignition and cable failure times. This result illustrates that the melting nylon ties were a factor in the ignition and failure times, but not an overriding one. The coatings had a more significant impact on the event times than did the metal ties.

The net results of the ten-cable bundle tests are summarized concisely in Table 12. All three coatings provided a measurable degree of protection, although, as in prior testing (e.g., the NRC-sponsored tests in the 1970s), performance varies widely. The large- bundle tests also gave far more consistent results than either the single cable or small-bundle tests. In all cases, the coatings offered substantial delays in both time to electrical failure and ignition. The greater consistency likely resulted from (1) the higher mass of the larger bundles and (2) the use of additional cable ties to secure the bundles. Also note that the delay times associated with the coatings all exceed the delays associated with the uncoated wire bound test configuration so there is a definitive effect associated with the coatings themselves.

Table 12. Summary of delay times by coating for the ten-cable bundle tests.

	Average delay in ignition time (min)	Average delay in circuit failure time (min)
Vimasco	14.6	15.5
Flamemastic	11.6	12.1
Carboline	35.6	36.7

6 CONCLUSIONS

6.1 General Conclusions Regarding Intumescent Coating Effects

The tests described provide evidence that the intumescent cable coatings can, under the appropriate circumstances, delay the time required for cables to exhibit electrical failure and delay the time to ignition under fire-exposure conditions. However, the circumstances under which this benefit might be realized are somewhat complex. Also note at the outset that the current study did not explore the effect of the coatings on cable flammability beyond observed ignition times (i.e., there was no investigation of fire-spread or fire-intensity behaviors in these tests).

One key behavior to recognize is that all three of the intumescent coating products tested here will burn exothermically. None of the coatings burn easily or well; rather, all earn very low flammability ratings in standard tests. However, the materials are combustible, and when they burn they produce a net heat output. This observation is based on both the behaviors observed in the current tests and on the results of cone calorimeter tests performed by NIST.

Given that the coatings burn exothermically, the coatings contribute heat to the thermal system represented by the coated cables. If the cable mass is low, then the heat contributed by the burning coating can overwhelm the beneficial insulation effects offered by the coatings. As the cable mass increases, the heat contributed by burning the coating becomes less significant. The reason for this is the coating mass increases proportionally to the surface area of the coated cable system (which is roughly proportional to the radius of the coated cables), whereas the cable mass increases with the volume of the coated cable system (which is roughly proportional to the square of the cable system radius). Hence, as bundle size increases, the ratio of coating mass to cable mass decreases. That is, if the coated cable system is large enough, it can absorb the heat from burning of the coatings without significantly raising the cable's own temperature, and a net time delay in the cable thermal response is seen. A delay in the cable thermal response (i.e., the cable temperature rise) translates to a delay in the electrical failure times. It would appear that the seven-cable bundles, at 2.8 kg/m (1.9 lb/ft), were slightly above this mass threshold, while the single cable lengths, at approximately 0.4 kg/m (0.28 lb/ft), were clearly below that threshold. Given the uncertainty in the test data, the discussions and observations made in section 6.2 conservatively assume a mass threshold of 4.0 kg/m (2.7 lb/ft) based on the more consistent performance of the ten-cable bundles. Further testing may resolve this threshold (see section 6.3).

A second behavior of importance is that the coatings must remain intact in order to maintain their beneficial effect. In the current tests, seven- and ten-cable bundles were tested and, during the heating process, the initially tight bundles separated as the cables expanded and relaxed. Separation of the cables tended to expose more of the cable surface to direct radiant heating and increased the cable temperature rise rates. For the coatings, one effect was to delay the bundle separation behavior, and this offered a degree of protection. The Carboline product in particular was more rigid in its cured form and appeared to hold the bundles together longer than did the Vimasco and Flamemastic products. Both the Vimasco and Flamemastic would become soft and somewhat runny when heated and appeared to offer little structural support to the bundles.

Hence, another aspect of the appropriate circumstances, in which beneficial effects are expected, would be configurations that are not subject to breach of the coating integrity due to shifting or expansion of the protected cables.

In general, of the three coatings, the Carboline product provided the most consistent and most significant beneficial effects. This difference is attributed to the fact that Carboline cures to a relatively hard, near-solid form as compared to both Flamemastic and Vimasco, which remained pliable even after curing. As a result, Carboline held bundle integrity together longer than either Flamemastic or Vimasco, which delayed ignition and damage times longer for the bundle tests. Carboline did not provide a net benefit for single lengths of the control cables, and this is attributed to the exothermic burning noted previously. In addition, it is not clear than the performance differences would extend to a configuration such as a random-fill cable tray, where bundle separation would not be an issue. However, for both the seven-cable bundles and the ten-cable bundles, a consistently positive effect was noted relative to the measure cable temperature response. However, the delays in electrical failure time were uneven. In the seven-cable bundle test, one of the three electrical performance monitoring circuits failed earlier during the coated bundle test than it did for an uncoated bundle test. For the ten-cable bundles, all three circuits consistently failed at later times than the uncoated bundles. The delay times for both ignition and electrical failure in the larger bundle tests were 30 minutes or greater across all three trials.

The Flamemastic and Vimasco coatings performed similarly in all test configurations. For the single-cable tests, no net benefit was seen and is attributed to the exothermic burning of the coatings themselves. In the seven-cable bundles, the thermal response of some cables was delayed while thermal response of other cables was not. The circuit failure results were also uneven with some circuits failing more quickly, and some delaying modestly. Both coatings performed better in the ten-cable bundles, which were also more robustly secured than the smaller bundles. Across all trials of the larger bundles, a net positive effect on all cables was observed, and ignition and circuit failure times were delayed consistently by 10 minutes or more.

Overall, the intumescent coatings have the potential to provide a beneficial effect relative to both time to ignition and time to electrical failure, provided (1) the mass of the coated cables is high enough to absorb the heat generated by burning of the coating product, without seeing a significant temperature increase, and (2) the coated cable system is well secured such that the cables will not shift or move as they heat and expand, potentially breaching the coating.

6.2 Conclusions Regarding Current Risk Analysis Practice

The current guidance for the treatment of fire-retardant coatings in a fire PRA is embodied in NUREG/CR-6850, Volume 2, Appendix Q. That document summarized the results of the NRC/SNL coatings tests performed in the latter half of the 1970s and states the following:

> "For application of the proposed approach, assume coated, nonqualified cables will not ignite for at least 12 minutes, and coated, nonqualified cables will not be damaged for at least 3 minutes for large exposure fires, and for cable tray fires, more likely about 10 minutes."

This guidance is not especially clear and was taken directly from an earlier EPRI document (TR-105928). Anecdotal information indicates that recent fire PRAs have given credit to fire-retardant coatings, although the specific methods applied have not been surveyed. One approach cited verbally to the author of this report[13] by a fire PRA analyst was to assume a minimum damage time of 10 minutes, given a coating, and apply that to all fire exposures in lieu of more detailed damage time analysis. A second analyst cited that their practice was to calculate a damage time using traditional methods, assuming no coating, and to then add 10 minutes given a fire-retardant coating. In both cases, the analysts confirmed that they included an assessment of the coating condition and verified that the coating (1) was one of the coatings shown in the 1970 tests to provide equivalent delay times, and (2) that the coating remained intact and free of visible physical degradation (e.g., no gaps or separation from the protected cables).

With regard to the tests conducted for this project, first note that these tests did not assess how the coatings impact cable flammability beyond the observed ignition times. The coating products are advertised primarily based on their fire-retardant properties. No recommendations are made regarding the potential benefits of the coatings relative to fire growth or fire intensity. Also note that all three of the products tested here are intumescent products. A coating product that does not combust exothermically would likely behave differently than the products tested here.

The test results documented here show that **no time delays should be assumed** for either ignition or electrical damage when intumescent cable coating is used under the following conditions:

- When applied to individual lengths of cable, including cable air drops, individual cables in a cable tray, or cables in trays with maintained spacing, unless the coated cable exceeds a mass of 4.0 kg/m (1.7 lb/ft).[14]
- When applied to cables in a cable tray where there is only a single row of cables (e.g., a single layer of cables spanning all or part of a tray and coated as a group) unless each of the individual cables exceeds a mass of 4.0 kg/m (1.70 lb/ft).
- Pending additional research, when applied to control and/or instrument cables in a cable tray where there are fewer than three rows of cables (e.g., two layers of cables spanning all or part of a tray and coated as a group). This restriction might well be relaxed given additional research (see section 6.3 for relevant follow-on recommendations).[15]

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[13] The author of this report, S. Nowlen, has been an instructor for the joint RES/EPRI fire PRA training courses offered bi-annually since 2006. The verbal communications reported here are based on interactions with students in those training programs.

[14] This value uses the mass of the ten-cable bundles as the threshold for a net coating benefit. The recommendation assumes that a single cable with sufficient mass, e.g., a medium-to-large power cable of very large control cable, would provide sufficient mass to allow for a time delay credit. Note that this is considered conservative in part because a single cable would not suffer the same separation effect that the bundles experienced; hence, single cables would likely perform better with a coating than would a similar mass cable bundle.

[15] This recommendation assumes that for power cable applications, a two-row fill should contain sufficient mass to ensure some level of coating effectiveness consistent with the recommendations immediately below. However, control and instrument cables tend to be smaller and may not provide sufficient mass to allow for credit.

- When applied to a bundle configuration that (1) is not known to be well secured with cable ties spaced no more than 60 cm (24 in.) apart or (2) has a mass less than 4.0 kg/m (2.7 lbs/ft) based on total coated cable mass per unit length. This would include both air drops and cables coated as a group within a cable tray.
- When the coating has been applied in substantially greater thickness (i.e., three times or more) than the recommended application thickness given that the coating material itself will combust exothermally. Because test data does not exist for thicknesses greater than three times the recommended application thickness and due to the combustibility of the material itself, performance of the coatings at thicknesses greater than that tested cannot be determined.

There are, however, some applications for which a time delay for ignition and electrical failure is suggested by the tests. Under the following conditions, an assumed ignition/damage time delay of 10 minutes for the Flamemastic and Vimasco products and a 20-minute time delay for the Carboline product was shown by the test results, compared to an uncoated configuration:

- Application of the tested products to random-fill cable trays with less than three times the recommended application thickness, with at least three layers of cables, and a minimum 15.2 cm (6 in.) width of cables coated as a group with a mass of at least 4.0 kg/m (2.7 lb/ft). Three layers of cables represent the number of layers tested in the bundled cable tests. Therefore this criteria is supported by observed performance behavior as well as the connection to the mass of the cables provided by three layers in a random-fill tray.
- Cable bundles, including air drops, that are well bound with ties at least every 60 cm (24 inches) and have a minimum mass per unit length of 4.0 kg/m (2.7 lb/ft).[16]

6.3 Recommendations for Follow-On Work

One question that was not answered by this test program was the potential effects if a coating is applied significantly in excess of the manufacturer recommended thicknesses. Anecdotal information indicates that some users applied coatings in far greater thicknesses than the manufacturer recommends, presumably, on the theory that “if a little is good, more is better.” It is not clear that this theory will hold true given that the coatings themselves contribute heat to the thermal system when they burn. In particular, while the coating materials themselves are not expected to sustain a fire condition, and the coating materials do not represent a significant combustible fuel source, the burning of a thick coating on even a higher thermal mass cable system may overcome the potential benefits of the coating. That is, as the coating thickness increases, more thermal mass may be needed to overcome the effects of the heat contributed when the coating itself burns. It is recommended that, if follow-on tests are performed, this effect be explored.

The threshold between the intermediate mass cable system and the higher mass cable system is a question not resolved. It would appear that the seven-cable bundles were near that threshold

[16] As noted in Section 6.1, this mass threshold corresponds to the ten-cable bundle mass and is considered conservative given that the 7-cable bundles appeared sufficient to overcome the effects of coating combustion.

because some cables in the bundle were significantly protected, and that is the basis for the recommendations made. However, the test articles used here were bundles of control cables, and this configuration likely affected the behavior. In particular, the cable bundles separated shifted during heating, especially when the bindings that tied the cables melted. This impacted the heating behavior (based on observation of temperature jumps concurrent with melting of the tie wraps). If, in contrast, a single, large cable of equivalent mass per unit length were coated, a more significant and consistent benefit might be anticipated. Current tests did not address this question. If follow-on tests are planned, exploration of single cables of higher mass (e.g., higher conductor counts and/or larger gage conductors) are recommended. These results would likely also apply to power cable trays with maintained spacing arrangements (i.e., where less than a single layer of cables is present and the cables are tied individually to the tray rungs with a gap between adjacent cables).

The impact of direct flame impingement was also not explored in these tests. This can be a significant fire exposure condition in some fire scenarios, and it is recommended that some exploration of this exposure mode be undertaken if follow-on tests are performed.

Another common application is using a fire-retardant coating to a random-fill cable tray. Under the appropriate conditions, random-fill trays are likely to receive at least as much benefit from the coating application as ten-cable bundles receive. However, the conditions that would allow for a beneficial credit are uncertain. For example, trays with light loading (e.g., a single layer of control, instrument or light power cables) would likely see no net benefit in terms of either ignition or failure times, but would likely behave much as the single cable tests here behaved. However, with a higher fill (e.g., two or more layers) a substantial benefit might be seen. Exploration of these types of effects would be recommended.

These tests did not explicitly investigate the effect of the coatings on flammability, although some relevant insights are documented in the body of this report. If follow-in tests are performed, it is recommended that this aspect be explored further. It is further recommended that the best configuration for such testing is exposing cable trays and/or cable bundles to actual exposure fire conditions rather than radiant heating.

One final effect of potential interest is the behavior of the materials over a prolonged period. This, unfortunately, will be an especially difficult effect to investigate. Field experience shows, for example, that some coatings discolor over time (e.g., a bright white coating may discolor to brown over time). Another possible effect would be longer term curing of the materials. The coatings in these tests were cured for typically 2 to 3 times the minimum recommended period. Longer curing times could impact the behavior when coated cables are exposed to fire conditions. It is recommended that efforts be considered to investigate coatings' aging behaviors. For example, are the observed color changes simply a surface effect or a more fundamental chemical change, and how would that change impact coating performance?

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Vimasco Corporation. "Cable Coating 3i Intumescent Fire-Retardant Cable Coating," May 24, 2006. Retrieved in 2013 from http://www.vimasco.com/information.html#fire, manufacturer's material data sheet.

APPENDIX A. Literature Search on Research Related to Cable Tray Covers and Use of Cable Fire Retardant Coatings

(Prepared by Gabriel J. Taylor, U.S. NRC)

A.1 Scope of Literature Review

This literature review was undertaken to better understand electrical cable fire retardant coating and cable tray cover fire testing conducted in the past with regards to time to ignition and time to electrical failure of the electrical cables enclosed by these systems. The purpose of this work is to supplement the information provided in NUREG/CR-6850 and identify areas for improvement. The following documents were reviewed in completing this review:

1. NUREG/CR-2607, *Fire Protection Research Program for the U.S. Nuclear Regulatory Commission*, April 1983.
2. SAND78-0518, *A Preliminary Report on Fire Protection Research Program, Fire Retardant Coatings Tests (December 7, 1988 – January 31, 1978),* March 1978.
3. NUREG/CR-0381, *A Preliminary Report on Fire Protection Research Program Fire Barriers and Fire Retardant Coatings Tests,* September 1978.
4. NUREG/CR-0366, *Fire Protection Research Quarterly Progress Report October-December 1977,* August 1978.
5. NUREG/CR-5384, *A summary of Nuclear Power Plant Fire Safety Research at Sandia National Laboratories, 1975-1987,* December 1989.
6. SAND77-1424, *A Preliminary Report on Fire Protection Research Program (July 6, 1977 Test),* October 1977.
7. Research Information Letter #46, "Effectiveness of Cable Tray Coating Materials and Barriers in Retarding the Combustion of Cable Trays Subjected to Exposure Fires and in Preventing Propagation Between Cable Trays (Horizontal Open Space Configurations," February 1979.

A.2 Cable Tray Fire Propagation

In the late 1970's cable tray fire tests were performed at Sandia National Laboratories (SNL) to evaluate the separation guidance of RG 1.75 and test standard IEEE 383 with regard to flame spread. The SNL testing showed deficiencies within the guidance and prompted additional testing of alternative methods of reducing the severity of cable tray fires and the likelihood of fire induced damage, including the addition of cable fire retardant coatings and cable tray covers.

Initial testing involved an array of cable trays filled with IEEE-383 qualified electrical cables. The cable trays were arranged in an open-space horizontal configuration with separation distances specified in RG 1.75 between those trays representing redundant safety divisions. Propane burners were used to produce a fully developed cable fire in one tray which then was allowed to spread to the other trays. The full-scale test apparatus is shown in Figure A-1.

Figure A-1. Full Scale Test Apparatus

The testing evaluated the spacing requirements on RG 1.75 under severe fire conditions. One division was represented as two vertical stacks of cable trays arranged with a 10.5 inch (0.27m) vertical separation and an 8 in (0.20 m) horizontal separations. The second, redundant division was represented by two trays 5 feet (1.52 m) above and one tray 3 feet (0.91 m) to the side at the same elevation as the highest tray in the 7 x 2 division. All horizontal trays were 12 feet (3.66 m) long.

The cable trays were filled with IEEE-383 qualified cable to the top of the 4 inch (10 cm) side rails. Cables were placed into the trays in figure 8 configurations to allow for ample air space. Two types of cables were used,

- 3/C, 12AWG, XLPE/XLPE (Supplier A)
- 1/C, 12AWG, XLPE/No Jacket (Supplier B)

The fire was ignited by two IEEE 383 burners located below one of the lowest cable trays in the 7 x 2 cable tray stack. In addition, an insulation board was placed above the lowest cable tray (donor tray) until the donor tray ignited and sustained burning.

The SNL report does not provide complete details on the circuit integrity, but it does mention that for the circuits monitored in the conduits, continuity measurements were normal (i.e., no open circuits) and insulation resistance showed short circuits in all conduits above level 3.

The report documents fire propagation upward vertically as the peak temperatures of each cable tray. This method of documenting flame spread is not as accurate as a time stamped video recording, as the cable tray likely ignites prior to reaching its maximum temperature. Therefore, the reader should exercise caution when interpreting the data in Table A-1.

Table A-1. Cable Failure Progression (Based On Peak Tray Temperature)

Circuit Failure Approximation		**Fire Prorogation**[17]	
Tray	**Time (minutes)**	**Tray**	**Time (minutes)**
1N	N/A – Donor Tray	1N	5
2N	10	2N	14
3N	10	3N	13
4N	14	4N	23
5N	23	5N	45
6N	21	6N	38
7N	26	7N	75[18]
8N	24	8N	35

Conclusions

This test demonstrated that upward fire propagation between cable trays with a vertical separation distance as specified in RG 1.75 [1.5-m (5-ft)] was creditable; if a fully developed cable tray fire occurs at lower elevations. The results from this testing prompted the NRC to sponsor additional fire research at SNL to evaluate the effectiveness of alternative cable fire protection measures (i.e., cable fire retardant coatings and metal cable tray covers).

[17] Caution: fire propagation is based on max tray temperature and not observations

[18] Temperature rose steady for 75 minutes

A.3 Cable Tray Fire Retardant Coatings

A.3.1 Small Scale Testing

Smithers Scientific Services of Akron, Ohio performed small scale tests on six types of fire retardant cable coatings applied to two types of cables supplied from independent manufactures. The cables used were the same as the full scale fire propagation test described above, namely a 3/C, 12AWG, XLPE/XLPE (Supplier A) and a 1/C, 12AWG, XLPE/No Jacket (Supplier B). The cable coatings were identified as A, C, D, E, F, and G.

Each cable types was cut into ½ ft (0.15 m) lengths and placed in wood forms lined with plastic to create a ½ ft by ½ ft. (0.15m by 0.15m) sample size. The fire retardant coatings were trowel onto the cable samples (a 1/c cable sample and a 3/C sample for each coating) to the manufactures specified wet thickness and allowed to dry for 30 days. The cured samples were then mounted vertically into a holding fixture and tested for ignition characteristics by placing a small pilot flame to impinge on the center of the lower edge of the sample. The sample was then exposed to a radiant heat flux of 10, 20, 30 or 40 kW/m^2 and a constant air flow rate of 84 ft^3/min (0.04 m^3/s) to allow for smoke and heat release measurements. Table A-2 provides the results of the small scale testing. The test report focused on the 40kW/m^2 heat exposure, because the researchers identified that it showed the largest discrimination between results for coatings and provided results consistent with full scale tests. Although the analytical method of correlation between small scale and full scale is vague, the time to ignition results tends to correlate well between small scale and full scale testing as will be described later.

Table A-2. Results of Small Scale Coatings

	Heat Flux = 40 kW/m^2		
Coating	**Time to Ignition (minutes)**	**Time to Maximum Heat Release (minutes)**	**Lowest Heat Flux for Ignition (kW/m^2)**
Flamemastic #71A (Item A)	8	16	4
Vimasco #1A (Item C)	8	17	2
Albi-Clad (Item D)	14	28	Note 1
Carboline Intumastic 285 (Item E)	24	34	2
Intumescent Paint (Item F)	5	12	3
Quelcor 703B (Item G)	13	22	2
383 Cable – No Coating	0.8	6	

Note 1: Coating D did not ignite, but showed signs of an intumescent reaction at 2 kW/m^2.

The report also identifies that coating F (intumescent paint) fell off during one of the tests and post test examination showed the coating exhibited low adhesion characteristics.

A.3.2 Full Scale Testing

The full scale testing was also conducted at SNL in Albuquerque, NM. Three horizontal test arrangements were used; 1) single tray propane burner, 2) two-tray propane burner, and 3) two-tray diesel pool fire configuration. A variety of cable coatings and tray covers were tested in all three configurations.

A.3.2.1 Single Tray Tests

The single horizontal tray fire test setup is shown in Figure A-2. The lower ignition tray was the only location used and loaded with coated cables. The ignition source were two IEEE 383 burners adjusted to provide a combined 140,000 Btu (41 kW-hr) and ignited in cycles for 5 minutes burn followed by 5 minute delay, until a sustained fire was observed in the cable tray. For each coating (A, B, C, D, E, and G) two tests were run; one each with the single-conductor cable (25 % cable tray fill) and the three-conductor cable (15% cable tray fill). Additionally, two uncoated IEEE-383 qualified cable (one with single conductor and one with three conductors) and one uncoated non-IEEE-383 qualified cable (PE/PVC) tests were performed. Table A-3 provides the results of the tests.

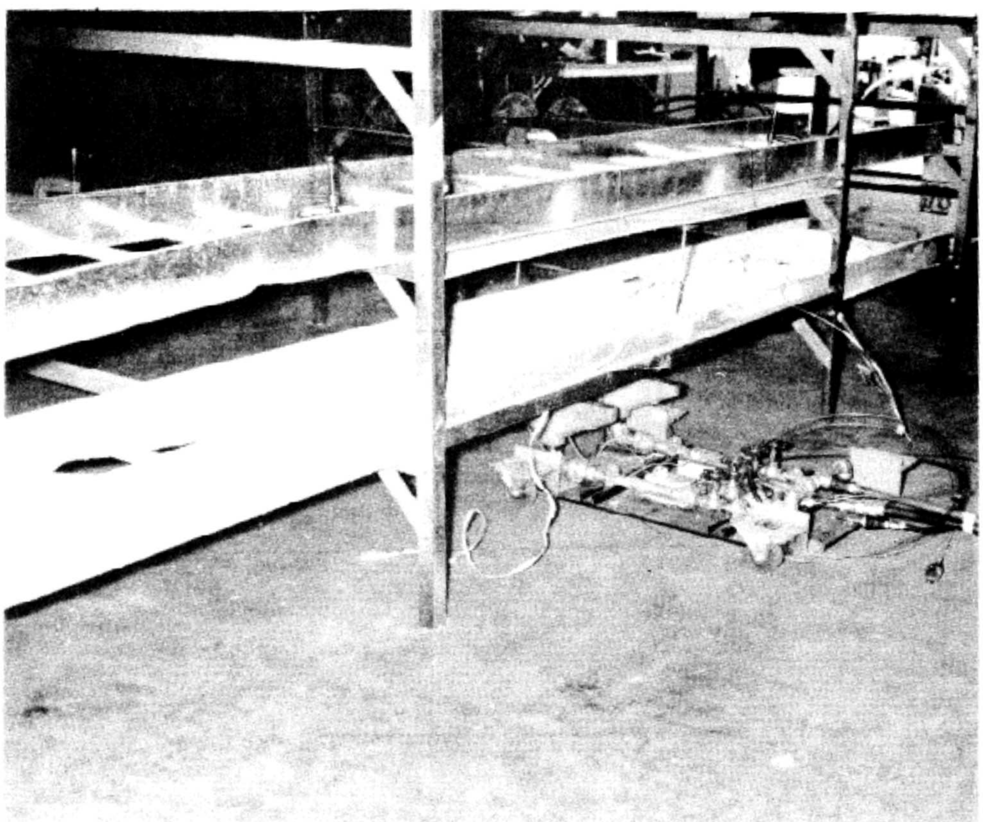

Figure A-2. Full Scale Single Tray Test Apparatus

Table A-3. Results of Full Scale Single Tray Tests

Coating	# Cycles to ignite	Time to Electrical Damage (minutes)	Fire Duration (minutes)	Flame Height Above Cables (in)	Affected Area (in^2)
A (1/C)	2	-	6	5-7	595
A (3/C)	2	26	15	7	450
B (1/C)	4	-	7	7-9	774
B (3/C)	3	-	7	5-8	680
C (1C)	2	24	15	9.5+	1044
C (3/C)	1	5	40	9.5+	774
D (1/C)	>6	-	N/A	N/A	648*
D (3/C)	>6	-	N/A	N/A	648*
E (1/C)	>6	-	N/A	N/A	N/A
E (3/C)	>6	-	N/A	N/A	N/A
G(1/C)	6	40	10	No data	540
G(3/C)	4	-	4	No data	792
None (1/C) Qualified	1	5	10	9.5+	612
None (3/C) Qualified	1	9	13	9.5+	486
None (3/C) Non-qualified	1	6	36	9.5+	1260

* This is the area where the intumescent coating reacted. Note 1. No value reported.

<u>Coating Key</u>
Coating A – Flamemastic #71A
Coating B – Flamemastic #77
Coating C – Vimasco #1A
Coating D – Albi-Clad
Coating E – Carboline Intumastic 285
Coating G – Quelcor 703B

A.3.2.2 Two-Tray Tests

The two-tray horizontal test apparatus is identical to that of the single tray, with the addition of a cable tray 10.5 in. above the ignition cable tray, as show in Figure A-3. The lower tray was filled with 3/C IEEE-383 qualified cables, while the upper tray was filled with 1/C IEEE-383 qualified cable. In addition, a removable fire barrier board was placed between the two cable trays. This barrier was removed, once the lower tray fire developed. The results from this testing are summarized in Table A-4 and Table A-5 in the *Conclusions on Cable Coatings* Section below. A complete table of the results is presented in Addendum 1 at the end of this appendix.

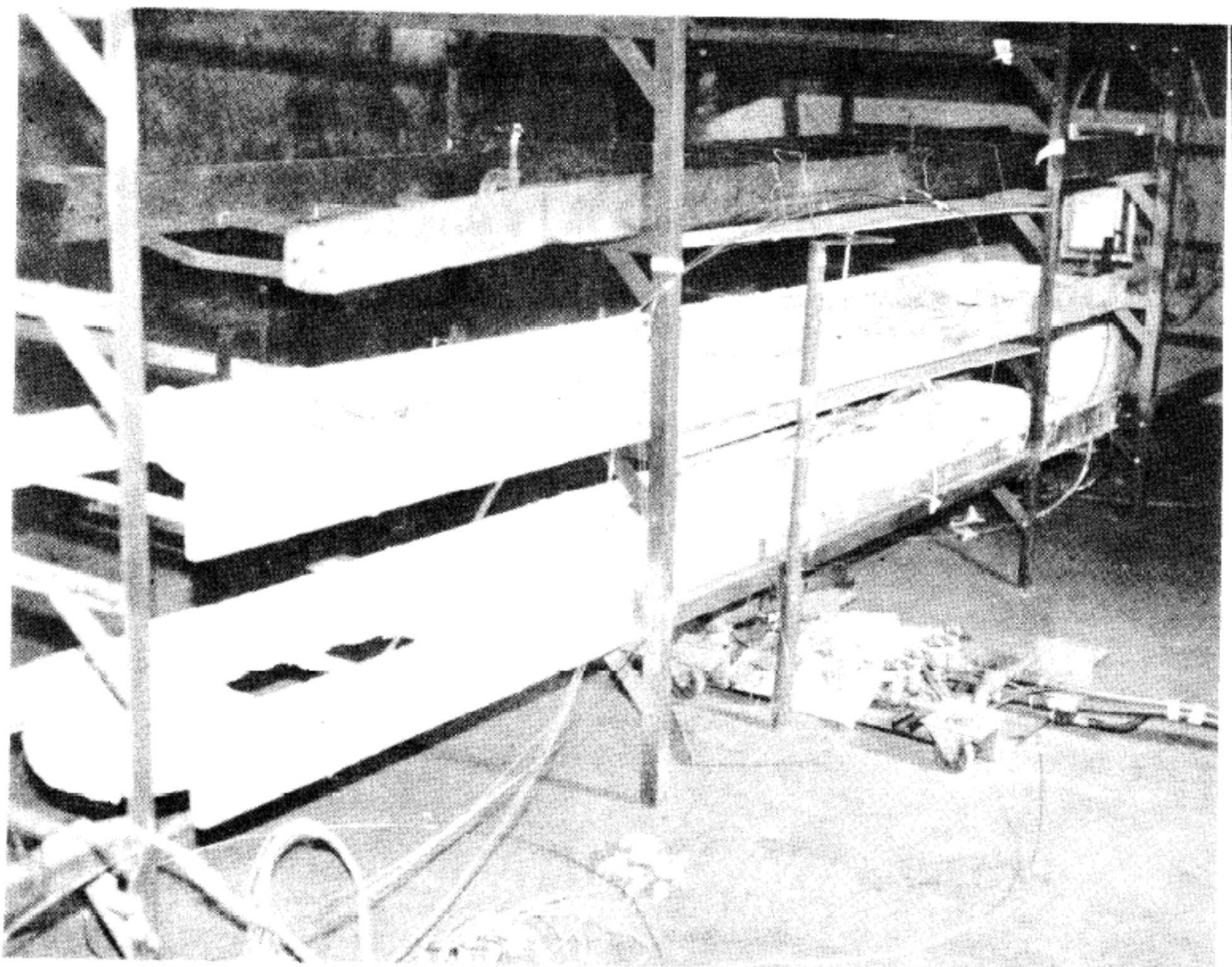

Figure A-3. Full Scale Two-Tray Test Apparatus

A.3.2.3 Diesel Hydrocarbon Pool Fire Two-Tray Tests

The two-tray diesel fuel pool fire test apparatus is identical to that of the two-tray, with the exception of the propane burners are replaced by a fuel pan 3 feet (91.4cm) x 15.5 feet (45.7 cm), located at the same height as the propane burners (4.75 inches below the bottom cable tray). Before each test, two gallons (7.6 x 10^{-3} m^3) of Diesel fuel #2 was poured into the pan and ignited with the aid of approximately 5 ounces (1.5 x 10^{-4} m^3) of mineral spirits. The diesel fuel burned for approximately 11-13 minutes.

Unlike the propane two-tray tests, there was no insulation board placed between the two cable trays in the diesel fuel tests. Diesel fuel fire tests were performed only on non-qualified IEEE-383 cables. The results indicated that only cable coating C (Vimasco #1A) resulted in fire propagation to the second cable tray. The results of this testing are presented below in Table A-4 and Table A-5.

A.4 Conclusions on Cable Coatings

Of the seven cable coatings tested[19], previous research indicates that all coatings provide some level of protection greater than the unprotected cable alone. However, there is a wide range of fire retardant effectiveness of the cable coatings. The relative ranking of the robustness of these cable coating products to resist ignition and cable damage is as follows:

Highest Protection	Albi-Clad
	Carboline Intumastic 285
	Flamemastic #77A
	Quelcor 703B
	Flamemastic #71A
	Vimasco #1A
	Intumescent Paint
	Uncoated 383 Cable
Lowest Protection	Uncoated non-383 Cable

In considering the results from these early cable coating tests, one point must be noted; namely, the reported cable failure results should be viewed with considerable skepticism. As noted earlier, the nature of the electrical failure testing apparatus is not specified in the test reports. Cable functionality testing has evolved substantially since the 1970's. Practices commonly applied in the 1970s are no longer considered appropriate.

This aspect of the tests was discussed with a current SNL staff member, Mr. Steven Nowlen, who was not with SNL at the time of these tests, but who had reviewed this work in some detail in 1988-89 (e.g., see NUREG/CR-5384). Mr. Nowlen did have access to many of the original test records and to one of the SNL technicians who had supported this testing. He was not able to fully discern the details of the cable monitoring systems, but was able to determine that the insulation resistance measurements were based on a low voltage (likely 28Vac) short circuit

[19] A list of fire retardant cable coatings not tested in NRC fire protection research programs is presented in Addendum 2 at the end of this appendix.

monitoring system. His conclusion was that the tests had likely used a 28Vac power source and panel mounted indicator lights (of unknown resistance) that would illuminate given a conductor-to-conductor short circuit. The use of a low voltage source for cable insulation resistance monitoring is no longer considered acceptable practice because it does not place a representative stress (in terms of both voltage and available fault current) on the cable insulation in comparison to, for example, a 120Vac or 125Vdc power source. Mr. Nowlen's recommendation is that these early cable integrity results should not be taken as accurate indications of actual cable condition during the tests. As a result, it is not appropriate to conclude that the same coating would have prevented cable failures given more realistic voltage levels. However, while the circuit integrity results are not definitive, Mr. Nowlen also concluded that they do provide a qualitative indication of the relative performance of the coating materials. That is, a coating that prevented low voltage cable integrity failures did indeed perform better than a coating that did not prevent those failures under the same exposure conditions.

Albi-Clad and Carboline Intumastic 285 were the best performing cable coatings, in that they did not ignite during any of the full scale testing. Nor was electrical failure observed in either of these two coatings for the IEEE-383 qualified cable specimen, cable damage did occur when the Carboline product was tested with non-IEEE-383 qualified cables. Albi-Clad was not tested in that configuration.

The lowest performing cable coatings was Vimasco #1A which provided marginal to no protection to cable for time to ignition and time to cable damage. In one case, a Vimasco coated cable actually experienced cable damage earlier than a non-coated cable.

Flamemastic #71A was also a low performer. Flamemastic #77 showed improvements in time to damage and ignition, falling in the middle range of protection. Quelcor 703B performed somewhere in the mid-range of performance.

Table A-4. Summary of Results - Time to Ignition

		Small-Scale Radiant (minutes)	Full Scale (minutes)			
				Two-Tray		Diesel Pool
	Coating		Single Tray	383	Non-383	Non-383
	Uncoated 383	0.8	5	4-5		Not tested
	Uncoated pre-383	Not tested	5		3-5	Not tested
A	Flamemastic #71A	8	10	10	10	13
B	Flamemastic #77	Not tested	15-20	10	15	13
C	Vimasco #1A	8	5-10	5	15	12
D	Albi-Clad	14	- - -	- - -	Not tested	Not tested
E	Carboline Intumastic 285	24	- - -	- - -	Not tested	- - -
F	Intumescent Paint	5	Not tested	Not tested		Not tested
G	Quelcor 703B	13	30	15	10	12

- - - indicates no ignition

Table A-5. Summary of Results - Time to Cable Damage (Electrical Failure)

	Coating	Single Tray	Two-Tray 383	Two-Tray Non-383	Diesel Pool Non-383
	Uncoated 383	5-9	9		
	Uncoated pre-383	6		2	
A	Flamemastic #71A	26	20	6	10-11
B	Flamemastic #77	- - -	23	14	6-11
C	Vimasco #1A	5-24[1]	8-20	6	3-7
D	Albi-Clad	- - -	- - -	Not tested	Not tested
E	Carboline Intumastic 285	- - -	- - -	32	10-19
G	Quelcor 703B	40		7	11

[1] NUREG/CR-2607 & SAND78-0518 provide different values for electrical failure, 5 and 15 minutes respectively (most conservative was chosen as lowest range for this table).

- - - Indicates no failure

A.4.1 General Conclusions

All fire retardant cable coatings offer some measure of additional protection (albeit minimal for products like Vimasco #1A and the intumescent paint). However, there is a wide range of effectiveness among the coatings in both their ability to retard combustion when exposed to a fire and in their ability to prevent fire propagation from one tray to another. No propagation to the second tray was observed in any of the two tray tests where IEEE-383 qualified cables were used. In the three tests where propagation to the second tray was observed, non-IEEE-383 qualified cable was used.

As would be expected, and as the results show, the non IEEE 383 qualified cables failed earlier than IEEE 383 qualified cables when tested in identical configurations and with the same cable coating.

The diesel fire exposure provided a more realistic fire exposure to the test assemblies than the propane burner tests where a fire barrier separated the lower tray from the upper trays until the lower tray developed. As the tables above indicate, the scales of testing and exposure conditions resulted in failures (ignition and cable damage) of roughly the same relative time frame. Thus, the radiant, single tray propane, two-tray propane, and two-tray diesel fuel results are consistent and could be used in fire hazard analysis or fire PRA for exposure conditions equal to or less severe than the test exposures.

Although, there are some cable coatings that did not fail from these exposures, they would likely fail at a more severe exposure conditions. As such, the analyst should NOT consider these coatings to provide infinite resistance to ignition and/or infinite resistance to electrical damage. Due to these limitations in the current data set, future research is needed to better understand the failure point of the more robust cable coatings.

Their wide relative resistance to fire damage and ignition also confirms that the analysts should use the data provided for the specific fire retardant cable coating under analysis and not use generalized values.

A.5 Cable Tray Metal Covers

SNL also performed eight (8) single tray and five (5) two-tray tests where various fire barriers or shields such as solid bottom trays, 2.54cm (1-in.) solid barriers (ceramic fiber board), and ceramic wool, used to reduce the severity of the fire and delay or prevent the electrical damage to cables. The results of the ceramic fiber board and wool are outside the scope of this review. Table A-6 identifies the configurations tested.

Table A-6. Tray Cover Test Matrix

Configuration	Coating	Single Tray			Two-Tray non-IEEE-383 PE/PVC
		3/C IEEE-383	1/C IEEE-383	3/c non-IEEE-383 PE/PVC	
Solid bottom cable tray, no cover	None	X	X	X	X
Solid bottom cable tray, vented cover	None	X	X	X	X
Solid cable tray cover	None			X	X

Findings reported in NUREG/CR-2607 indicated that, “no propagation to the second tray was observed in any of the two-tray tests where IEEE 383 qualified cable was used. In three tests where propagation to the second tray was observed, non-qualified cable was installed.” Table A-7 and Table A-8 present the results from this testing.

Table A-7. Summary of Single Tray Results for Tray Covers

Configuration	Time to Ignition (minutes)	Time to Damage* (minutes)	Max Cable Temp (°F)
Non-IEEE-383 Qualified			
Solid Top	5	3	1050
Solid Bottom	10	4	1400
Solid Bottom, Vented Top	10	5	1000
IEEE-383 Qualified			
Solid Bottom	No ignition	No damage	350-400
Solid Bottom, Vented Top	No ignition	No damage	440-590

* Damage refers to electrical shorting and NOT physical damage to cable (i.e., melting, charring, blistering, etc.)

Table A-8. Summary of Two-Tray Results for Tray Covers

Configuration		Time to Ignition (minute)	Time to Damage* (minutes)	Burning Duration (minutes)	Max Cable Temp (ºF)
Solid Top					
	Lower Tray	10	5	68	
	Upper Tray	No ignition	No damage	0	250
Solid Bottom					
	Lower Tray	20	8	4	650
	Upper Tray	No ignition	No damage	0	91
Solid Bottom, Vented Top					
	Lower Tray	10	5	55	1300
	Upper Tray	No ignition	45	0	265

* Damage refers to electrical shorting and NOT physical damage to cable (i.e., melting, charring, blistering, etc.)

A.6 General Conclusions

Note that the same limitations on the cable damage tests that were noted above for the cable coating tests also apply to the cable tray cover tests since the exact same testing apparatus was used in both test series. Hence, the cable damage results should not be taken as reliable indications of cable performance under realistic voltage and available fault current loading conditions, but can be taken as indicative of the relative performance of one cover configuration in comparison to others.

Cable tray covers impede ignition and electrical damage by limiting the availability of oxygen within the cable tray to support combustion. Although flaming may occur within a cable tray enclosure, it is unlikely that a fully developed cable tray fire will develop. The testing identified no instances where the protected cable tray with IEEE-383 qualified cables ignited. The two-tray testing also indicated that no propagation to the second tray occurred of non-IEEE-383 qualified cable. Therefore, lack of ignition reduced the heat exposure to the cables and increases the time to damage.

Only horizontal configurations were tested. Therefore, it is difficult to predict the effects cable tray covers have on time to ignition and time to cable damage of vertical cable trays.

A.7 Suggested Areas of Future Research

1. Evaluation and comparison of electrical performance for cable protected with fire retardant cable coatings and metal tray covers while exposed to fire conditions against current fire-induced electrical failure information.

2. Testing to address aging characteristics of cable coatings and how the cable coatings performance is affected by age.
    a. long term reaction of the fire retardant coating material with the cable jacket
    b. premature aging caused by cable heating
    c. chemical and mechanical stability of fire retardant coatings as they age
    d. various fire retardant coatings may age differently due to composition and trace minerals used in the manufacturing process

3. Testing to evaluate the sensitivity of fire retardant cable coating thickness and the effect of applied cable thickness with regard to shelf life.
    a. The wet consistency (which may be affected by shelf life) may have a significant effect on the ability to apply the material evenly.
    b. Application methods may differ (trowel, spray, gap fill)

A.8 References

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9. http://www.fire-stopsystems.com/thermalastic.html
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Addendum 1. Complete Full Scale Two-Tray Propane Burner Test Results

Coating	Time to Electrical Short	Time to Ignition (minutes)	Fire Duration (minutes)	Affected Area (in^2)	IR to Ground (ohms) Post
IEEE 383 Qualified					
A (3/C)	20	10	18	442	132k
A (1/C)	+++	- - -		442	23.7
B (3/C)	23	10	9	510	2.4k
B (1/C)	+++	- - -		None	720k
C (3/C)	8	5	26	810	120k
C (1/C)	20	- - -		1170	0.41
D (3/C)	+++	- - -	N/A	N/A	>20M
D (1/C)	+++	- - -		N/A	>20M
E (3/C)	+++	- - -	N/A	N/A	4M
E (1/C)	+++	- - -		N/A	>20M
G (3/C)	+++	15	14	684	>20M
G (1/C)	+++	- - -	N/A	N/A	>20M
Uncoated Bottom	+++	5	9	432	26k
Uncoated Top	9	- - -	16	972	0.375
Non-383 Qualified (3/C)					
E (bottom)	32	- - -	N/A	N/A	5M
E (top)	+++	- - -	N/A	N/A	>20M
G (bottom)		10	15		0.74
G (top)		No Propagation			
Uncoated non-qualified Bottom	2	5	39	1206	1.1
Uncoated non-qualified Top	6	N/A	59	1512	0.46

- - - indicates no ignition　　　　+ + + indicates no electrical damage

Addendum 2. Fire Retardant Cable Coatings Not Tested in NRC Fire Protection Research Program

FSS Thermalastic 83C™ is a Factory Mutual Approved fire retardant cable coating. The product website identifies the following fire retardant mechanisms. During fire conditions a chemical reaction produces cooling vapors from metallic hydrates in the coating. Inorganic components in the coating form a surface of high emissivity that results in the radiation of significant amounts of heat away from the protected cables. Fire retardants in the material form products that inhibit combustion in the immediate vicinity of the cables.

KBS Cable Coating is a Factory Mutual approved, water-based, ablative fire proofing material developed for the fire protection of grouped or bundled electrical cables and penetration seals. KBS cable coating consumes thermal energy through an endothermic process by which the coating ablates by chemical and physical reactions, creating gases in the process that displace oxygen and dilutes flammable gases. This coating has been tested in accordane with BS476 Part 7 “Flame Spread”, and IEC60331-11 “Flame Rate Cable 52 min.”

Firefree® Cable is a factory mutual approved (FM3971), ablative fire retardant coating material.

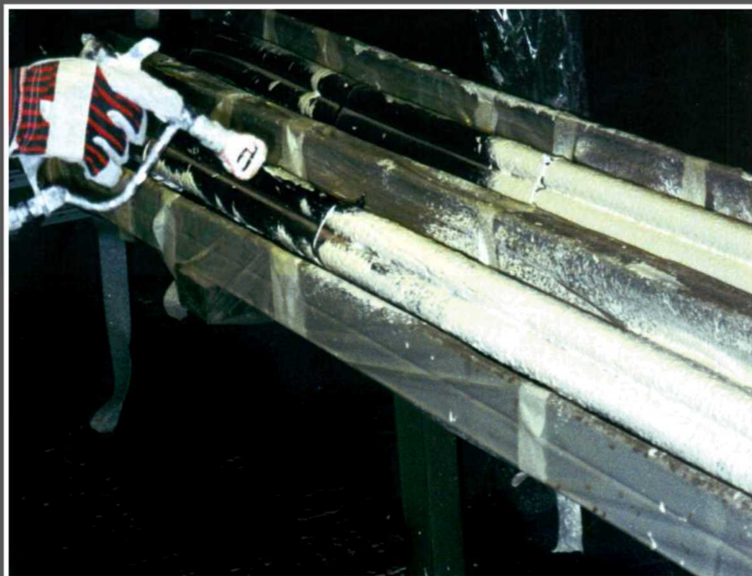
<u>Other FM approved products:</u>

- Flammadur A77 Cable Coating, (Germany), AIK Flammadur Brandschutz GmbH
- Thermo-Lag 270, (USA), Carboline Co
- Nelson FSC, (USA), EGS Nelson Firestop Products Miles
- FIRESEC FS 5, (Norway), Fire Security A/S
- Thermalastic 83C, (USA/Canada), Fire-Stop Systems
- Hilti CP 678 Cable Coating & Hilti CP679A Ablative Cable Coating, (Liechtenstein), Hilti Aktiengesellschaft Div Bauchemie
- Intertherm 677WB (Australia), International Paint
- Intumex AC (Austria), bip GmbH
- CAFCO T.P.S., Type CT (USA), Isolatek International
- PROMASTOP CIS, (Malaysia), Promat International (Asia Pacific) Ltd
- Metacaulk, BioFireshield, Industrial Cable Coating (USA), ReactorSeal Corporation
- Hemsomastik 5 KS, (Germany), Rudolf Hensel GmbH
- SpecSeal Cable Spray CS105, (USA), Specified Technologies Inc.,
- PYRO-SAFE FLAMMOPLAST KS1 & PYRO-SAFE FLAMMOTECT-A, (Germany), svt BRANDSCHUTZ Vertriebsgesellschaft GmbH International
- Vimasco Cable Coatings Nos. 2-B, 3i, (USA), Vimasco Corp.

APPENDIX B. **Vendor Information**

Intumastic® 285

A single package, water-based, flexible mastic fire protective coating for cables and cable trays.



PRODUCT DETAILS

Intumastic 285 has a proven track record of performance protecting electrical cables worldwide. It has been used to provide fire protection for electrical cables and cable trays for over 30 years.

Intumastic 285 was designed to inhibit the combustion process and reduce heat transmission to the protected cables. The coating envelops the protected cables with a fire retardant jacket that protects against flame propagation and maintains circuit integrity during a fire.

Intumastic 285 has successfully passed extensive 3rd party testing to IEC (International Electrotechnical Commission) standards and has been tested and approved by FM Global @ 1/16" (1.6 mm).

Intumastic 285 is designed to last the lifetime of the cables it protects. It does not derate the electrical cables, and is resistant to weather, making it suitable for exterior and interior use. It protects cables in electrical equipment, cable trays and control rooms. It is a proven cable protection coating that is durable, extremely flexible and easily applied.

PRODUCT FEATURES

- 30+ years of successful case histories
- FM Global (Factory Mutual) certified
- International Electrotechnical Commission (IEC) certified
- 120 minute flame propagation protection (IEC 60332-3-22)
- 50 minute circuit integrity protection (IEC 60331-1)
- Class A (Class 1) rated for flame spread & smoke development
- Water based, single pack
- Exterior rated
- Flexible and durable
- Ampacity derating testing - 0% (FM Global testing)
- Manufactured to ISO 9001 standards

APPLICATIONS

PETROCHEMICAL PLANTS

POWER PLANTS

STEEL & ALUMINUM MILLS

MANUFACTURING FACILITIES

carboline
Coatings - Linings - Fireproofing

Intumastic® 285

QUALITY PRODUCT BACKED BY QUALITY SERVICE

- Carboline Company has been solving tough corrosion and fireproofing problems since 1947
- Industrial service centers and sales offices located around the world
- Over 20 worldwide manufacturing locations with a global network of sales and technical support
- Industry leading field service and technical engineering support team
- Certified to ISO 9001

INTUMASTIC 285 TEST DATA

TEST METHOD	RESULTS	THICKNESS	LABORATORY
Circuit Integrity (IEC 60331-1)	50 minutes	62 mils (1.6 mm)	Intertek (ITS)
Flame Propagation (IEC 60332-3-22)	120 minutes	62 mils (1.6 mm)	Intertek (ITS)
Flame Spread (ASTM E84)	Class A (Class 1)	N/A	FM Global
Smoke Development (ASTM E84)	Class A (Class 1)	N/A	FM Global
Halogen Gas Content (IEC 60754)	Pass (<5.0 mg/g HCl)	N/A	Intertek (ITS)
Ampacity (EPS 96202)	0% derating	62 mils (1.6 mm)	FM Global
Weathering (FM 3971)	Exterior rated	N/A	FM Global
Accelerated Aging (DIN EN ISO 4892-2)	Passed (No loss in fire properties)	N/A	Intertek (ITS)

INTUMASTIC 285 PHYSICAL DATA

TEST	RESULT
Weight per Gallon	10.6 lbs. (4.8 kg)
Hardness (ASTM D2240)	Shore D 30-40
Flexibility	Excellent
Abrasion Resistance	Very Good
Impact Resistance	Excellent
Solids by Volume	53%
V.O.C.	0.24 lb/gal (28 g/l)
Coverage (Per Gallon)	13.1 ft² @ 1/16" (1.6 mm)
Shelf Life	18 Months

*All values derived under controlled laboratory conditions.

carboline®
Coatings - Linings - Fireproofing

2150 Schuetz Road • St. Louis, MO 63146 • PH: 800-848-4645 • carboline.com

01-46-1012-523

product data **carboline**®

Intumastic® 285

fireproofing systems

Selection & Specification Data

Generic Type Single package, water-based, flexible mastic fire protective coating for cables and cable trays.

Description A water based mastic that can be applied to electrical cables to retard fire propagation. Once applied, it meets code and insurance requirements for interior and exterior use. It provides a hard and flexible surface that will not dust, flake, or spall.

Features
- Extremely flexible
- Hard, dust free surface
- Impact and abrasion resistant
- Water-based product, low odor
- Asbestos-Free – complies with EPA and OSHA regulations
- Factory Mutual tested and approved
- Does not de-rate cables
- Approved for interior and exterior use
- Provides protection at 1/16" (1.6 mm) dry film thickness

Color Grey

Finish Textured

Textured finish varies depending on the method of application.

Primers Primer is not required.

Fireproofing Topcoats Topcoats are generally not required. In severely corrosive atmospheres, contact Carboline Technical Service for a topcoat reccomendation most suitable for the operating environment.

Fireproofing Wet Film Thickness 1/8" (3mm)

Fireproofing Dry Film Thickness 1/16" (1.6 mm)

Solids Content By Volume 53%

Theoretical Coverage Rates 13.1 ft² @ 1/16" (1.6 mm) DFT

VOC Values As Supplied 0.24 lb/gal (29 g/l)

Limitations Not recommended for long-term surface temperatures over 195°F (91°C) in continuous use, 220°F (104°C) in non-continuous use.

Substrates & Surface Preparation

General Before applying Intumastic® 285 to electrical cables, the cables must be dry and free of all oil, grease, condensation or any other contamination.

Typical Chemical Resistance

Exposure	Fumes	Splashes & Spills
Acids	Very Good	Fair
Alkalies	Very Good	Fair
Salt	Excellent	Very Good
Solvents	Good	Good

Performance Data

Test Method	Results
ASTM D2240 Hardness	Shore D 30-40
ASTM E84 Surface Burning	Class A
DEFSTAN 02-711-2 Smoke Index	Class A
EPS 96202 Ampacity	No de-rating
IEC 60331-1 Circuit Integrity	50 minutes @ 1/16" (1.6 mm)
IEC 60332-3-22 Flame Propagation	2 hours @ 1/16" (1.6 mm)
IEC 60754 Halogen Gas Content	Pass (<5.0 mg/g HCl)

*All values derived under controlled laboratory conditions.
*Test reports and additonal information available upon written request.

Application Equipment Guidelines

Listed below are general equipment guidelines for the application of this product. Job site conditions may require modifications to these guidelines to achieve the desired results.

Air Spray Graco 5:1 Bulldog with Even-Flo regulator valve, 4.6 gpm (17 lpm) output
Graco 10:1 President with Even-Flo regulator valve, 1.7 gpm (6.4 lpm) output

Air line must be a minimum 100 psi (6.9 kPa). Use 3/8"(9 mm) I.D. line from gun to Even-Flo regulator valve with an air adjusting valve attached at the gun end for atomization control.

Airless Spray Graco 30:1 Bulldog, 3.0 gpm (11.0 lpm) output (6.4 lpm) output

Spray Gun For Airless Spray Use:
Graco Mastic Golden Gun with Graco HDRAC 0.059" - 0.063" tips
For Air Spray Use:
Binks 7E2 Gun with 47-49 fluid tip / 3/8" or 1/2" air cap
Graco 204000 Gun with 164331 fluid tip / 160658 air cap

Material Hose 3/4" (19 mm) I.D. minimum (50') is recommended for all pump recommendations listed. For hose lengths over 50' (15.3 m), a 1-1/2" I.D. hose is recommended. A 10' (3 m) 3/4" (19 mm) whip hose may be added to better facilitate handling.
Minimum bursting pressure on material lines should be 1000 psi (68.9 kPa) when using 5:1 or 10:1 pumps. When using a 30:1 pump, the minimum bursting pressure should be 3,000 psi (206.7 kPa).

Compressor Be certain that the air supply is a minimum of 75 cfm @ 100 psi (6.9 kPa). Air volume and pressure required will depend on equipment used.

Mixing & Thinning

Mixer Use 1/2" electric or air driven drill with a slotted paddle mixer (300 rpm under load).

Mixing Intumastic® 285 must be mixed using a 1/2" electric or air driven drill with a slotted paddle or Jiffy mixer blade. Mix material for a minimum of 5 minutes to achieve the necessary texture required before spraying.

Thinning Intumastic® 285 may be thinned with clean potable water up to 5% by volume.

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Intumastic® 285

Application Procedures

General Intumastic® 285 may be applied by spray, trowel or hand application. When spray applying, Intumastic® 285 must be thinned 5% by volume (1 quart water per 5 gallons maximum). A single coat built up with a number of quick passes allows greater control over quantities, thickness and finish. In most conditions, it is advantageous to apply two thin coats rather than one thick coat.

*Material losses during mixing and application will vary and must be taken into consideration when estimating projects.

Application Rates At an ambient temperature of 70°F (21°C), apply 1/8" (3mm) per coat (wet)

Wet Film Thickness Frequent thickness measurements with a wet film gauge are recommended during the application process to ensure uniform thickness.

Palming Hand application of Intumastic® 285 may be more economical when cables are "ganged" or for protecting individual strands. Rubber gloves are recommended.

Trowel A standard plasterer's hawk and trowel may be used for suitable applications. Selection of instruments is left to the discretion of the applicator.

Application Conditions

Condition	Material	Surface	Ambient	Humidity
Minimum	50 °F (10 °C)	40 °F (4 °C)	40 °F (4 °C)	0%
Maximum	110 °F (43 °C)	95 °F (35 °C)	95 °F (35 °C)	90%

*Air and substrate temperature must be at least 40°F (4.4°C) and rising. Surface temperature should be a minimum of 5°F (3°C) above the dew point. The maximum humidity is 90%. Area must be protected from rain or running water during application until material is cured. Minimum ambient temperatures must be maintained for 24 hours after application.

Curing Schedule

Surface Temp. & 50% Relative Humidity	Dry to Touch	Final Cure Time
70 °F (21 °C)	24 Hours	15 Days

*Curing times are dependent on thickness, humidity and temperature. Normal dry times are based on a wet thickness of 1/8" (3.2 mm).

Cleanup & Safety

Cleanup Pump, gun, tips and hoses should be cleaned with clean, potable water at least once every 4 hours at 70°F (21°C) and more often at higher temperatures.

Safety Follow all safety precautions on the Intumastic® 285 Material Safety Data Sheet. It is recommended that personal protective equipment be worn including spray suits, gloves, eye protection and respirators when applying Intumastic® 285.

Overspray All adjacent and finished surfaces shall be protected from damage and overspray. Wet overspray may be cleaned with soapy or clean potable water. Cured overspray may require chipping or scraping to remove.

Ventilation In enclosed areas, ventilation shall not be less than 4 complete air exchanges per hour until the material is dry.

Cleanup & Safety

Caution Intumastic® 285, like most water based coatings, is electrically conductive until it is dry. Extreme caution should be exercised when the material is applied to energized cables and equipment. The material should never be applied without the supervision of plant safety personnel.

Testing / Certification / Listing

Intertek Intumastic® 285 has been successfully tested at Intertek laboratories to the following international test standards:
IEC 60331-1 - Circuit Integrity
IEC 60332-3-22 - Flame Propagation
IEC 60754-1 - Halogen Gas Content
DEFSTAN 02-711-2 - Smoke Index

FM Global Intumastic® 285 has been tested and approved by Factory Mutual Research Corporation at 1/16" (1.6 mm) dry thickness, and evaluated by Sandia Laboratories in tests sponsored by the U.S. Nuclear Regulatory Commission using both propane and diesel fueled fires.
Ampacity tests run by Factory Mutual show "No electrical derating necessary when a cable is coated (and cured properly) with Intumastic® 285." The temperature attained was well below the maximum temperature rating of the cable insulation. Heat transfer calculations should be used to calculate derating requirements of large groups of conductors.

Factory Mutual Research Corp.

Sandia Labs
•Diesel (Cable Tray)
•Propane (Cable Tray)

Electrical Power System
•Ampacity - No derating of cables required
•Report EPS 96202
Fire Retardant coating for Electrical Power and Control Cables at 1/16" (1.6 mm) dry film thickness.

*Test reports are available upon request.

Packaging, Handling & Storage

Shelf Life 18 Months

*Shelf Life: (actual stated shelf life) when kept at recommended storage conditions and in original unopened containers.

Shipping Weight (Approximate) 11 lbs. per gallon

Flash Point (Setaflash) >300°F (148°C)

Storage Store indoors in a dry environment between 40°F - 110°F (4.4°C - 43.3°C). Keep from freezing.

Packaging 5 gallon

carboline®
Coatings - Linings - Fireproofing
2150 Schuetz Rd., St. Louis, MO 63146
PH: 314-644-1000 Toll-Free: 800-848-4645
www.carboline.com

An RPM Company

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carboline **Material Safety Data Sheet**	**CHEMTREC Transportation Emergency Phone: 800-424-9300** **Pittsburgh Poison Control Center Health Emergency No.: 412-681-6669** NOTE: The CHEMTREC Transportation Emergency Phone is to be used only in the event of chemical emergencies involving a spill, leak, fire, exposure or accident involving chemicals

Section 1 - Chemical Product / Company Information

Product Name:	INTUMASTIC 285	**Revision Date:**	03/15/2012
Identification Number:	PLMSDS 0143S7NL	**Supercedes :**	07/20/2011
Product Use/Class:	FOR INDUSTRIAL USE ONLY		
		Preparer:	Regulatory, Department
Manufacturer:	**Carboline Company 2150 Schuetz Road St. Louis, MO 63146 (800) 848-4645**		

Section 2 - Composition / Information On Ingredients

Chemical Name	CAS Number	Weight % Less Than	ACGIH TLV-TWA	ACGIH TLV-STEL	OSHA PEL-TWA	OSHA-CEIL
PLASTICIZER	1330-78-5	5.0	NE	N/E	NE	NE
ALIPHATIC HYDROCARBON	64742-88-7	5.0	N/E	N/E	N/E	N/E
BARIUM METABORATE	13701-59-2	5.0	0.5 MGM3	N/E	0.5 MGM3	NE
SODIUM TETRABORATE	1303-96-4	5.0	2 MGM3	6 MGM3	10 MGM3	NE
TITANIUM DIOXIDE	13463-67-7	0.6	10 MGM3	N/E	10 MGM3	N/E
FIBREGLASS	65997-17-3	0.5	N/E	N/E	N/E	N/E
MICROCRYSTALLINE SILICA	14808-60-7	0.2	0.025 MG/M3 (respirable)	N/E	0.1 MG/M3 (respirable)	N/E

Section 3 - Hazards Identification

Emergency Overview: Contains SILICA which can cause cancer. Risk of Cancer depends on duration and level of exposure. Use ventilation necessary to keep exposures below recommended exposure limits, if any.

Effects Of Overexposure - Eye Contact: May cause eye irritation.

Effects Of Overexposure - Skin Contact: May cause skin irritation.

Effects Of Overexposure - Inhalation: Harmful if inhaled, may affect the brain or nervous system, causing dizziness, headache, or nausea. May cause nose and throat irritation. Use in inadequately ventilated areas may result in irritation headache and nausea.

Effects Of Overexposure - Ingestion: May be harmful if swallowed.

Effects Of Overexposure - Chronic Hazards: Crystalline silica is known to cause silicosis. Crystalline silica (Quartz) is classified as a known human carcinogen (Group 1) by IARC. Exposure is by route of inhalation. If material is in a liquid matrix it is unlikely to be inhaled. However, when sanding or grinding the finished product, there may be potential for crystalline silica to become airborne. Under normal use conditions, this product is not expected to cause adverse health effects. Reports have associated repeated and prolonged occupational overexposure to solvents with permanent brain and nervous system damage.

Primary Route(s) Of Entry: Skin Contact, Skin Absorption, Inhalation, Ingestion, Eye Contact

Medical Conditions Prone to Aggravation by Exposure: If you have a condition that could be aggravated by exposure to dust or organic vapors, see a physician prior to use.

Section 4 - First Aid Measures

First Aid - Eye Contact: If material gets into eyes, flush with water immediately for 15 minutes. Consult a physician.

First Aid - Skin Contact: Launder clothing before reuse. In case of contact, wash skin immediately with soap and water.

First Aid - Inhalation: If inhaled, remove to fresh air. Administer oxygen if necessary. Consult a physician if symptoms persist or exposure was severe.

First Aid - Ingestion: If swallowed do not induce vomiting. Seek immediate medical attention.

Section 5 - Fire Fighting Measures

Flash Point, F: 300F (148C) (Setaflash)

Lower Explosive Limit, %: 1.0
Upper Explosive Limit, %: 17.4

Extinguishing Media: Carbon Dioxide, Dry Chemical, Foam, Water Fog

Unusual Fire And Explosion Hazards: This is a water based product, however it does contain small amounts of volatile organic compounds (See Section II). Vapors are heavier than air and will accumulate. Vapors will form explosive concentrations with air. Vapors travel long distances and will flashback.

Special Firefighting Procedures: Evacuate hazard area of unprotected personnel. Use a NIOSH approved self-contained breathing unit and complete body protection. Cool surrounding containers with water in case of fire exposure.

Section 6 - Accidental Release Measures

Steps To Be Taken If Material Is Released Or Spilled: Eliminate all ignition sources. Handling equipment must be grounded to prevent sparking. Evacuate the area of unprotected personnel. Wear appropriate personal protection clothing and equipment. Follow exposure controls/personal protection guidelines in Section 8. Contain and soak up residual with an aborbent (clay or sand). Take up absorbant material and seal tightly for proper disposal. Dispose of in accordance with local, state and federal regulations. Refer to Section 15 for SARA Title III and CERCLA information.

Section 7 - Handling And Storage

Handling: Do not get in eyes, on skin, or on clothing. Keep container tightly closed when not in use. Wear personal protection equipment. Do not breathe vapors. Wash thoroughly after handling. If pouring or transferring materials, ground all containers and tools. Do not weld, heat, cut or drill on full or empty containers. Use only in accordance with Carboline application instructions, container label and Product Data Sheet. Avoid breathing vapors or spray mist.

Storage: Protect from Freezing! Keep away from heat, sparks, open flames and oxidizing agents. Keep containers closed. Store in a cool, dry place with adequate ventilation.

Section 8 - Exposure Controls / Personal Protection

Engineering Controls: Use explosion-proof ventilation when required to keep below health exposure guidelines and Lower Explosion Limit (LEL).

Respiratory Protection: Use only with ventilation to keep levels below exposure guidelines listed in Section 2. User should test and monitor exposure levels to ensure all personnel are below guidelines. If not sure, or not able to monitor, use MSHA/NIOSH approved supplied air respirator. Follow all current OSHA requirements for respirator use. For silica containing coatings in a liquid state, and/or if no exposure limits are established in Section 2 above, supplied air respirators are generally not required.

Skin Protection: Recommend impervious gloves and clothing to avoid skin contact. If material penetrates to skin, change gloves and clothing. The use of protective creams may be beneficial to certain individuals. Protective creams should be applied before exposure.

Eye Protection: Recommend safety glasses with side shields or chemical goggles to avoid eye contact.

Other protective equipment: Eye wash and safety showers should be readily available.

Hygienic Practices: Wash with soap and water before eating, drinking, smoking, applying cosmetics, or using toilet facilities. Use of a hand cleaner is recommended. Launder contaminated clothing before reuse. Leather shoes can absorb and allow hazardous materials to pass through. Check shoes carefully after soaking before reuse. Contaminated clothing should be changed and washed before reuse. Eating, drinking and smoking in immediate work area should be prohibited.

Section 9 - Physical And Chemical Properties

Boiling Range:	162 F (72 C) - 491 F (255 C)	**Vapor Density:**	Heavier than Air
Odor:	Ammoniacal	**Odor Threshold:**	N/D
Appearance:	Grey to White Paste	**Evaporation Rate:**	Slower Than Ether
Solubility in H2O:	N/D		
Freeze Point:	N/D	**Specific Gravity:**	1.21
Vapor Pressure:	N/D	**PH:**	N/D
Physical State:	Paste		

(See section 16 for abbreviation legend)

Section 10 - Stability And Reactivity

Conditions To Avoid: Heat, sparks and open flames.

Incompatibility: Avoid contact with strong oxidizing agents.

Hazardous Decomposition Products: Carbon monoxide, nitrogen oxides, and unidentified organic compounds. Consider all smoke and fumes from burning material as very hazardous. Welding, cutting or abrasive grinding can create smoke and fumes. Do not breathe any fumes or smoke from these operations.

Hazardous Polymerization: Will not occur under normal conditions.

Stability: This product is stable under normal storage conditions.

Section 11 - Toxicological Information

Product LD50: N/D

Product LC50: N/D

Chemical Name	CAS Number	LD50	LC50
PLASTICIZER	1330-78-5	>20,000 MG/KG, ORAL , RAT	11.1 MG/L, RAT, INH
ALIPHATIC HYDROCARBON	64742-88-7	>25 ML/KG RAT, ORAL	>700 PPM/4 HOURS (RAT)
BARIUM METABORATE	13701-59-2	>2,000 MG/KG	> 3.5 MG/L
SODIUM TETRABORATE	1303-96-4	NOT AVAILABLE	NOT AVAILABLE
TITANIUM DIOXIDE	13463-67-7	>25 G/KG, ORAL, RAT	>6.82 MG/L 4 HR, RAT
FIBREGLASS	65997-17-3		
MICROCRYSTALLINE SILICA	14808-60-7	NOT AVAILABLE	NOT AVAILABLE

Section 12 - Ecological Information

Ecological Information: No data

Section 13 - Disposal Information

Disposal Information: Dispose of in accordance with State, Local, and Federal Environmental regulations. Responsibility for proper waste disposal is with the owner of the waste.

Section 14 - Transportation Information

DOT Proper Shipping Name:	Not Regulated	**Packing Group:**	N/A
DOT Technical Name:	N/A	**Hazard Subclass:**	N/A
DOT Hazard Class:	None	**Resp. Guide Page:**	N/A
DOT UN/NA Number:	None		

Additional Notes: None.

Section 15 - Regulatory Information

CERCLA - SARA HAZARD CATEGORY

This product has been reviewed according to the EPA Hazard Categories promulgated under Sections 311and 312 of the Superfund Amendment and Reauthorization Act of 1986 (SARA Title III) and is considered, under applicable definitions, to meet the following categories:

IMMEDIATE HEALTH HAZARD, CHRONIC HEALTH HAZARD, FIRE HAZARD

SARA SECTION 313

This product contains the following substances subject to the reporting requirements of Section 313 of Title III of the Superfund Amendment and Reauthorization Act of 1986 and 40 CFR part 372:

No Section 313 Substances exist in this product

TOXIC SUBSTANCES CONTROL ACT

All components of this product are listed on the TSCA inventory.

This product contains the following chemical substances subject to the reporting requirements of TSCA 12(B) if exported from the United States:

No TSCA 12(B) Substances exist in this product

U.S. STATE REGULATIONS AS FOLLOWS:

NEW JERSEY RIGHT-TO-KNOW

The following materials are non-hazardous, but are among the top five components in this product.

Chemical Name	CAS Number
WATER	7732-18-5
ALUMINUM HYDROXIDE	21645-51-2
ACRYLIC EMULSION	TRADE SECRET
ACRYLIC LATEX	26604-01-3
VERMICULITE	1318-00-9

PENNSYLVANIA RIGHT-TO-KNOW

The following non-hazardous ingredients are present in the product at greater than 3%.

Chemical Name	CAS Number
WATER	7732-18-5
ALUMINUM HYDROXIDE	21645-51-2
ACRYLIC EMULSION	TRADE SECRET
ACRYLIC LATEX	26604-01-3
VERMICULITE	1318-00-9
FULLERS EARTH	8031-18-3

CALIFORNIA PROPOSITION 65

Warning: The following ingredients present in the product are known to the state of California to cause Cancer:

Chemical Name	CAS Number
TITANIUM DIOXIDE	13463-67-7
FIBREGLASS	65997-17-3
MICROCRYSTALLINE SILICA	14808-60-7
FORMALDEHYDE	50-00-0
CARBON BLACK	1333-86-4
ETHYL ACRYLATE	140-88-5

Warning: The following ingredients present in the product are known to the state of California to cause birth defects, or other reproductive hazards:

No California Proposition 65 Reproductive Toxins exist

INTERNATIONAL REGULATIONS AS FOLLOWS:

CANADIAN WHMIS

This MSDS has been prepared in compliance with Controlled Product Regulations except for the use of the 16 headings.

CANADIAN WHMIS CLASS: D2A D2B

Section 16 - Other Information

HMIS Ratings
Health: 2 **Flammability:** 1 **Reactivity:** 1 **Personal Protection:** X

VOLATILE ORGANIC COMPOUNDS, GR/LTR MIXED (UNTHINNED): 0

REASON FOR REVISION: Changes made in Section(s) 11 and 15.

Legend: N.A. - Not Applicable, N.E. - Not Established, N.D. - Not Determined

The information contained herein is, to the best of our knowledge and belief accurate. However, since the conditions of handling and use are beyond our control, we make no guarantee of results, and assume no liability for damages incurred by use of this material. It is the responsibility of the user to comply with all applicable federal, state, and local laws and regulations

Flamemastic 77 System

Technical Bulletin
June 2007

PRODUCT DESCRIPTION

Flamemastic 77 System Coatings, are compounded of water based thermoplastic resins flame-retardant chemicals and inorganic, incombustible fibers. These coatings contain no asbestos. One or more of the following patents protect the Flamemastic 77. United States - 3642531, 3928210; Great Britain - 1297710; West Germany - 2039969; or other patents pending.

Factory Mutual Research Corporation has tested and approved Flamemastic-77 for use on grouped electrical cables.

FIRE PROTECTION

Flamemastic 77 protects electrical cables from fire and prevents propagation of fire on grouped electrical cables. (Fire Protection against shorting out varies in time with fire intensity, cable size, type of cable insulation and thickness of coating. See page 4 of Loss Prevention Economics for typical examples.) The coating has shown exceptional fire protection in independent tests ranging from 3 hour ASTM E119 Wall Penetration Test, where the coating was used in conjunction with insulation board, to horizontal, stacked tray tests on several types of cables under fire loads of 140,000 BTU/hr.

When grouped electrical cables are covered with the recommended thickness of Flamemastic 77, the cable jacket and insulation no longer are a source of fuel for a fire.

EFFECT ON AMPACITY

Reduction of current carrying capacity varies with the size of the cable and the thickness of the coating. At the recommended coating thickness there is no effect on the ampacity of the coated cables.

PERMANENCE

Flamemastic 77 continues the formulated from proven flame retardants material as well as inert non-asbestos fillers that have proven their permanence and effectiveness for over thirty years.

EFFECT OF RADIATION

Flamemastic 77 coated cables were subjected to 3×10^8 rad of gamma radiation at a rate of 5×10^5 rad per hour for 600 hours. This exposure had no significant effect on the coating or its fire protective capability.

Supersedes June 2005
Flamemaster Corporation
13576 Desmond Street
Pacoima, CA 91331-2315
Phone (818) 890-1401 *** Fax (818) 890-6001**

Flamemastic 77 System

	Flamemastic 77 Sprayable	Flamemastic 77 Mastic
Weight per Gallon	12.4 lb/per gallon	12 lb/per gallon
Hardness of dried film	85 shore A	85 shore A
% Solids	69%	69%
Consistency	Thixotropic	Heavy Mastic

SPECIAL NOTES

Protect Flamemastic-77 from freezing during shipment and storage. Do not store at temperatures below 35° F or above 90° F.

Flamemastic 77, like most water base coatings, can conduct electricity until it thoroughly dries. Exercise extreme caution when applying the material to energized cables or equipment. Never apply Flamemastic without supervision of plant safety personnel. Hazards include, but are not limited to, open buss ducts, cable potheads, exposed conductors, faulty cable insulation and transformer bushings.

The information presented herein is based on data believed to be reliable. The Flamemaster Corporation makes specific recommendations for the use and application of Flamemastic 77, which are important factors in its performance. Since the Flamemaster Corporation has no control over the use and application it cannot insure that your results will be the same as those described.

Supersedes June 2005

Flamemaster Corporation
13576 Desmond Street
Pacoima, CA 91331-2315
Phone (818) 890-1401 *** Fax (818) 890-6001**

Material Safety Data Sheet	HMIS HAZARD RATING		One part water base
May be used to comply with OSHA's Hazard Communication Standard 29 CFR 1910. 1200 Standard must be consulted for specific requirements	Health	1	FED-STD-313 Latest Revision
	Flammability	0	
	Reactivity	0	
	PPE	H	

OMB registration Number None	Type of Data Sheet New Revised X **reformatted**
SECTION I General Information	Number of revised section: **supercedes 09-01-2004**
Commercial ID (as on label and list) **Flamemastic F-77**	Government contract or order number **N / A**
Manufactures Name **Flamemaster Corporation**	National Stock Number /CAN LSN /SIN **N / A**
Manufactures Address (No Street, City, State and zip) **Chem Seal Division** **13576 Desmond Street** **Pacoima, CA 91331-2315**	Part number, product and or trade name **Flamemastic F-77**
	Hazardous items Yes No **X**

Emergency Telephone Number **(800) 424-9300 CHEM TREC**	Information telephone number **(818) 890-6001**	Date prepared **07-2007**
Mfgr. CAGE code **14439**	Name of Preparer **Herbert Moore**	Signature of preparer **On File**
NRC License number **N / A**	EPA Registration Number **N / A**	Specification Number **N / A**
Spec. Type **Sprayable / Mastic**	Spec. Grade. **N / A**	Spec. Class **N / A**

SECTION II - Hazardous Ingredients SARA III Information*

Hazardous Components (Specific chemical identity: Common Name (s)	Other limits	By % weight	OSHA PEL	ACGHI TLV	NIOSH #	CAS #
Antimony Oxide		4.7%	N / A	0.5mg/ M^3	CC5650000	1309-64-4
				(dust)		
Proprietary Formulation						

All remaining Constituents are non-hazardous per FED-STD-313 All Constituents are listed in TSCA inventory; complete mixture is excluded Per TSCA Par. 710.4 (d) 95 (6) (7) Constituents are not listed in TSCA 12b CORR. LIST

* Indicates toxic chemical (s) subject to the reporting requirements of section 313 of Title III and of 40 CFR 372

SECTION III Physical /Chemical Characteristics

Boiling Point **212^0 F - 100^0 C**	Specific Gravity (H_2O = 1) **1.4**	Auto ignition Temperature **N / A**	Decomposition Temperature **N / A**
Vapor Pressure (mm hg) Water at room temperature	PH 7.4	% Volatile by Volume 31	Magnetism (milligauss) N / A
Vapor Density Air = 1 Water vapor	Evaporation rate (Butyl Acetate = 1) N / A	Viscosity 80,000 cps	Corrosion Rate: N / A
Solubility in Water Miscible	Melting Point Liquid at room temperature	Blank	Temp Material Reference
Appearance and Odor : White Heavy Bodied Paint - Slight Odor			Volatile Organic Compound VOC 5 grams / liter

SECTION - IV Fire and Explosion Hazard Data

Flash Point (method used) None Water - Base	Flammable Limits N / A	LEL **N / A**	UEL **N / A**
Extinguishing Methods: None required			
Special Fire Fighting Procedures **N / A**			
Unusual Fire and Explosion Hazards None			

SECTION V - Reactivity Data

Stable X	Unstable	Conditions to avoid Slight corrosive effects on stainless steel	Neutralizing Agents N / A
Incompatibility (materials to avoid) Strong oxidizing agents		Hazardous Decomposition products Oxides of carbon, nitrogen, hydrogen Chloride	
Hazardous Polymerization May Occur	Will not Occur X	Conditions to avoid None Known	

FED-STD-313 Latest Rev	Material: Flamemastic F-77	Date 07-2007	Page 2 One part water base

SECTION VI - Health Hazard Data

Route (s) of entry	Inhalation?	Skin?	Ingestion?
	No	No	yes

Health Hazards (Acute and Chronic) Non established (possible skin irritation)

INJESTION: can cause irritation of the gastrointestinal tract

Carcinogsnicity:	NTP?	IARC Monographs?	OSHA Regulated?
	NO	NO	NO

Medical conditions generally aggravated by exposure:
None known

Signs and symptoms of exposure:
Skin or eye irritation

Emergency and first aid Procedures: Eyes: Flush with large amounts of water consult physician. Skin: wash with soap and water.
Ingestion: If swallowed dilute by giving 2 (two) glasses of water get immediate medical attention.

SECTION VII - - Precautions for Safe Handling and Use

Steps to be taken in the event the material is released or spilled:
Scoop up and transfer to container. Clean up remainder with sand or sweeping compound. Wash area with soap and water. Wear appropriate clothing and protective equipment. (section VIII)

Waste disposal method:
Allow waste to dry and dispose as solid waste per Federal, State and local regulations

Precautions to be taken handling or storing:
Water Based Material Keep From Freezing

Other precautions:
Wash hands thoroughly after handling this product prior to eating , drinking or smoking

SECTION VIII - Control Measures

Respiratory protection (specify type)
When applying in any circumstances likely to produce airborne levels of solvent vapors in excess of the TLV or when mechanically abrading the cured material use an organic vapor cartridge or air supplied respirator.

Ventilation:	Local exhaust	Special:	Mechanical (general)	Other
	Air	N / A	Fan	N / A

Protective gloves Type:	Eye protection Type:
Neoprene	Plastic - goggles

Other protective clothing or Equipment
Appropriate clothing when spraying water based coatings

Work /Hygienic practices:
Safety shower, eye wash station and washing facilities should be available

SECTION IX - Transportation

Applicable regulations:

49CFR X	IMO X	IATA X	Military Air (AFR 71-4)	IMDG	Marine Pollutant No	UN number

Shipping name:	ID Number	Reportable Quantity
Not regulated	N / A	N / A
Unit container	**DOT Spec. container**	**Net explosive weight:**
5 gallon metal pail	37A - 80	N / A

Hazard class:	Labels:
N / A	Not required
DOT Exempt /DOD CCN	**Limited Quantity:**
N / A	N / A
Aerosol propellant (s)	**U.S. Postal regulations:**
N / A	124.122 Harmful mater

Disposal Information:
Water based material

EPA hazardous waste number /Code:	Hazardous waste characteristics:
N / A	Sludge

Disposal methods:
Allow to dry and dispose as solid landfill waste. The material must be handled, packaged and transported according to Federal, State or local regulations

We have obtained the information in this MSDS from sources that we believe to be reliable. However since much of this information has been received from sources outside of the company, it is provided without any warranty expressed or implied regarding its correctness or suitability for specific situations. The conditions of handling, storage, use and disposal are beyond our control and may be beyond our knowledge.

VIMASCO CORPORATION

"Coatings and Adhesives for the World's Industries"

CABLE COATING 3i
INTUMESCENT FIRE-RETARDANT CABLE COATING

APPROVED BY FACTORY MUTUAL
PASSES IEEE-383 FIRE TEST

Cable Coating 3i is a heavy-bodied, water-based intumescent coating which 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. CC3i will also prevent a short circuit within an electrical cable from starting a fire and will help identify the location of such a short circuit by forming an intumescent char at the spot. CC3i can be applied to grouped cables or single cables.

Cable Coating 3i is a unique 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.

Cable Coating 3i is approved by Factory Mutual at our recommended dried film thickness of 1/16th inch and it does not require cable derating (see complete Factory Mutual

COLOR
Yellow, Gray, Black, White
(Special colors available upon request)

COVERAGE (ASTM C 461)
14 sq. ft./gal. @ 1/16" dry
(.34 m^2/liter @ 1.59 mm)
Actual flat surface coverage.

Note: Because of the irregular surfaces, a nominal square foot of cable tray, when loaded with cables, will present more than a square foot of surface area to be coated.

DRYING TIME (ASTM D 1640)
To touch: 2 hours
Through: 24 to 48 hours
(Dependent upon substrate temperature, ambient temperature and relative humidity)

WEIGHT PER U.S. GALLON (ASTM D 1475)
9.9 pounds (1.19 kg)

SOLIDS
62% by weight
53% + 2% by volume

APPLICATION TEMPERATURE RANGE
40ºF (4ºC) to 110ºF (43ºC)

FLAMMABILITY
Passess IEEE-383 flame propagation test
(full test report available upon request)

Test Report).

Cable Coating 3i forms a protective intumescent char when exposed to flame or to a temperature above 350ºF. This char should be removed completely and clean cables should be recoated if intumescence should occur.

Cable Coating 3i is easily applied by brush or spray and it adheres well to cables, allowing for vertical or overhead application. Care should be taken to see that cables are clean and dry before application, particularly that they are free of oil, grease and grit. Cable Coating 3i should be applied in 2 coats to ensure complete coverage.

NOTE: CABLE COATING 3i MUST BE PROTECTED FROM FREEZING DURING STORAGE. During application it must be protected from freezing, moisture, oil, grease, and foot traffic until it is thoroughly cured.

Special Features of Vimasco Cable Coating 3i

Product Photographs

Will not support combustion in wet or dry state.

FLAME SPREAD INDEX
ASTM E 84: 15
ASTM E 162: 16
@ 1/16" dry film (1.59 mm)

INTUMESCENCE
600% to 700% typical after 10 minute exposure to 1600ºF

RADIOACTIVITY DECONTAMINATION FACTOR
(ASTM D 4256-83 and ANSI 5.12-1974)
5.83 after 10 weeks curing time

CLEANUP
Wet state - water
Dry state - safety solvent

RECOMMENDED SHELF LIFE
12 months in unopened container
@40ºF (4ºC) to 90ºF (32ºC)

CAUTION
The addition of water or any thinning agent to this product will change its physical properties and will adversely affect its performance. No expressed or implied warranty will be offered on applications where this product has been thinned or altered in any manner.

GO BACK

Vimasco Corporation
P.O. Box 516
Nitro, WV 25143

Phone (304)755-3328
Fax (304)755-7153
Toll Free in North America (800) 624-8288

Material Safety Data Sheet
For Coatings, Resins and Related Materials

Manufacturer's Name:
Vimasco Corporation, P. O. Box 516, Nitro, WV 25143

Emergency Phone:
(304) 755-3328

Date of Preparation: Updated ( ) Revised (X)
September 24, 2003 New ( )

Information Phone
(304) 755-3328

Section I - Product Identification

Product Number: Cable Coating 3i Product Name: Cable Coating 3i

Product Class: Fire Retardant Latex Coating (Mixture)

Transportation Information: Ship as Paint, Class 55 - Non-hazardous water-base material

Section II - Hazardous Ingredients

Ingredient	Percent By Weight	Occupational Exposure Limits TLV	Vapor Pressure
Ethylene Glycol [107-21-1]	1 - 2%	50ppm (ceiling-STEL) (vapor & mist)	.10mmHg 68ºF
Tri(B-chloroethyl)Phosphate [115-96-8]	0.9 - 1.5%	Not established	17.5mmHg 70ºF
Chlorinated Paraffin [61788-76-9]	6 - 7.5%	Not established	Not applicable

Section III - Physical Data

Boiling Range: 212ºF - 216°F Vapor Density: Lighter than air pH: 9

Evaporation Range: Slower than ether Volatile Volume: 43% Wt/Gal: 10.0 lb.

VOC: 0.31 lbs/gal Decomposition Temperature: Approx. 240ºF (115ºC)

Specific Gravity: 1.20 Viscosity: Normal range 60,000 to 70,000 cps Freezing Point: 30ºF (-1ºC)

Solubility in Water: Appreciable

Section IV - Fire and Explosion Hazard Data

Flammability Classification: OSHA - IIIB; DOT - Not regulated; Flash Point - No flash to boiling 212ºF (TCC)

Extinguishing Media: Foam, Alcohol Foam, CO_2, Dry Chemical, Water Fog

Unusual Fire and Explosion Hazards: Products of combustion can be irritating to eyes & nose.

Special Firefighting Procedure: Product will not burn until after water has boiled or evaporated. For dried film or residual solids, full protection equipment is recommended, including self-contained breathing apparatus.

Section V - Health Hazard Data

Effects of Overexposure: TLV for this mixture has not been established.

Mixture is believed to be a relatively non hazardous product. Medical care should be directed at control of symptoms. Major hazards would be splashing in eyes and accidental ingestion.

Medical Conditions Prone to Aggravation by Exposure: Persons with preexisting lung disorders may be more susceptible.

Primary Routes of Entry: Dermal, inhalation or eyes

Emergency and First Aid Procedure: *Skin:* Wash with soap and water. *Eyes:* Flush with clean water at least 15 minutes. If irritation persists, consult physician. *Inhalation:* Remove to fresh air. If breathing is difficult, administer oxygen. If irritation persists, consult physician. *Ingestion:* Give two glasses of water, induce vomiting, consult physician or poison control center. ***Never give anything by mouth to an unconscious person.***

Section VI - Reactivity Data

Stability: Stable Hazardous Polymerization: Will not occur

Hazardous Decomposition Products: Thermal decomposition will yield CO, CO_2, Chlorinated Compounds, HPOx, antimony-oxychloride, and traces of fragmented short chain hydrocarbons.

Conditions to Avoid: None known

Incompatibility (Materials to avoid): Materials incompatible with water

Section VII - Spill or Leak Procedure

Steps to be Taken in Case Material is Released or Spilled: Major spills should be collected for disposal. Minor spills may be flushed to sewer if regulations permit. Before drying, product may be washed away with water; after drying, remove with paint scraper or strong solvent.

Waste Disposal Method: In accordance with all applicable regulations. Review hazard section of this sheet before attempting cleanup. Empty containers are non hazardous under RCRA as industrial waste.

Section VIII - Safe Handling and Use Information

Respiratory Protection: In restricted ventilation areas, use approved chemical vapor respirator. In applications where mists or spray may be generated, avoid inhalation of airborne particulates by using an approved respirator with organic vapor cartridge with prefilter for mist or dust.

Ventilation: General (mechanical) room ventilation is expected to be satisfactory.

Protective Gloves: Impervious gloves Other Protective Equipment: None

Eye Protection: Goggles, faceshield, or other eyewear to protect from splash

Hygienic Practices: Thoroughly cleanse hands after handling. Launder contaminated clothing before reuse.

Section IX - Special Precautions

Precautions to be Taken in Handling and Storing: Use with adequate ventilation. Avoid prolonged breathing of vapors and application to hot surfaces. Keep container closed when not in use. Store indoors at temperatures of 40ºF to 110ºF.

Other Precautions: For industry/professional use only. Not intended for retail sale or use by individual consumers. Do not reuse container for potables or edibles.

Section X - Sara Status

This mixture contains the following materials regulated under Section 313:

Ethylene Glycol [107-21-1]	1 - 2% by weight
Antimony Oxide [1309-64-4]	2 - 3% by weight

Note: If you repackage or redistribute this product to industrial customers, a MSDS similar to this one should be sent.

APPENDIX C. **Temperature Plots for All Single and Seven-Cable Bundle Tests**

C.1 Introduction

This Appendix contains temperature histories from all thermocouple measurements for all single and seven-cable bundle baseline tests that were conducted as part of this project. It also contains tables with the parameters for tests in which only temperature data was collected. Test description tables for tests in which electrical data from SCDU and IRMS were collected are presented in Appendix C and D, respectively.

C.2 Temperature History Plots

Figure C-1 through Figure C-35 present the temperature history for all channels from all single and seven-cable bundle tests. Plots are ordered by test number.

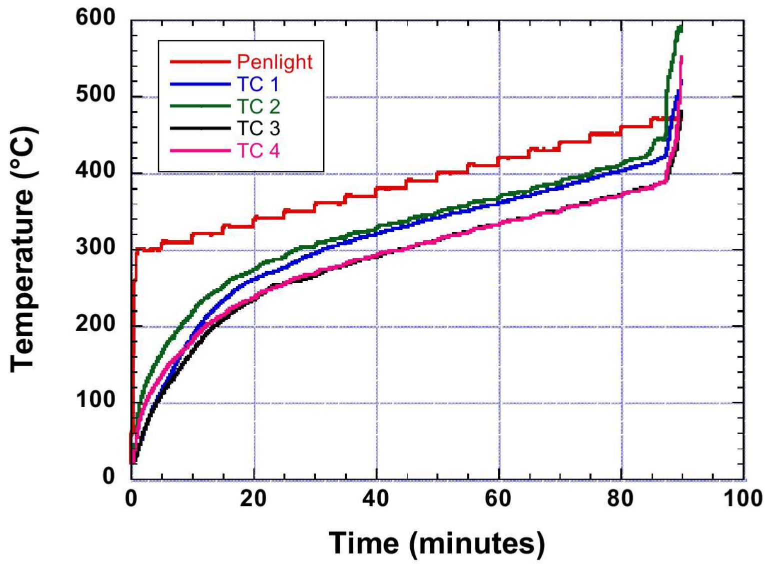

Figure C-1. Temperature history of test 1

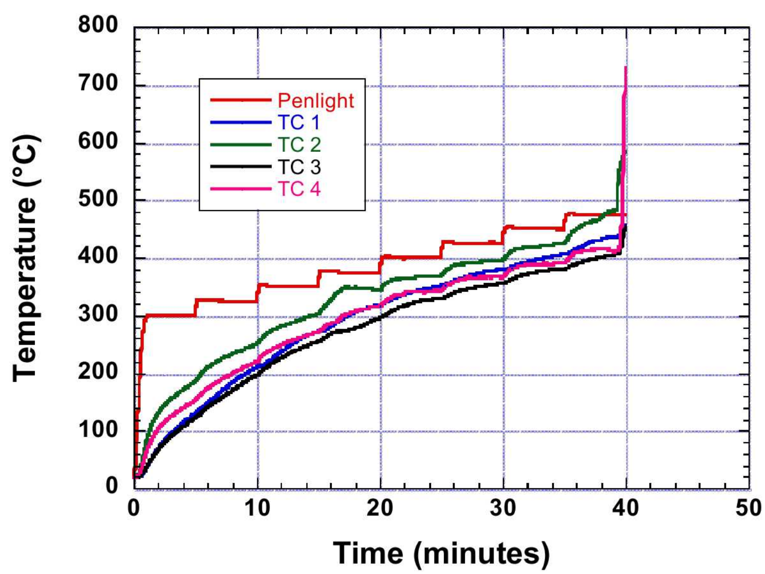

Figure C-2. Temperature history of test 1a

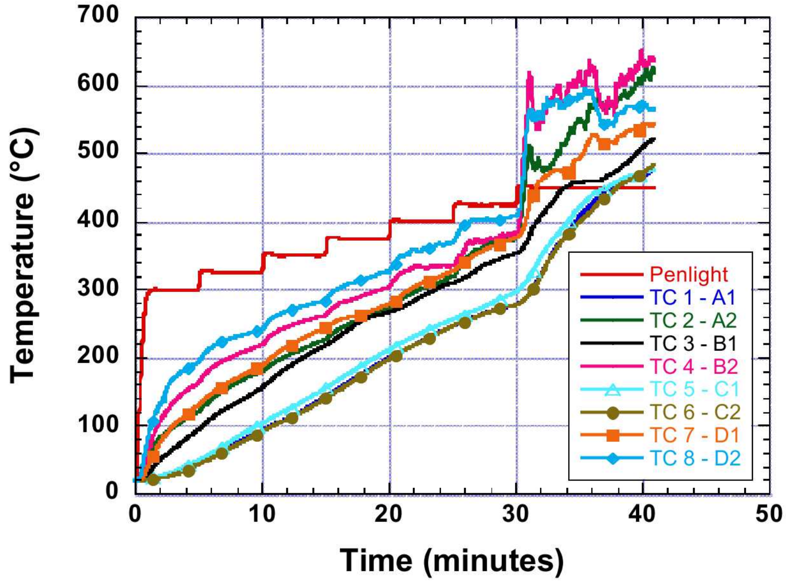

Figure C-3. Temperature history of test 2

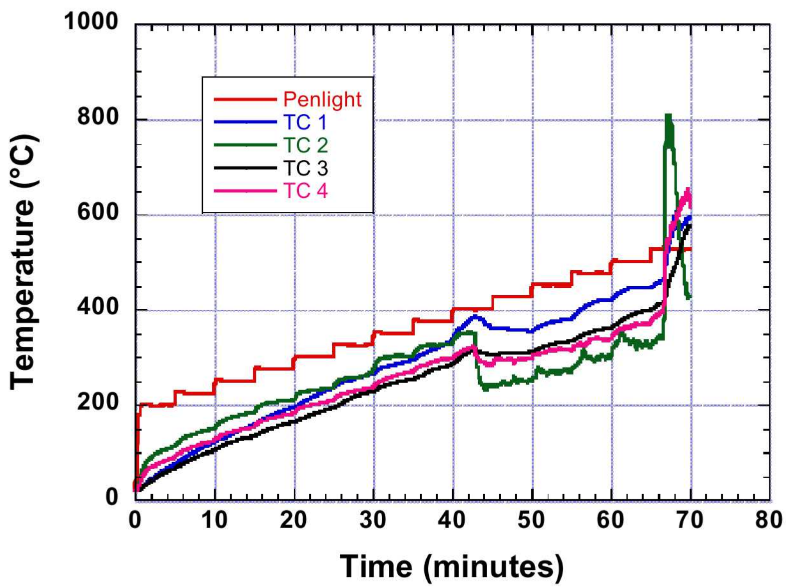

Figure C-4. Temperature history of test 3

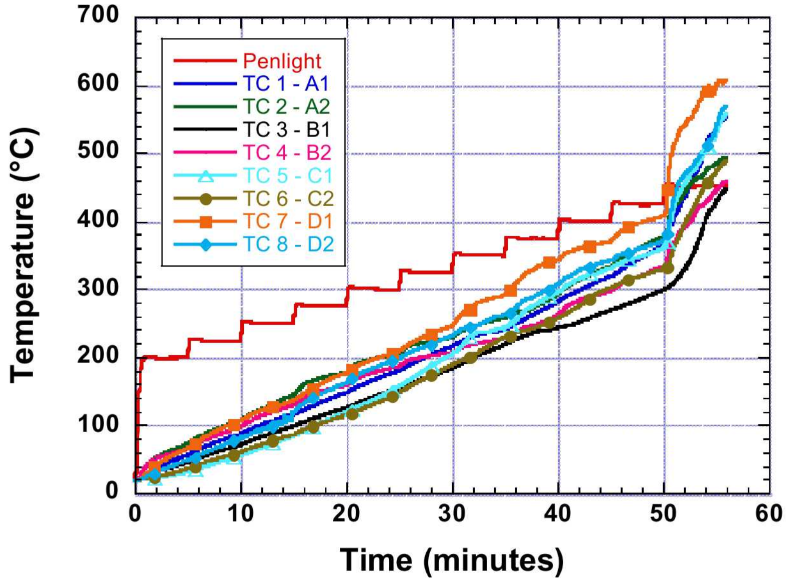

Figure C-5. Temperature history of test 4

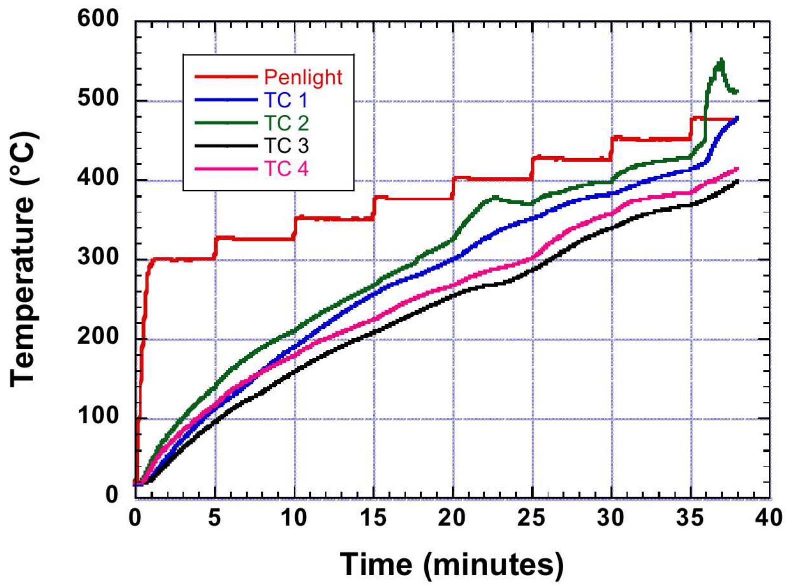

Figure C-6. Temperature history of test 5

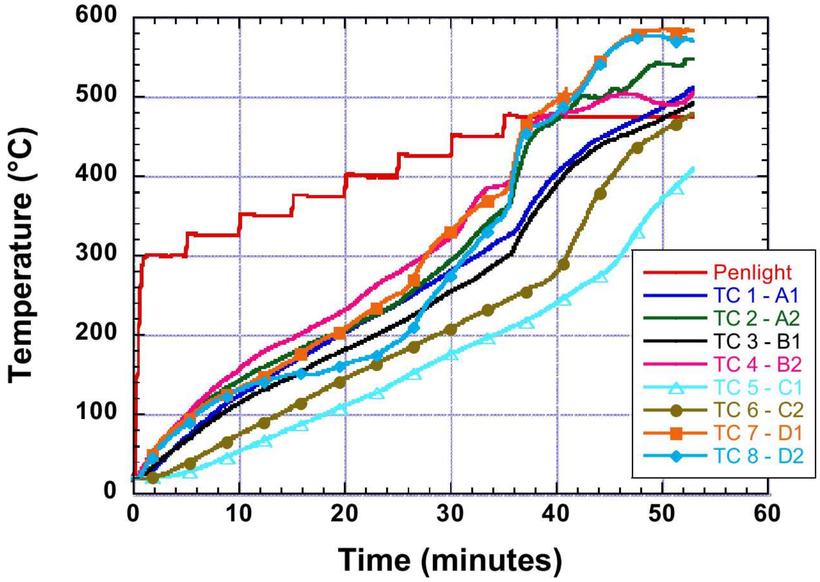

Figure C-7. Temperature history of test 6

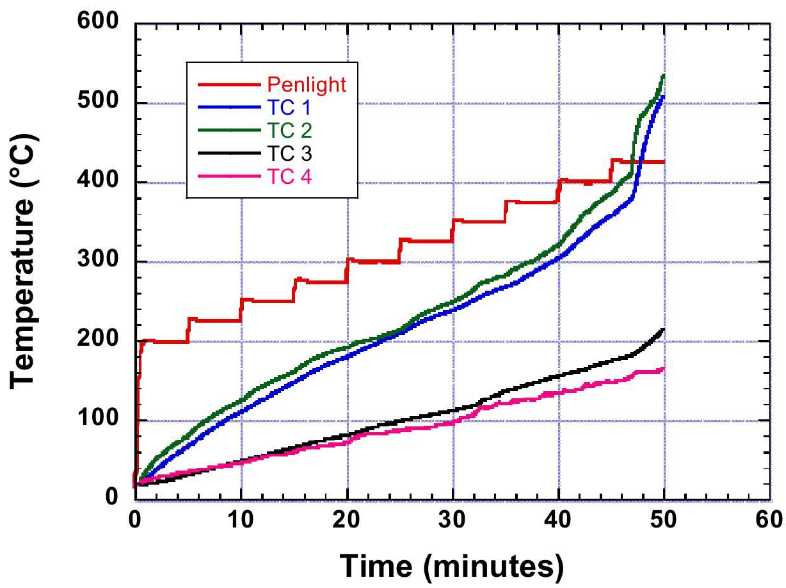

Figure C-8. Temperature history of test 7

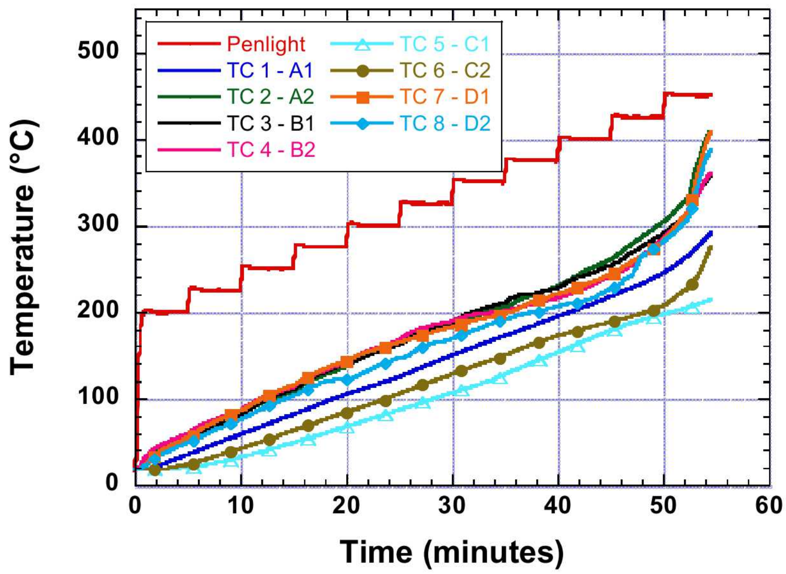

Figure C-9. Temperature history of test 8

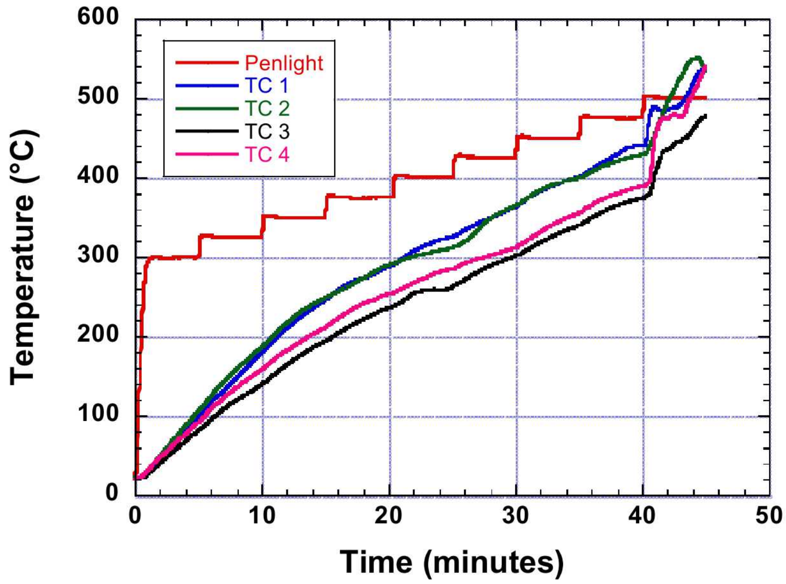

Figure C-10. Temperature history of test 9

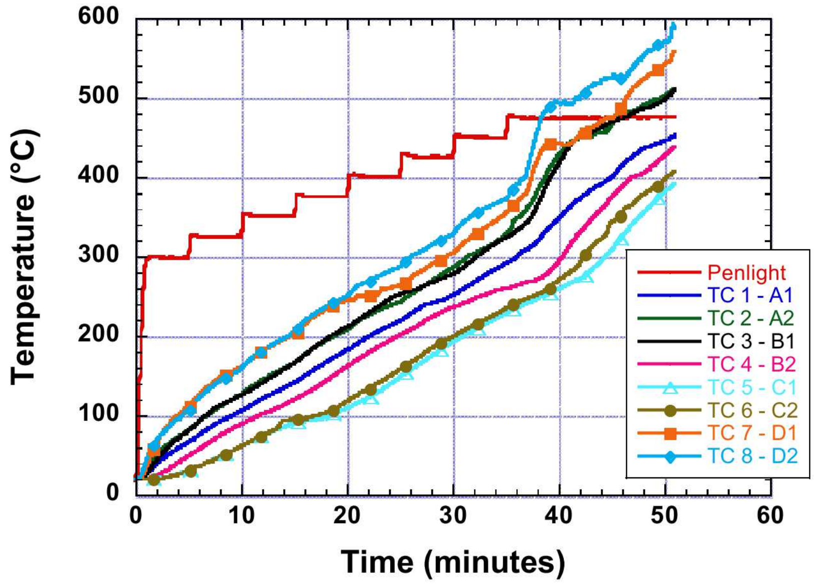

Figure C-11. Temperature history of test 10

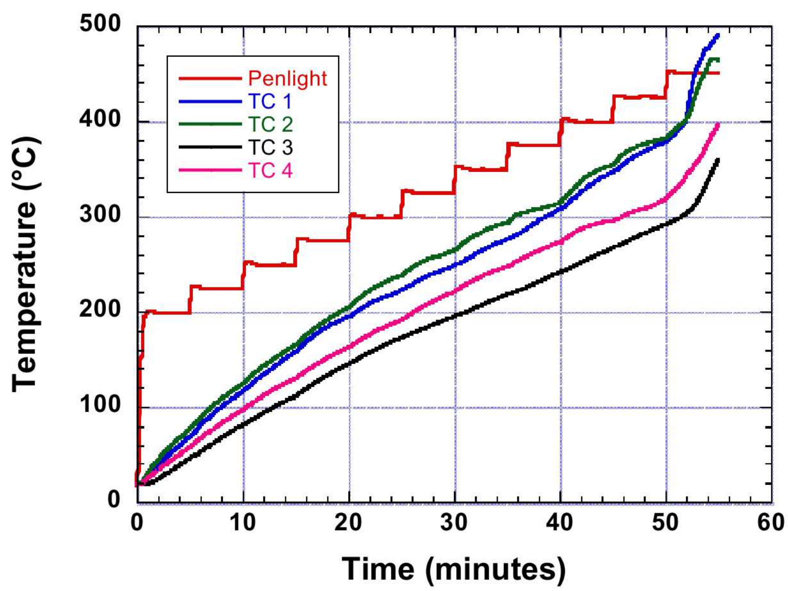

Figure C-12. Temperature history of test 11

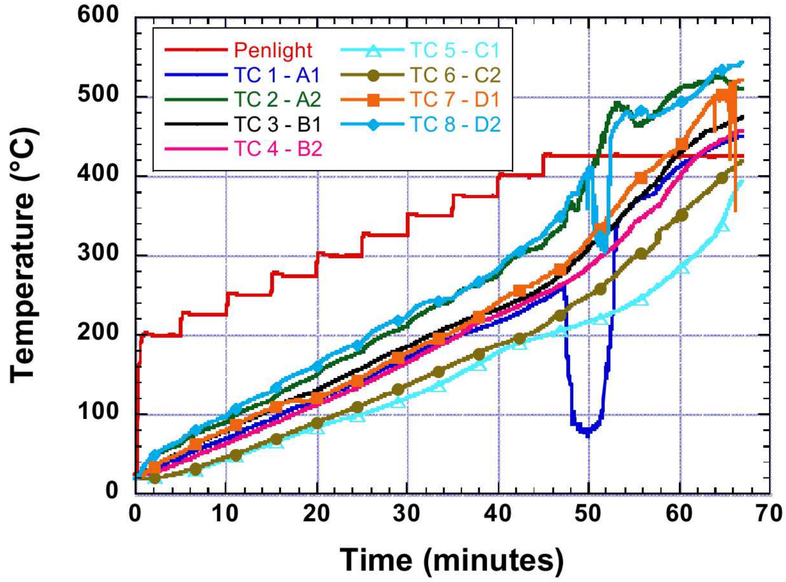

Figure C-13. Temperature history of test 12

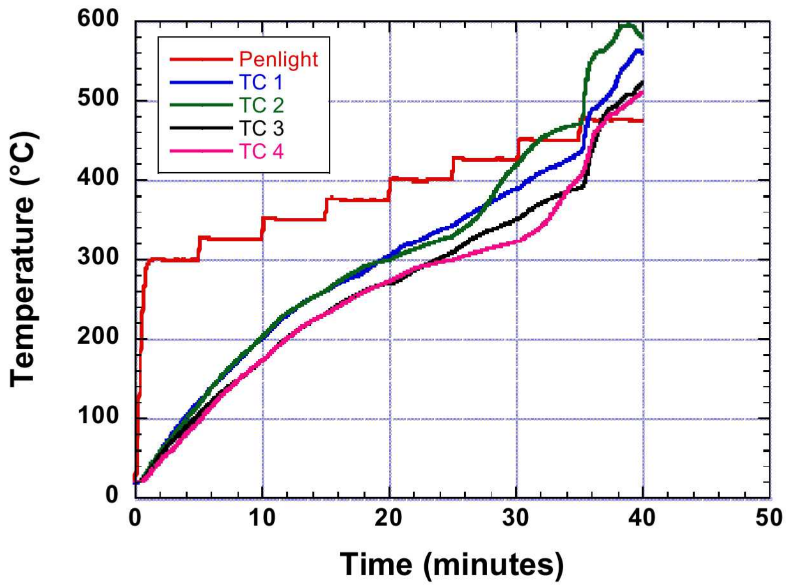

Figure C-14. Temperature history of test 13

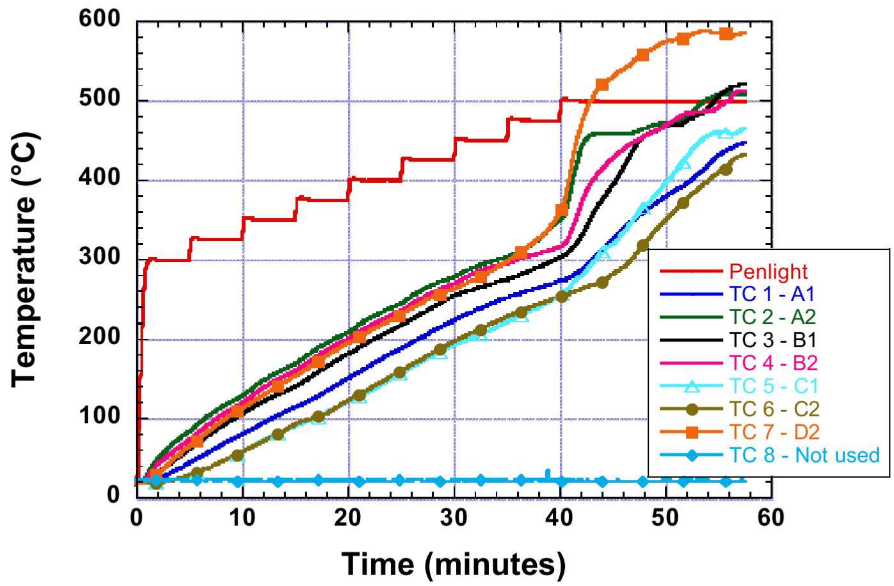

Figure C-15. Temperature history of test 14

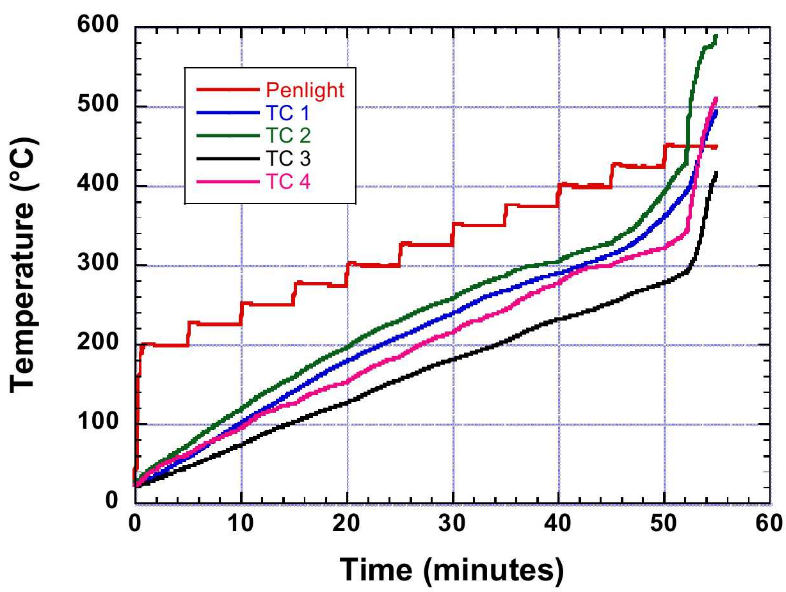

Figure C-16. Temperature history of test 15

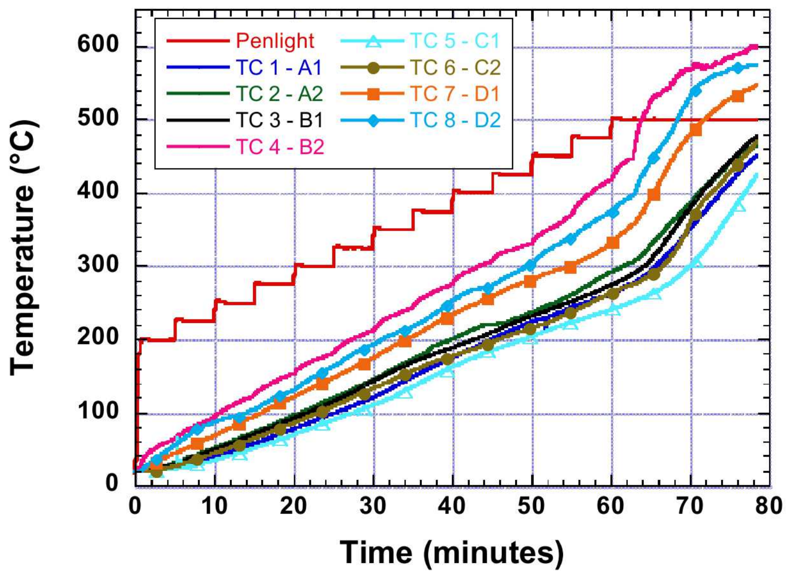

Figure C-17. Temperature history of test 16

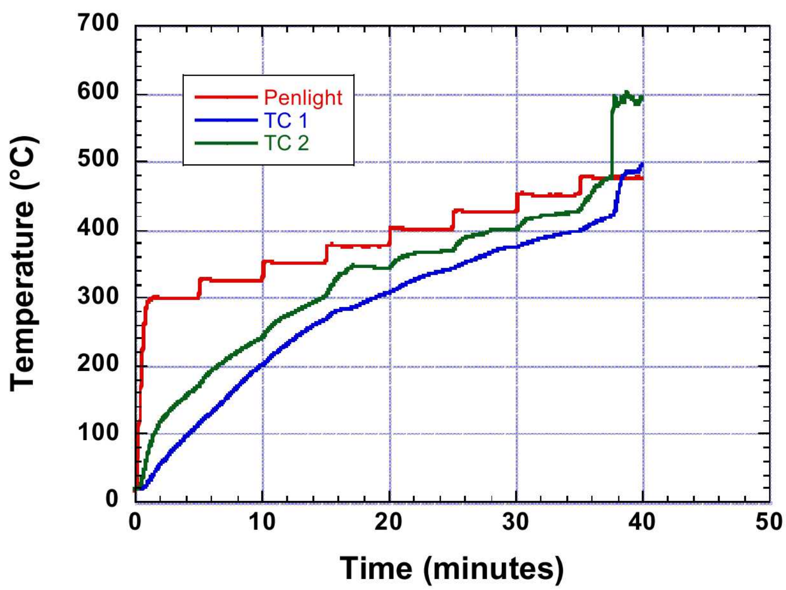

Figure C-18. Temperature history of test 17

One factor to note is that during test 18, one of the uncoated cable tests, the primary sub-jacket thermocouple, TC-1, experienced an intermittent fault. For purposes of data analysis and illustration, only the filtered data stream for this particular case will be shown.

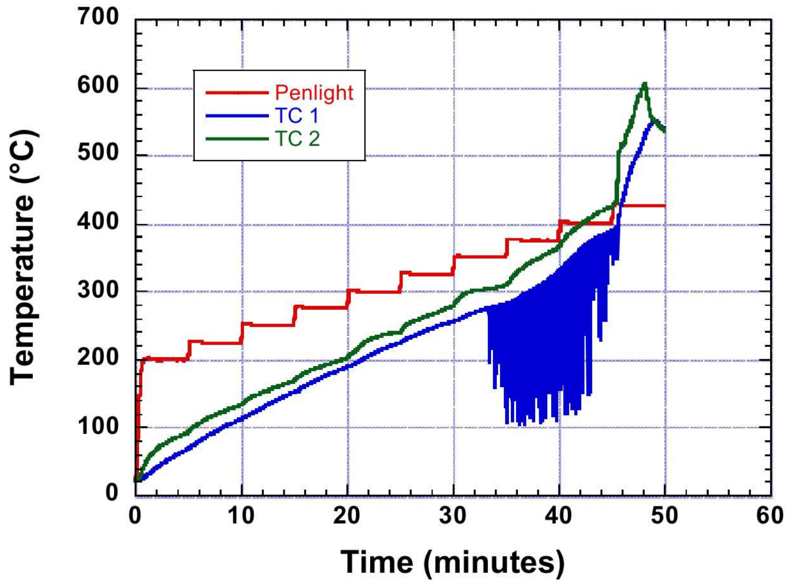

Figure C-19. Temperature history of test 18

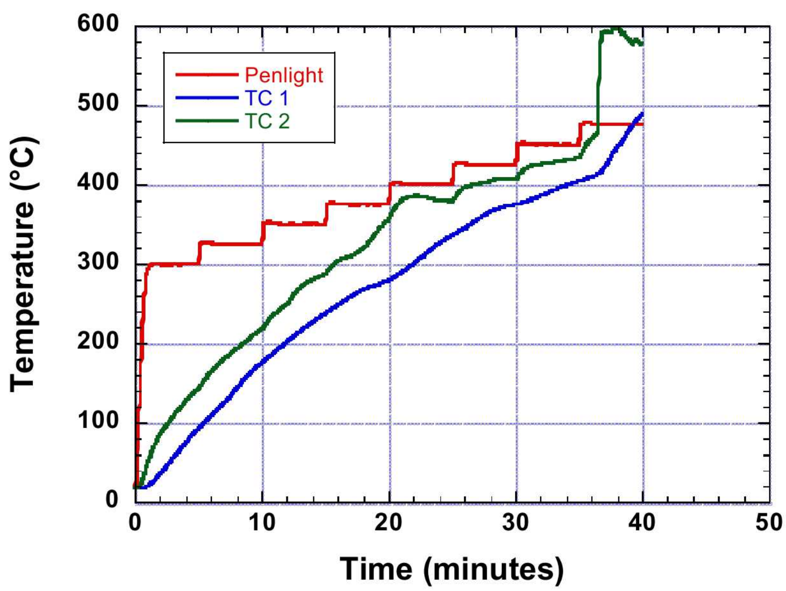

Figure C-20. Temperature history of test 19

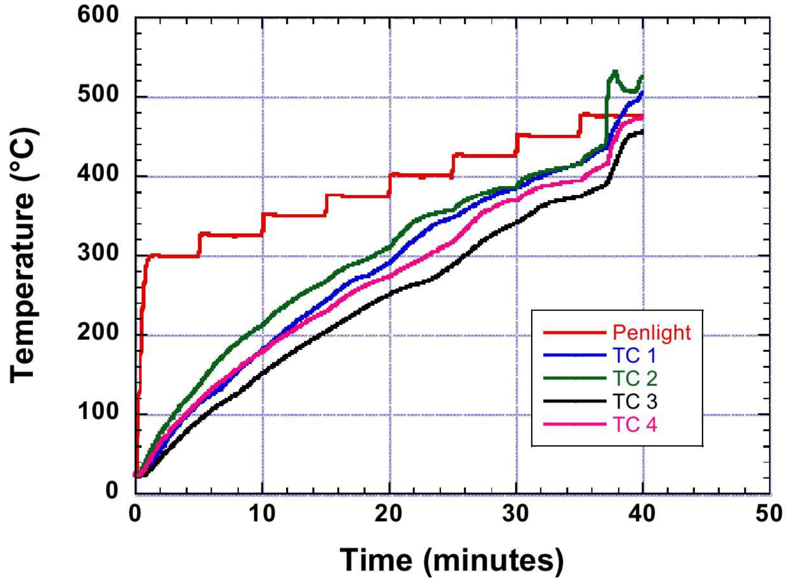

Figure C-21. Temperature history of test 19a

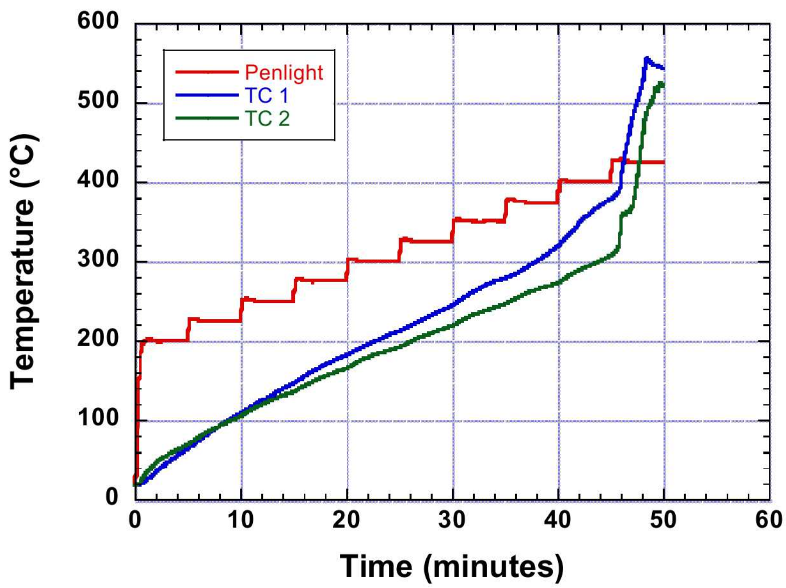

Figure C-22. Temperature history of test 20

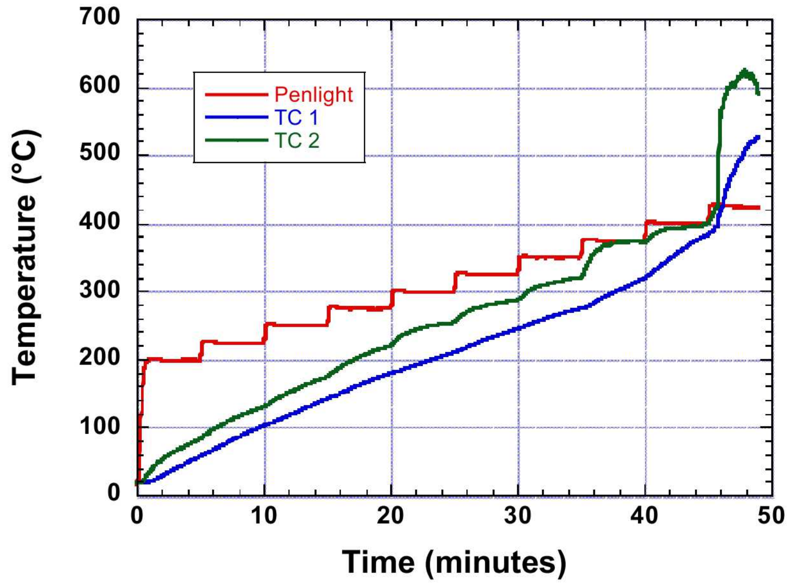

Figure C-23. Temperature history of test 20a

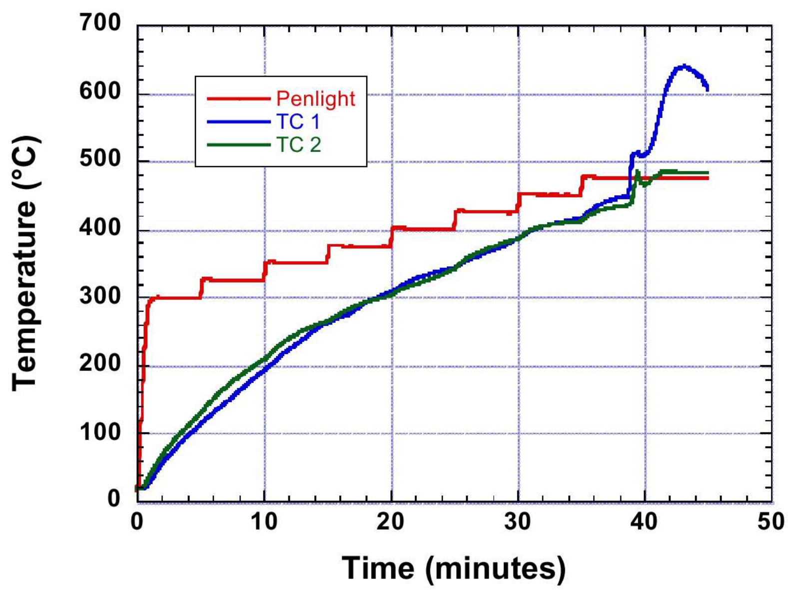

Figure C-24. Temperature history of test 21

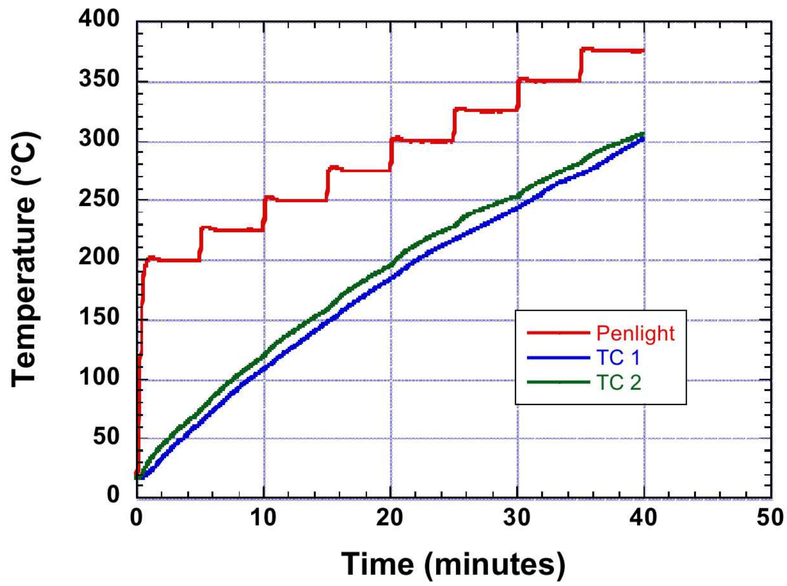

Figure C-25. Temperature history of test 22

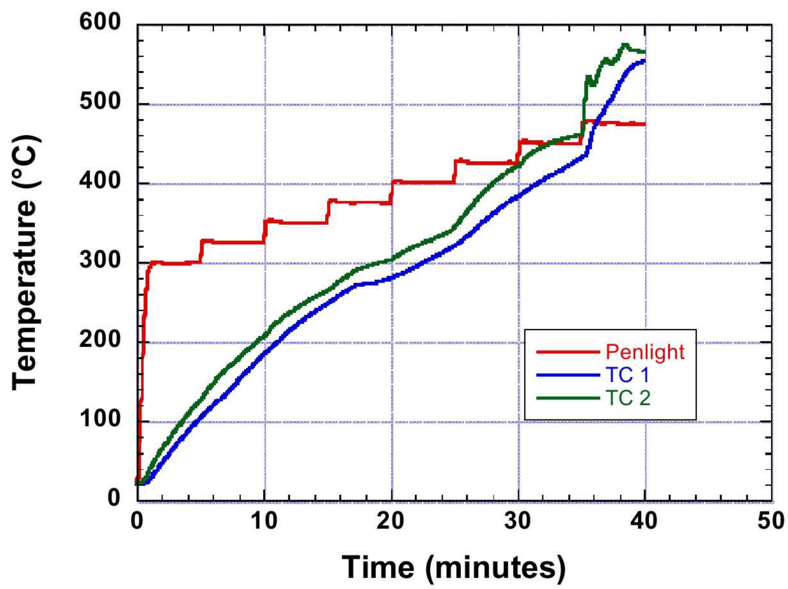

Figure C-26. Temperature history of test 23

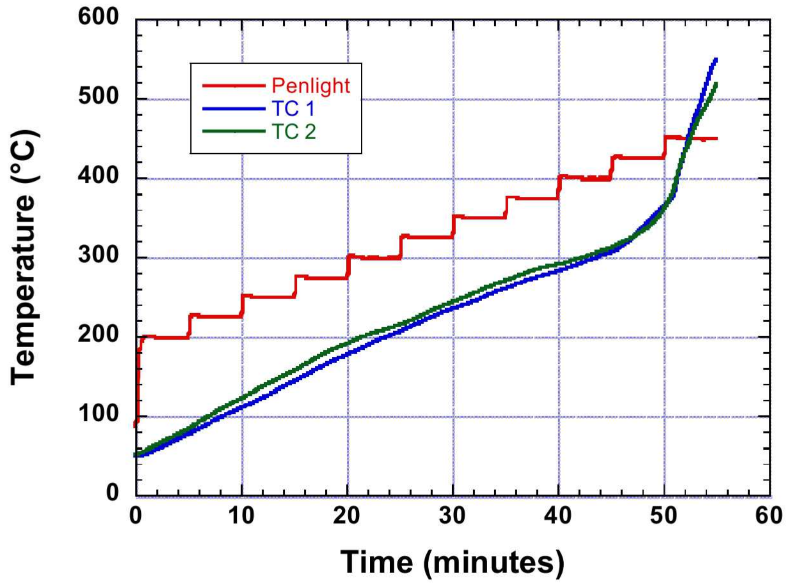

Figure C-27. Temperature history of test 24

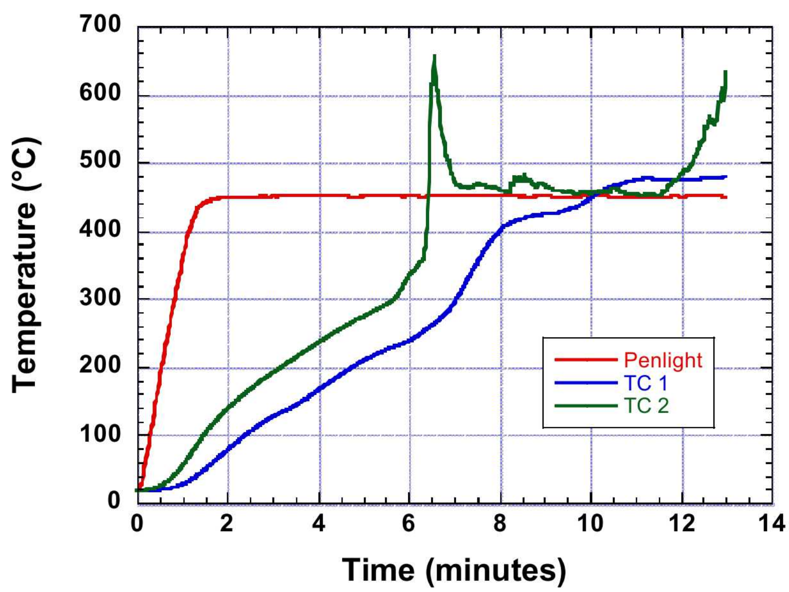

Figure C-28. Temperature history of test 25

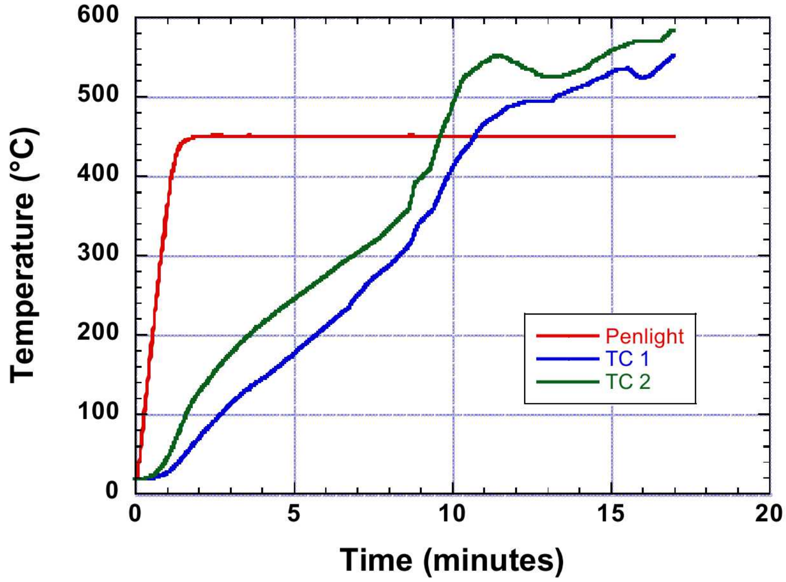

Figure C-29. Temperature history of test 26

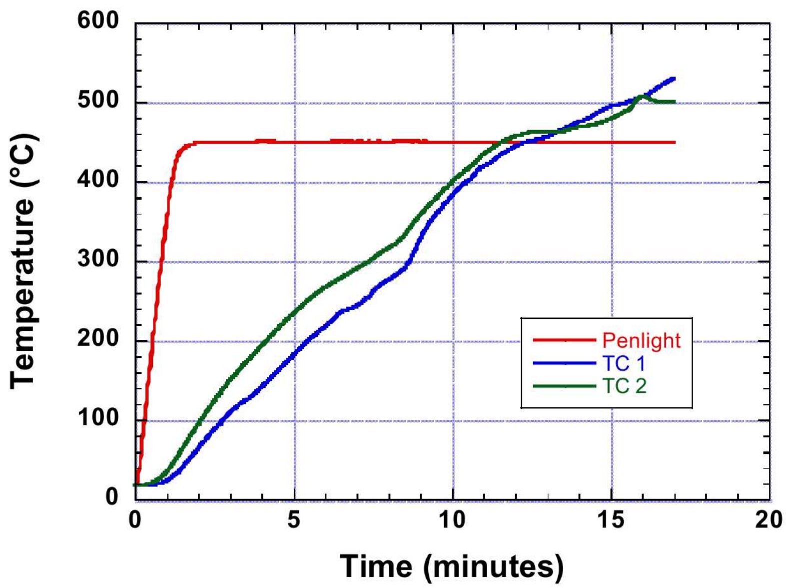

Figure C-30. Temperature history of test 27

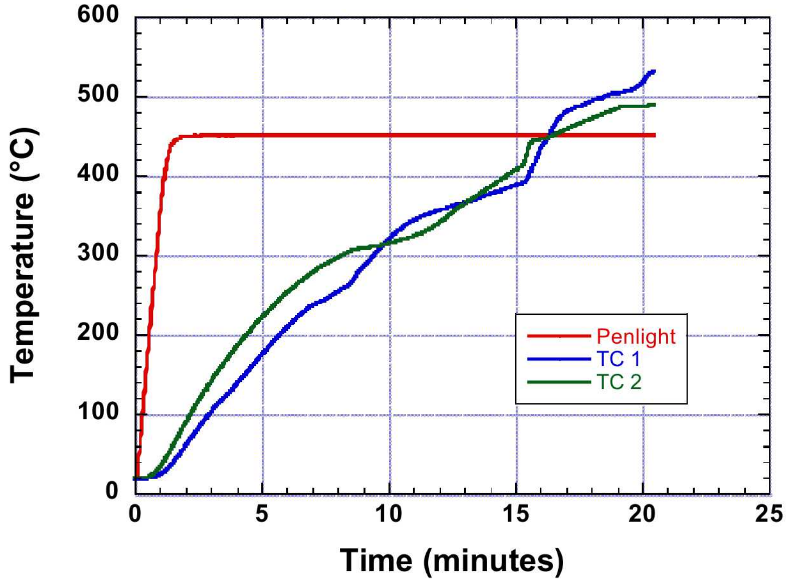

Figure C-31. Temperature history of test 28

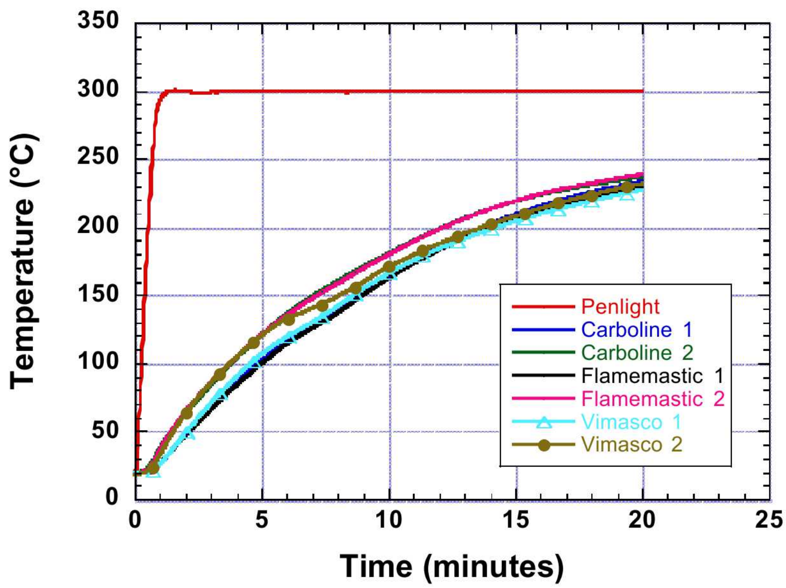

Figure C-32. Temperature history of test 29

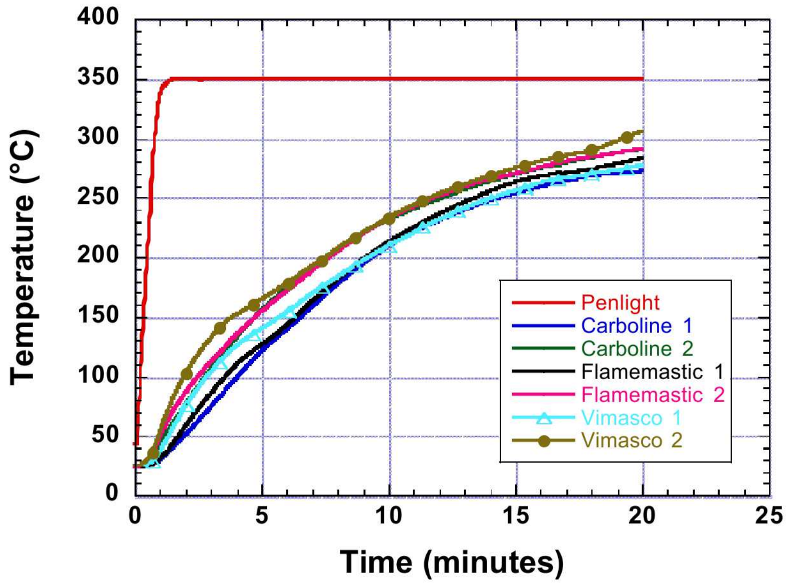

Figure C-33. Temperature history of test 30

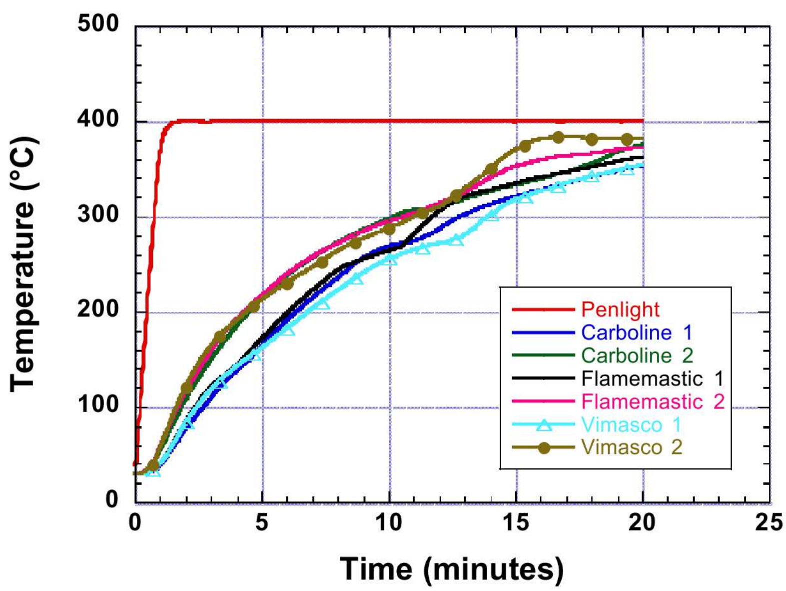

Figure C-34. Temperature history of test 31

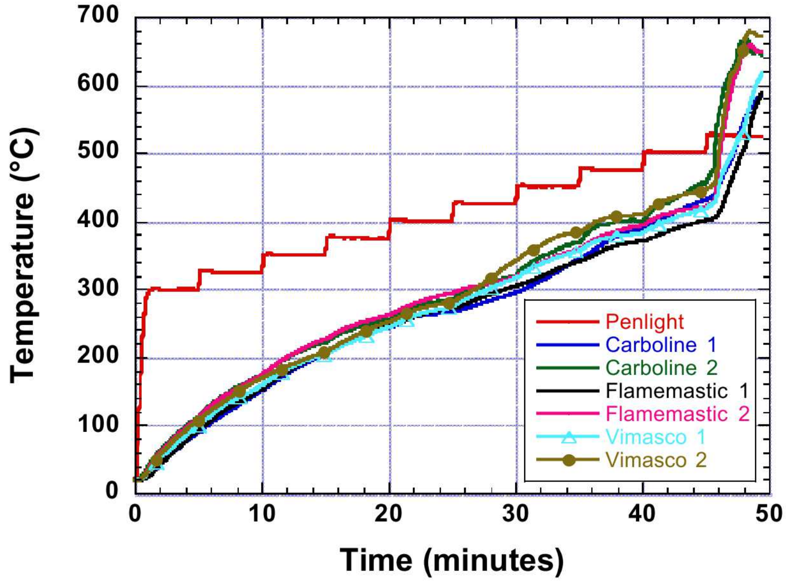

Figure C-35. Temperature history of test 32

C.3 Test Description Tables for Temperature-Only Tests

This section of the appendix contains tables with the parameters for tests in which only temperature data was collected.

Table C-1 to Table C-4 present test parameters for single thermoset cables.

Table C-1. Test 1a parameters

Test Parameters	
Test Name	Test 1a
Test Date	10/19/11
Coating	None
Coating Thickness (inches)	NA
Cable Type	XLPE/CSPE
Thermally Monitored Cables	1
Penlight Starting Temperature	300 °C
Penlight Final Temperature	475 °C
Time to Observed Ignition (min)	39.38

Table C-2. Test 5 parameters

Test Parameters	
Test Name	Test 5
Test Date	11/25/11
Coating	Vimasco 3i
Coating Thickness (inches)	0.0780
Cable Type	XLPE/CSPE
Thermally Monitored Cables	1
Penlight Starting Temperature	300 °C
Penlight Final Temperature	475 °C
Time to Observed Ignition (min)	36.10

Table C-3. Test 9 parameters

Test Parameters	
Test Name	Test 9
Test Date	10/21/11
Coating	Flamemastic F-77
Coating Thickness (inches)	0.1430
Cable Type	XLPE/CSPE
Thermally Monitored Cables	1
Penlight Starting Temperature	300 °C
Penlight Final Temperature	500 °C
Time to Observed Ignition (min)	40.33

Table C-4. Test 13 parameters

Test Parameters	
Test Name	Test 13
Test Date	10/21/11
Coating	Carboline Intumastic 285
Coating Thickness (inches)	0.1538
Cable Type	XLPE/CSPE
Thermally Monitored Cables	1
Penlight Starting Temperature	300 °C
Penlight Final Temperature	475 °C
Time to Observed Ignition (min)	35.28

Table C-5 to Table C-8 present test parameters for tests in which three single thermoset cables with different coatings were tested simultaneously.

Table C-5. Test 29 parameters

Test Parameters	
Test Name	Test 29
Test Date	12/6/11
Coating One	Carboline Intumastic 285
Coating Thickness (inches)	0.1118
Coating Two	Flamemastic F-77
Coating Thickness (inches)	0.0677
Coating Three	Vimasco 3i
Coating Thickness (inches)	0.0795
Cable Type	XLPE/CSPE
Thermally Monitored Cables	3
Penlight Starting Temperature	300 °C
Penlight Final Temperature	
Time to Observed Ignition (min)	No ignition observed

Table C-6. Test 30 parameters

Test Parameters	
Test Name	Test 30
Test Date	12/6/11
Coating One	Carboline Intumastic 285
Coating Thickness (inches)	0.1627
Coating Two	Flamemastic F-77
Coating Thickness (inches)	0.0728
Coating Three	Vimasco 3i
Coating Thickness (inches)	0.1005
Cable Type	XLPE/CSPE
Thermally Monitored Cables	3
Penlight Starting Temperature	350 °C
Penlight Final Temperature	
Time to Observed Ignition (min)	No ignition observed

Table C-7. Test 31 parameters

Test Parameters	
Test Name	Test 31
Test Date	12/6/11
Coating One	Carboline Intumastic 285
Coating Thickness (inches)	0.1643
Coating Two	Flamemastic F-77
Coating Thickness (inches)	0.1273
Coating Three	Vimasco 3i
Coating Thickness (inches)	0.0782
Cable Type	XLPE/CSPE
Thermally Monitored Cables	Three
Penlight Starting Temperature	400 °C
Penlight Final Temperature	
Time to Observed Ignition (min)	No ignition observed

Table C-8. Test 32 parameters

Test Parameters	
Test Name	Test 32
Test Date	12/6/11
Coating One	Carboline Intumastic 285
Coating Thickness (inches)	0.1233
Coating Two	Flamemastic F-77
Coating Thickness (inches)	0.1492
Coating Three	Vimasco 3i
Coating Thickness (inches)	0.1380
Cable Type	XLPE/CSPE
Thermally Monitored Cables	Three
Penlight Starting Temperature	300 °C
Penlight Final Temperature	525 °C
Time to Observed Ignition (min)	43.70

Table C-9 to Table C-12 present test parameters for single thermoplastic cables.

Table C-9. Test 3 parameters

Test Parameters	
Test Name	Test 3
Test Date	10/19/11
Coating	None
Coating Thickness	NA
Cable Type	PE/PVC
Thermally Monitored Cables	1
Penlight Starting Temperature	200 °C
Penlight Final Temperature	525 °C
Time to Observed Ignition (min)	66.90

Table C-10. Test 7 parameters

Test Parameters	
Test Name	Test 7
Test Date	10/31/11
Coating	Vimasco 3i
Coating Thickness (inches)	0.0747
Cable Type	PE/PVC
Thermally Monitored Cables	1
Penlight Starting Temperature	200 °C
Penlight Final Temperature	425 °C
Time to Observed Ignition (min)	46.93

Table C-11. Test 11 parameters

Test Parameters	
Test Name	Test 11
Test Date	11/2/11
Coating	Flamemastic F-77
Coating Thickness (inches)	0.0857
Cable Type	PE/PVC
Thermally Monitored Cables	1
Penlight Starting Temperature	200 °C
Penlight Final Temperature	450 °C
Time to Observed Ignition (min)	51.87

Table C-12. Test 15 parameters

Test Parameters	
Test Name	Test 15
Test Date	11/2/11
Coating	Carboline Intumastic 285
Coating Thickness (inches)	0.1490
Cable Type	PE/PVC
Thermally Monitored Cables	1
Penlight Starting Temperature	200 °C
Penlight Final Temperature	450 °C
Time to Observed Ignition (min)	52.35

APPENDIX D. **SCDU Results for the Single and Seven-Cable Bundle Tests**

The content of Appendix D is located on the accompanying DVD due to its length.

APPENDIX E. **Insulation Resistance Measurement System (IRMS) Results for the Single and Seven-Cable Bundle Tests**

E.1 Introduction

The purpose of this appendix is to provide the circuit analysis for the single and seven-cable bundle tests that were electrically monitored with Sandia's Insulation Resistance Measurement System (IRMS). Each test had a single cable monitored on the IRMS. The data was analyzed the same way it was done in NUREG/CR-6931, which describes the detailed setup of the IRMS and discusses the data analysis process.

For these tests, failure is defined to occur when R drops below 1000 Ohms. In this appendix, CG and CC are abbreviations for Conductor-to-Ground and Conductor-to-Conductor, respectively. Note that times listed are "shifted."

E.2 Cable Coating Test 17

The test parameters and sequence of events for test 17 are shown below in Table E-1. This was a non-coated, single cable monitored electrically and thermally.

Table E-1. Test 17 parameters and sequence of events

Test Parameters	
Test Name	17
Test Date	10/20/11
Coating	None
Coating Thickness	NA
Cable Type	XLPE/CSPE
Thermally Monitored Cables	1
Circuit 1	IRMS
Penlight Starting Temperature	300 °C
Penlight Final Temperature	475 °C
Sequence of events	
Time to Cable Ignition	37.65 min.
Time to Electrical Damage	38 min.

Figure E-1 displays the resistance measured by IRMS for the entire test and Figure E-2 shows a close up of the same data near the CC failure period. For this test, CC failure occurs between 2280-2340 seconds (38-39 minutes).

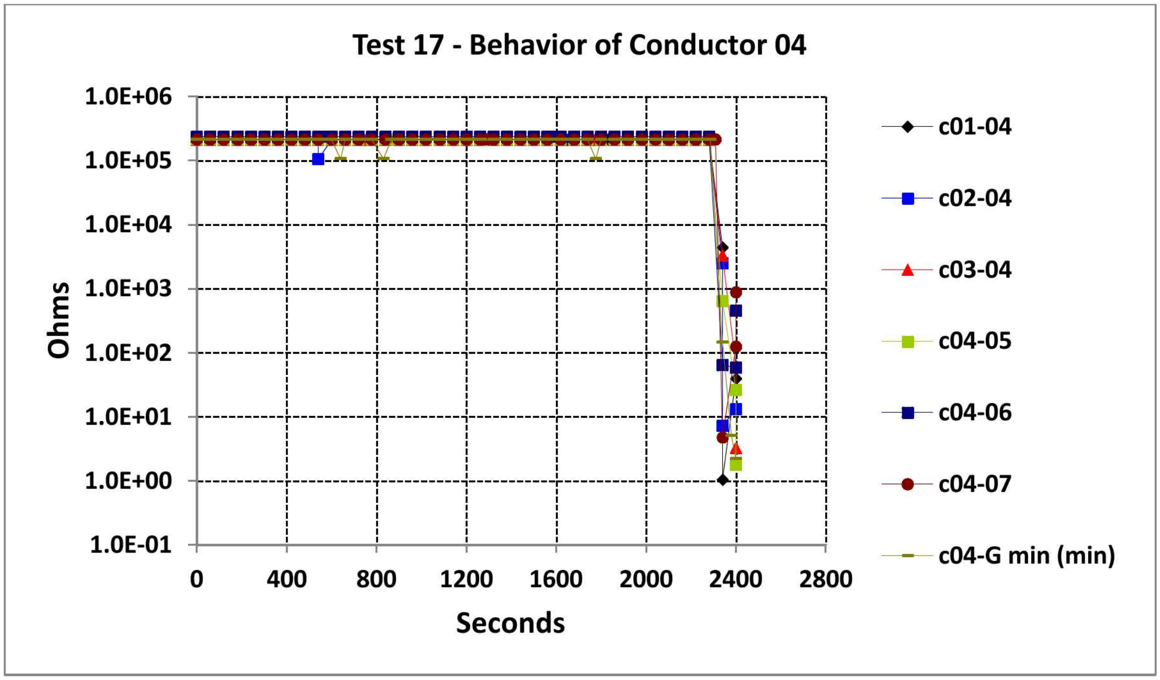

Figure E-1. Behavior of cable from the beginning to the end of test 17

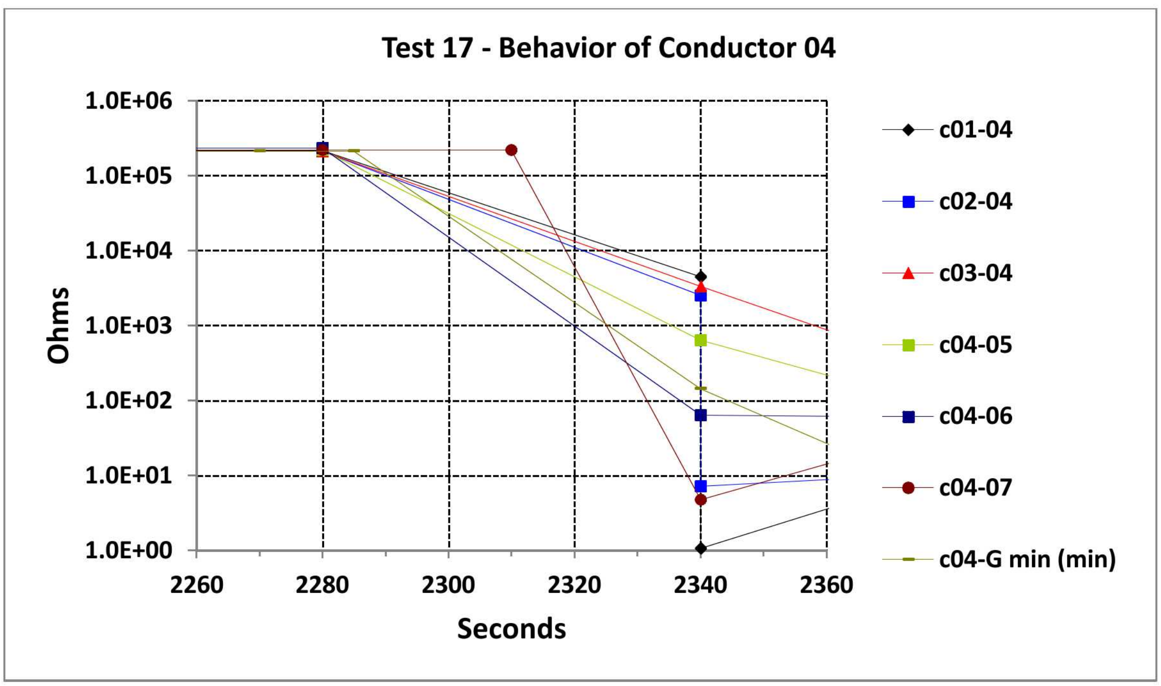

Figure E-2. Behavior of cable from near CC failure period in test 17

E.3 Cable Coating Test 18

The test parameters and sequence of events for test #18 are shown below in Table E-2. This was a non-coated, single cable arrangement monitored electrically and thermally.

Table E-2. Test 18 parameters and sequence of events

Test Parameters	
Test Name	Test 1
Test Date	10/20/11
Coating	None
Coating Thickness	NA
Cable Type	PE/PVC
Thermally Monitored Cables	1
Circuit 1	IRMS
Penlight Starting Temperature	200 °C
Penlight Final Temperature	425 °C
Sequence of Events	
Time to Cable Ignition	45.57 min.
Time to Electrical Damage	32.08 min.

Figure E-3 displays the resistance measured by IRMS for the entire test and Figure E-4 shows a close up of the same data near the CC failure period. For this test, CC failure occurs between 1925-1963 seconds (32-32.7 minutes).

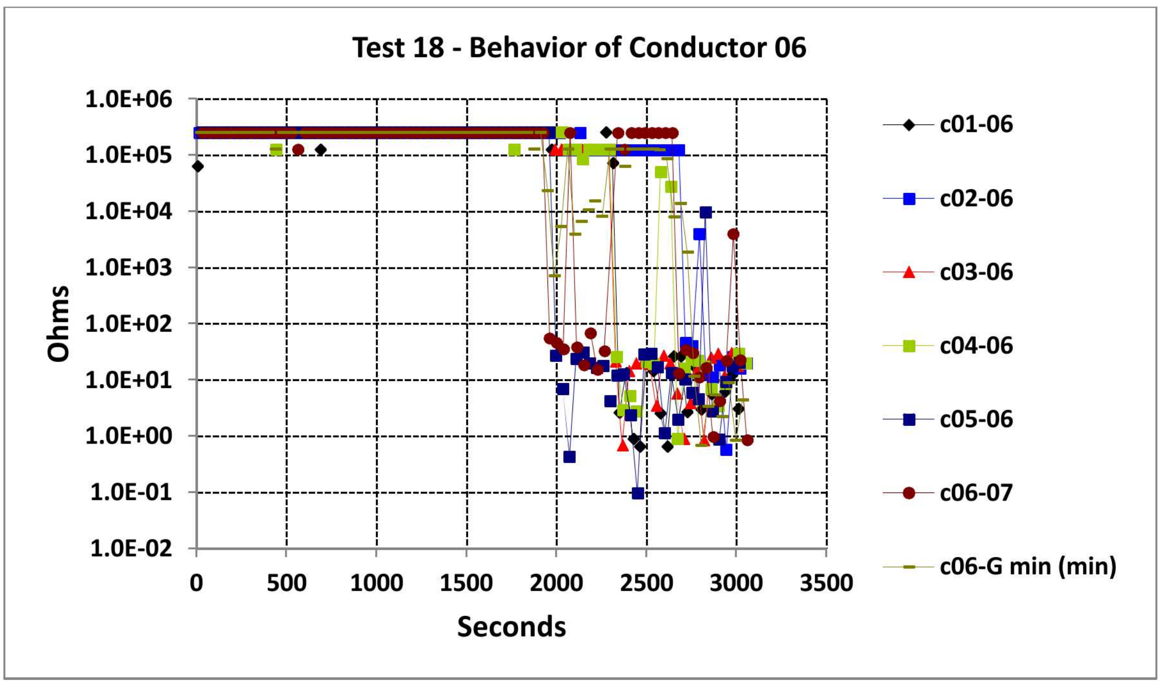

Figure E-3. Behavior of cable from the beginning to the end of test 18

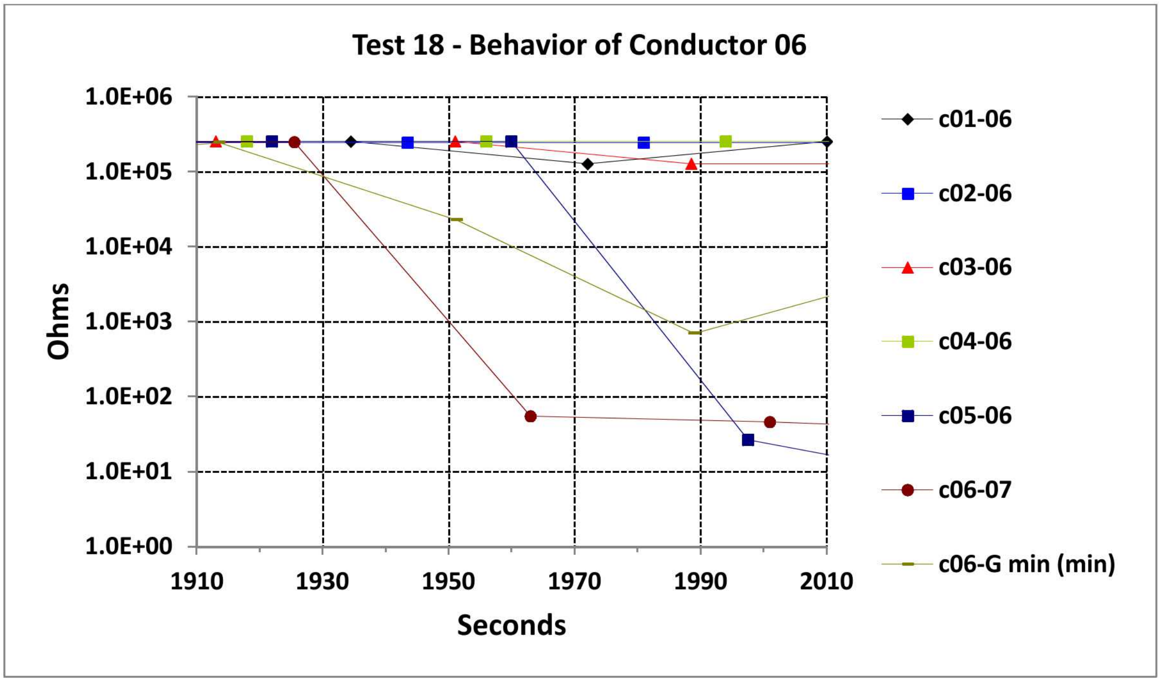

Figure E-4. Behavior of cable from near CC failure period in test 18

E.4 Cable Coating Test 19

The test parameters and sequence of events for test 19 are shown below in Table E-3. This was a coated, single cable arrangement monitored electrically and thermally.

Table E-3. Test 19 parameters and sequence of events

Test Parameters	
Test Name	19
Test Date	11/7/11
Coating	Vimasco
Coating Thickness	0.0377"
Cable Type	XLPE/CSPE
Thermally Monitored Cables	1
Circuit 1	IRMS
Penlight Starting Temperature	300 °C
Penlight Final Temperature	475 °C
Sequence of events	
Time to Cable Ignition	36.52 min.
Time to Electrical Damage	38 min.

Figure E-5 displays the resistance measured by IRMS for the entire test and Figure E-6 shows a close up of the same data near the CC failure period. For this test, CC failure occurs between 2280-2318 s (38-38.6 minutes).

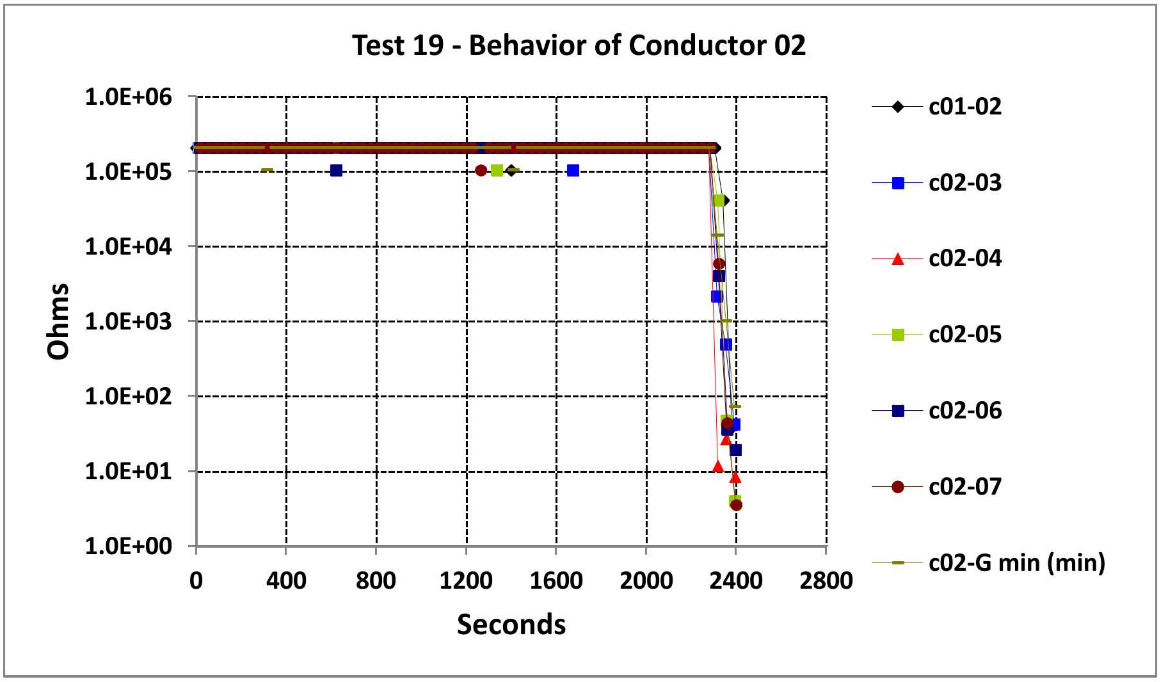

Figure E-5. Behavior of cable from the beginning to the end of test 19

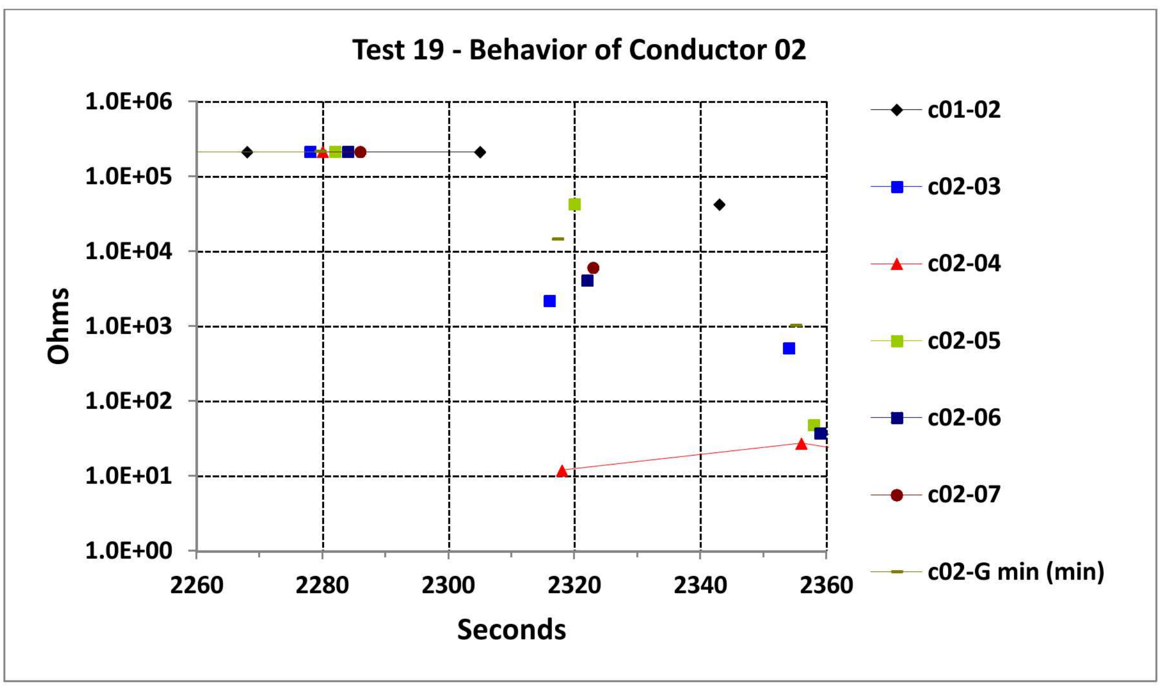

Figure E-6. Behavior of cable from near CC failure period in test 19

E.5 Cable Coating Test 19a

The test parameters and sequence of events for test 19a are shown below in Table E-4. This was a coated, single cable arrangement monitored electrically and thermally.

Table E-4. Test 19a parameters and sequence of events

Test Parameters	
Test Name	19a
Test Date	11/22/11
Coating	Vimasco 3i
Coating Thickness	0.1343"
Cable Type	XLPE/CSPE
Thermally Monitored Cables	1
Circuit 1	IRMS
Penlight Starting Temperature	300 °C
Penlight Final Temperature	475 °C
Sequence of events	
Time to Cable Ignition	37.13 min.
Time to Electrical Damage	39.15 min.

Figure E-7 displays the resistance measured by IRMS for the entire test and Figure E-8 shows a close up of the same data near the CC failure period. For this test, CC failure occurs between 2349-2387 seconds (39.15-39.8 minutes).

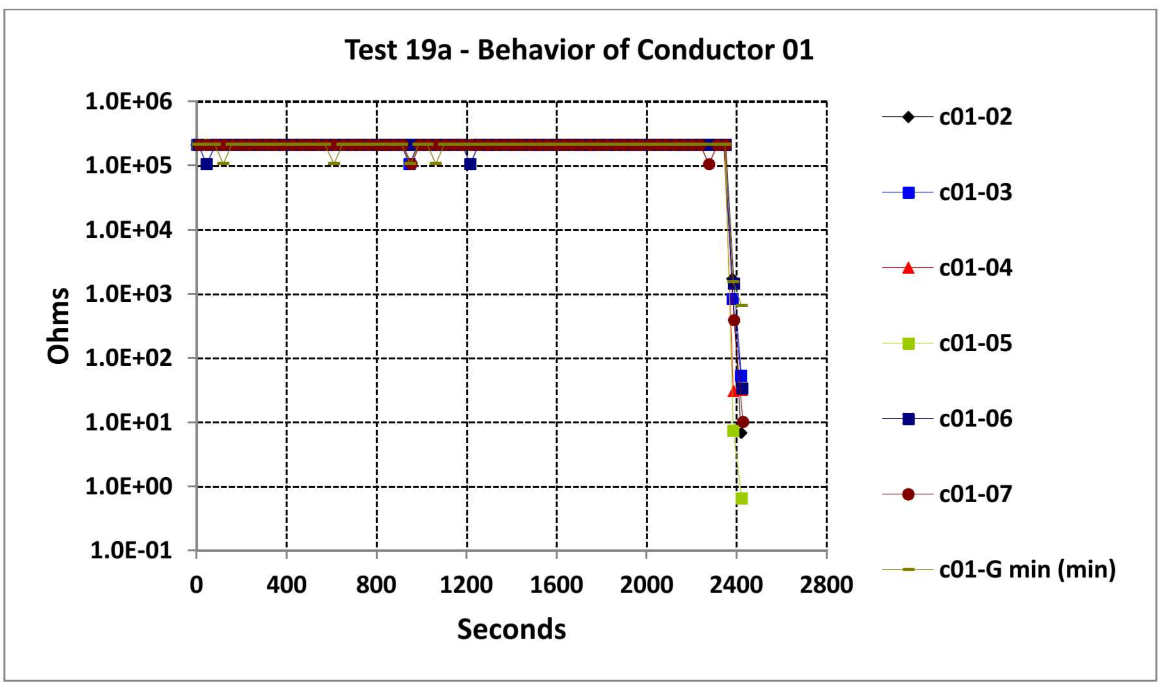

Figure E-7. Behavior of cable from the beginning to the end of test 19a

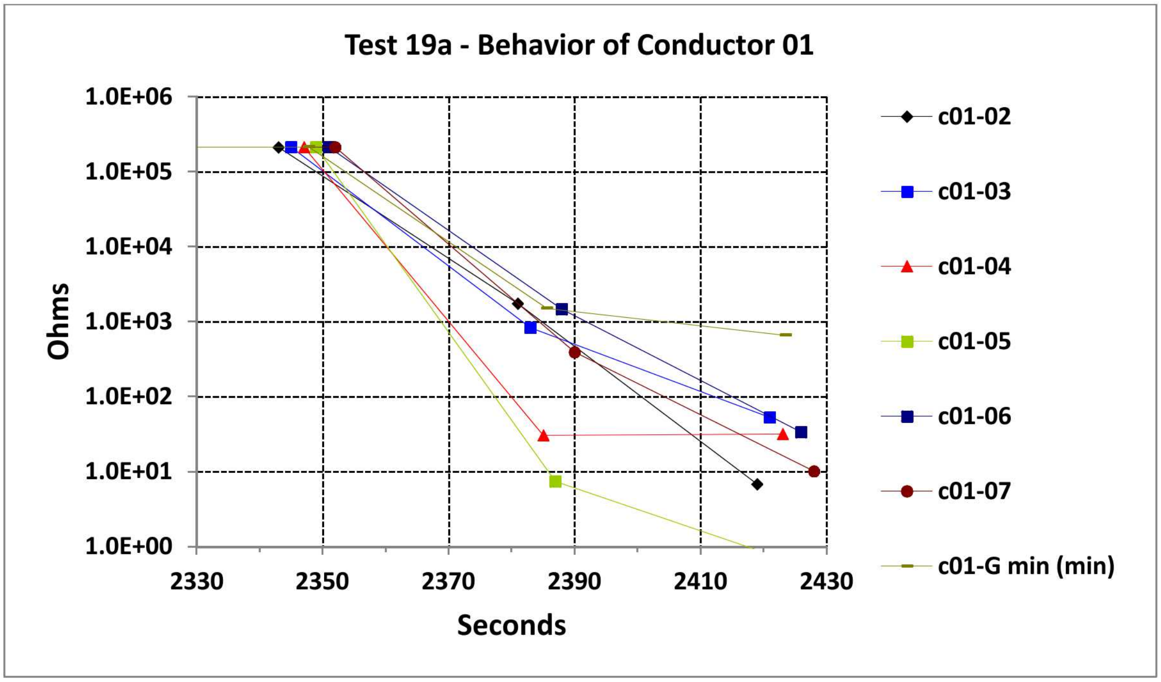

Figure E-8. Behavior of cable from near CC failure period in test 19a

E.6 Cable Coating Test 20

The test parameters and sequence of events for test 20 are shown below in Table E-5. This was a coated, single cable arrangement monitored electrically and thermally.

Table E-5. Test 20 parameters and sequence of events

Test Parameters	
Test Name	20
Test Date	11/8/201
Coating	Vimasco 3i
Coating Thickness	0.0760"
Cable Type	PE/PVC
Thermally Monitored Cables	1
Circuit 1	IRMS
Penlight Starting Temperature	200 °C
Penlight Final Temperature	425°C
Sequence of events	
Time to Cable Ignition	45.87 min.
Time to Electrical Damage	28.87 min.

Figure E-9 displays the resistance measured by IRMS for the entire test and Figure E-10 shows a close up of the same data near the CC failure period. For this test, CC failure occurs between 1729.5-1767 seconds (28.8-29.5 minutes).

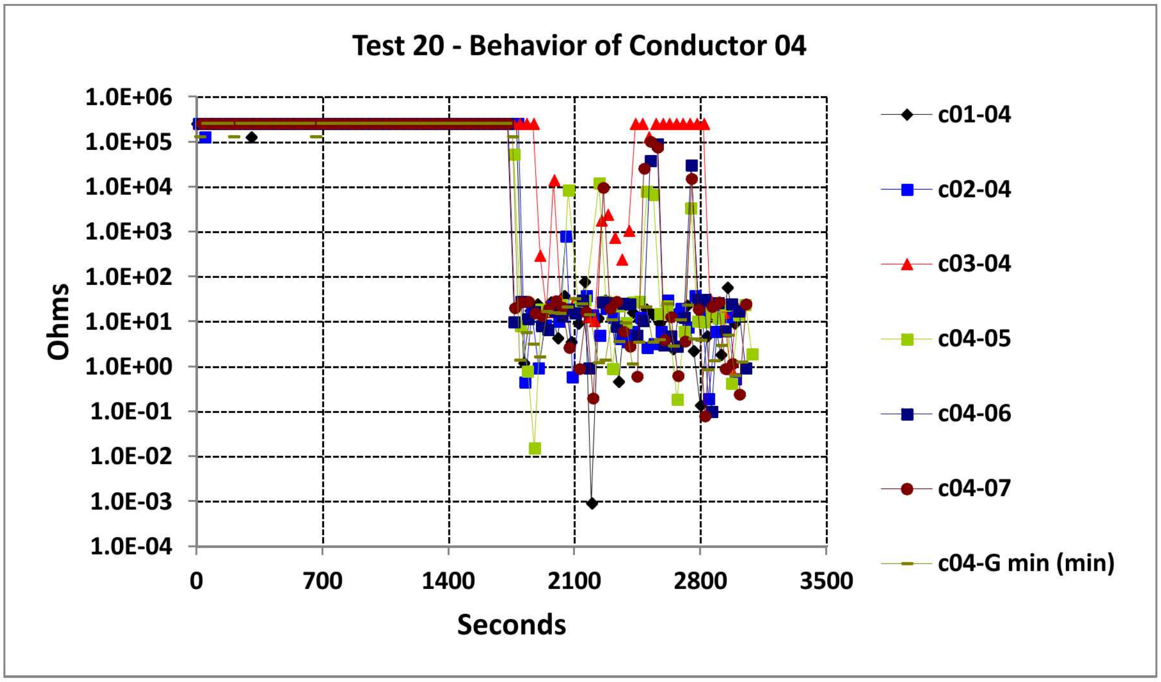

Figure E-9. Behavior of cable from the beginning to the end of test 20

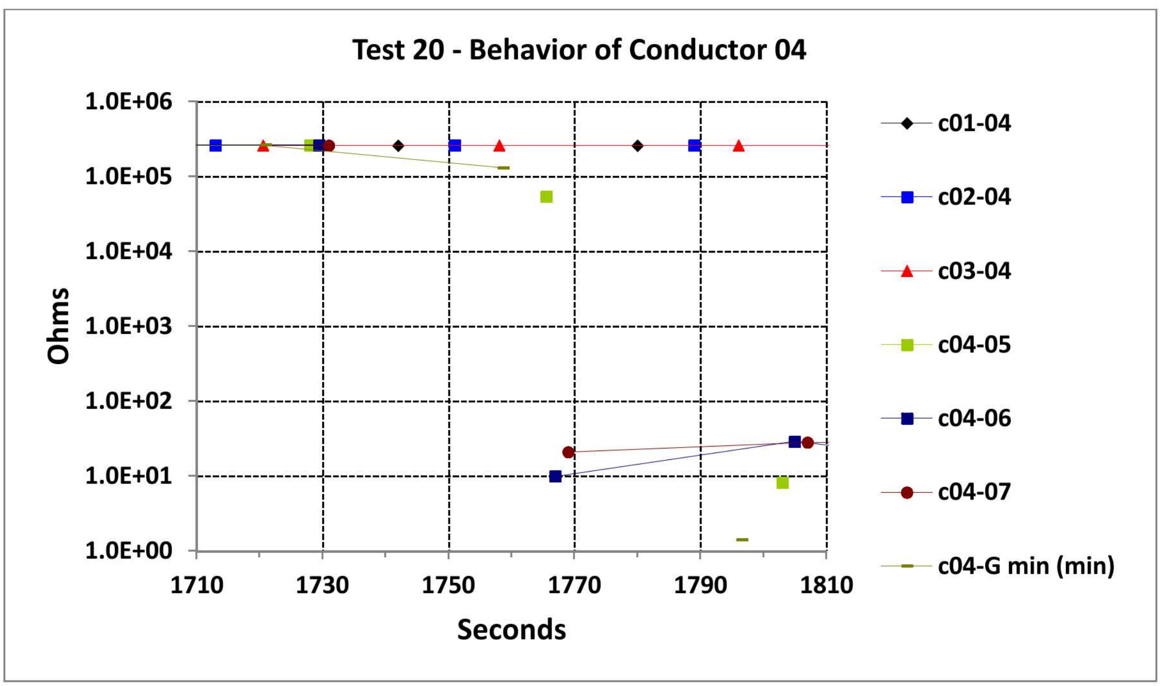

Figure E-10. Behavior of cable from near CC failure period in test 20

E.7 Cable Coating Test 20a

The test parameters and sequence of events for test 20a are shown below in Table E-6. This was a coated, single cable arrangement monitored electrically and thermally.

Table E-6. Test 20a parameters and sequence of events

Test Parameters	
Test Name	20a
Test Date	11/22/11
Coating	Vimasco 3i
Coating Thickness	0.0828”
Cable Type	PE/PVC
Thermally Monitored Cables	1
Circuit 1	IRMS
Penlight Starting Temperature	200 °C
Penlight Final Temperature	425 °C
Sequence of events	
Time to Cable Ignition	45.85 min.
Time to Electrical Damage	27.37 min.

Figure E-11 displays the resistance measured by IRMS for the entire test and Figure E-12 shows a close up of the same data near the CC failure period. For this test, CC failure occurs between 1642-1680 seconds (27.4-28 minutes).

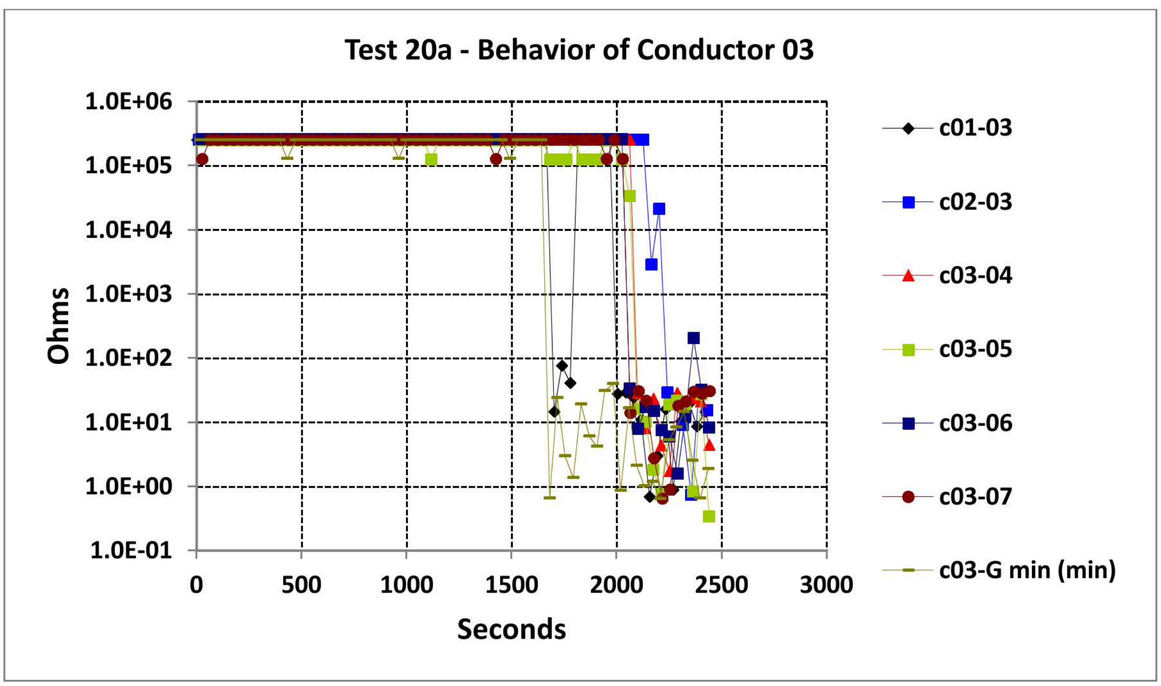

Figure E-11. Behavior of cable from the beginning to the end of test 20a

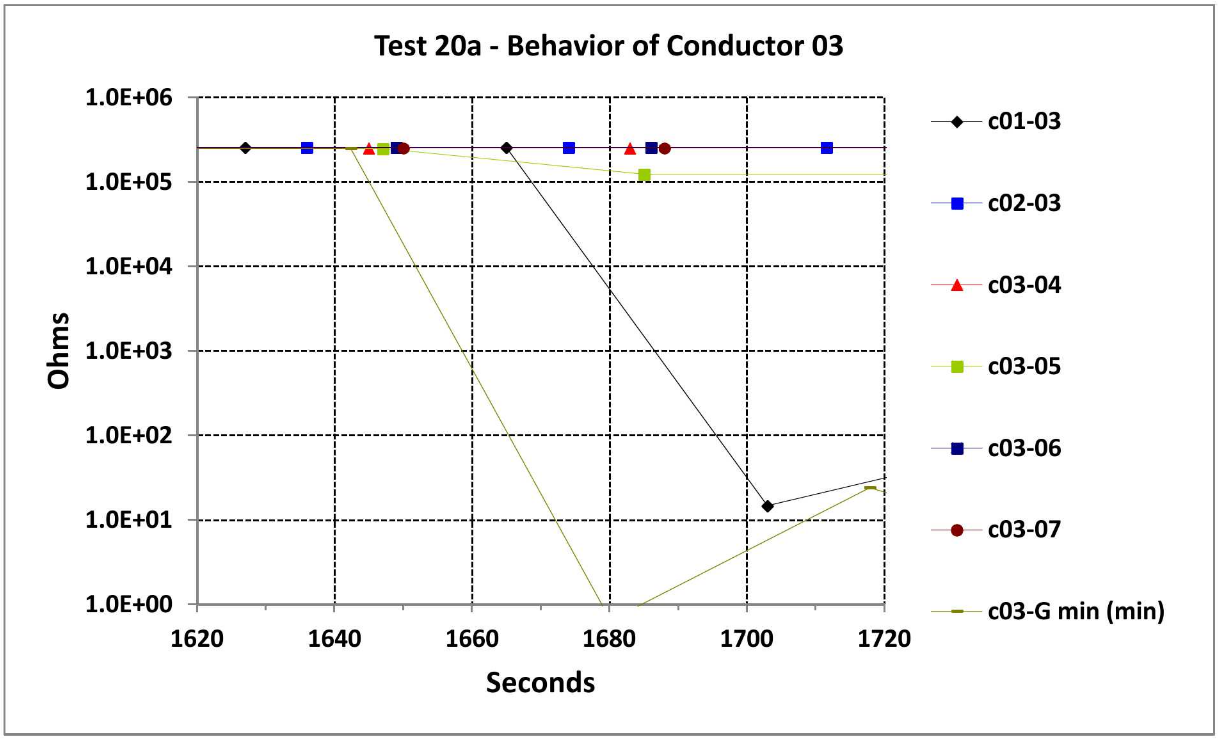

Figure E-12. Behavior of cable from near CC failure period in test 20a

E.8 Cable Coating Test 21

The test parameters and sequence of events for test 21 are shown below in Table E-7. This was a coated, single cable arrangement monitored electrically and thermally.

Table E-7. Test 21 parameters and sequence of events

Test Parameters	
Test Name	21
Test Date	11/1/11
Coating	Flamemastic F-77
Coating Thickness	0.0940"
Cable Type	XLPE/CSPE
Thermally Monitored Cables	1
Circuit 1	IRMS
Penlight Starting Temperature	300 °C
Penlight Final Temperature	475 °C
Sequence of events	
Time to Cable Ignition	38.8 min.
Time to Electrical Damage	39.78 min.

Figure E-13 displays the resistance measured by IRMS for the entire test and Figure E-14 shows a close up of the same data near the CC failure period. For this test, CC failure occurs between 2386-2425 seconds (39.8-40.4 minutes).

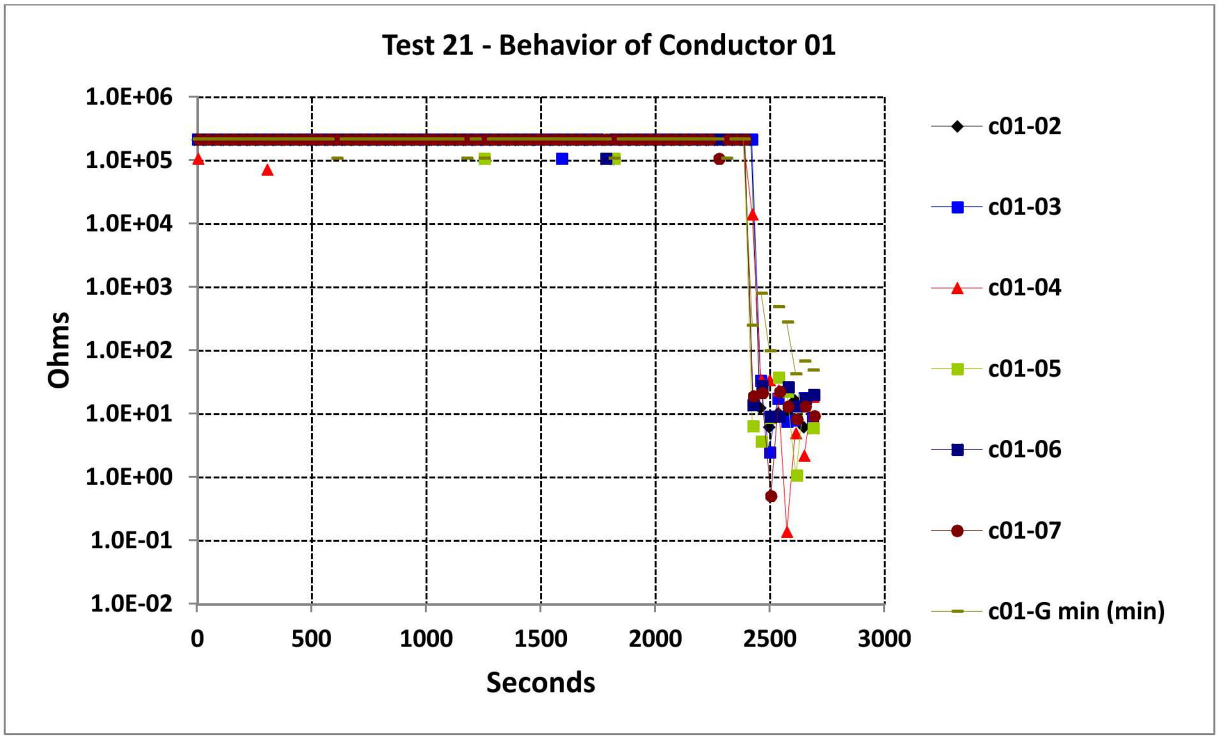

Figure E-13. Behavior of cable from the beginning to the end of test 21

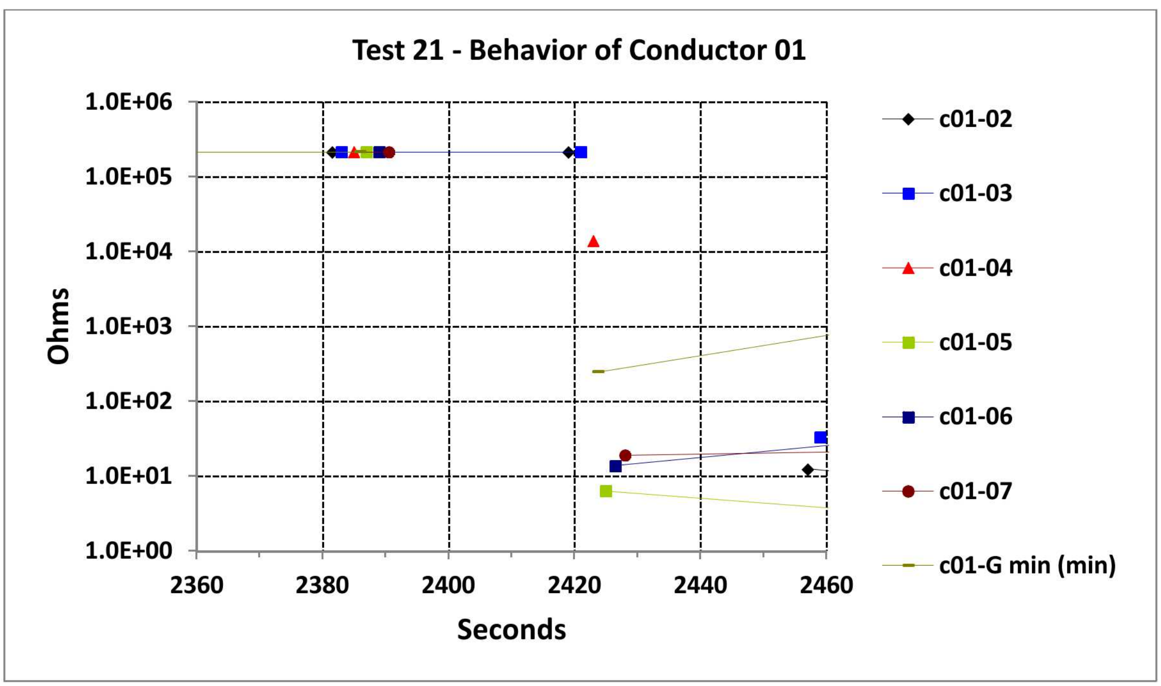

Figure E-14. Behavior of cable from near CC failure period in test 21

E.9 **Cable Coating Test 22**

The test parameters and sequence of events for test 22 are shown below in Table E-8. This was a coated, single cable arrangement monitored electrically and thermally.

Table E-8. Test 22 parameters and sequence of events

Test Parameters	
Test Name	22
Test Date	11/3/11
Coating	Flamemastic F-77
Coating Thickness	0.0612"
Cable Type	PE/PVC
Thermally Monitored Cables	1
Circuit 1	IRMS
Penlight Starting Temperature	200 °C
Penlight Final Temperature	375°C
Sequence of events	
Time to Cable Ignition	N/A
Time to Electrical Damage	31.58 min.

Figure E-15 displays the resistance measured by IRMS for the entire test and Figure E-16 shows a close up of the same data near the CC failure period. For this test, CC failure occurs between 1895-1933 seconds (31.6-32.2 minutes).

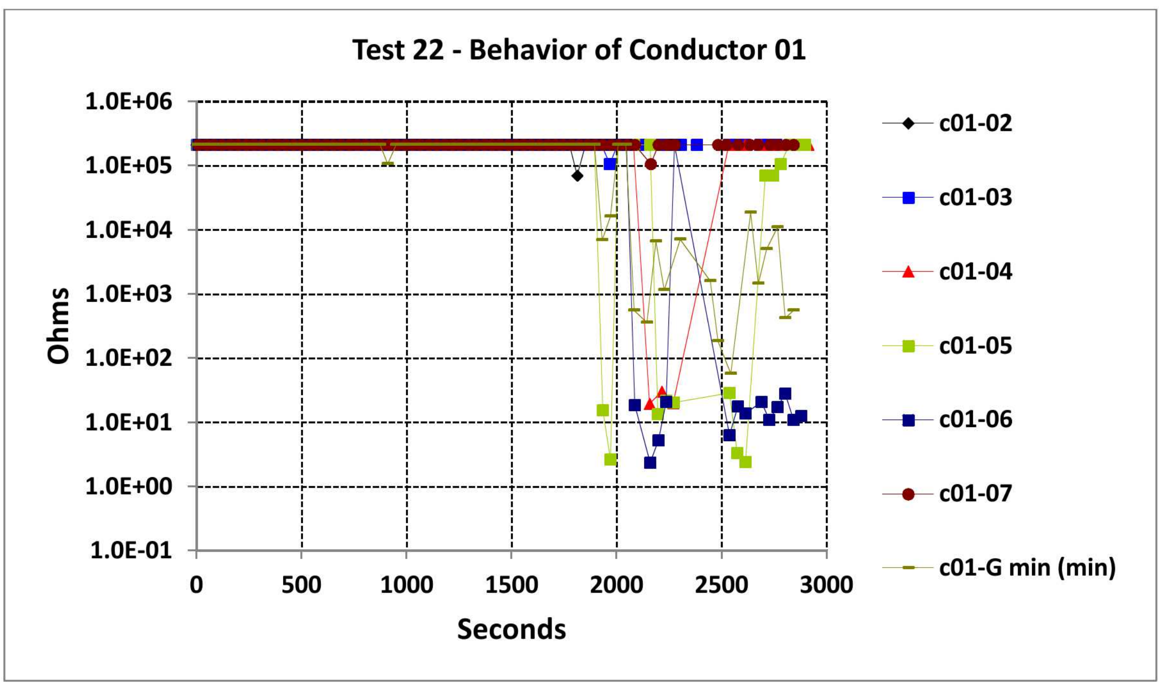

Figure E-15. Behavior of cable from the beginning to the end of test 22

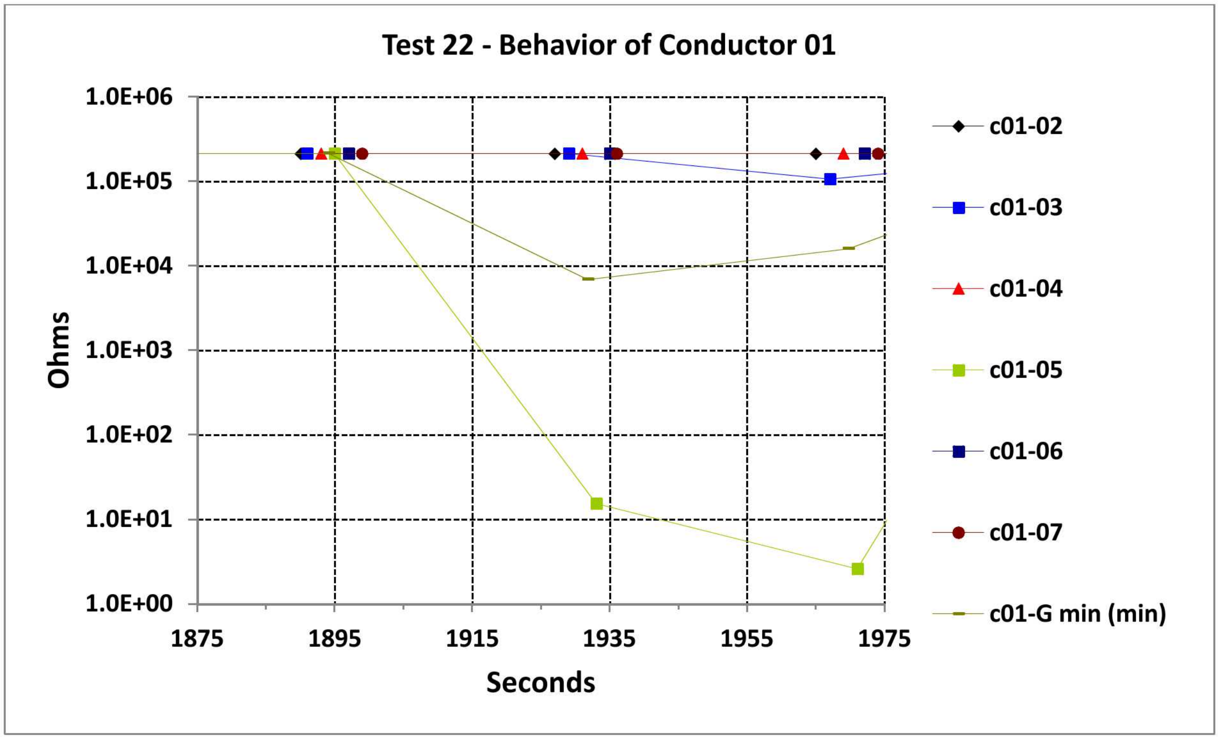

Figure E-16. Behavior of cable from near CC failure period in test 22

E.10 Cable Coating Test 23

The test parameters and sequence of events for test 23 are shown below in Table E-9. This was a coated, single cable arrangement monitored electrically and thermally.

Table E-9. Test 23 parameters and sequence of events

Test Parameters	
Test Name	23
Test Date	10/31/11
Coating	Carboline Intumastic 285
Coating Thickness	0.1433"
Cable Type	XLPE/CSPE
Thermally Monitored Cables	1
Circuit 1	IRMS
Penlight Starting Temperature	300 °C
Penlight Final Temperature	475 °C
Sequence of events	
Time to Cable Ignition	35.22 min.
Time to Electrical Damage	36.28 min.

Figure E-17 displays the resistance measured by IRMS for the entire test and Figure E-18 shows a close up of the same data near the CC failure period. For this test, CC failure occurs between 2177-2215 seconds (36.3-36.9 minutes).

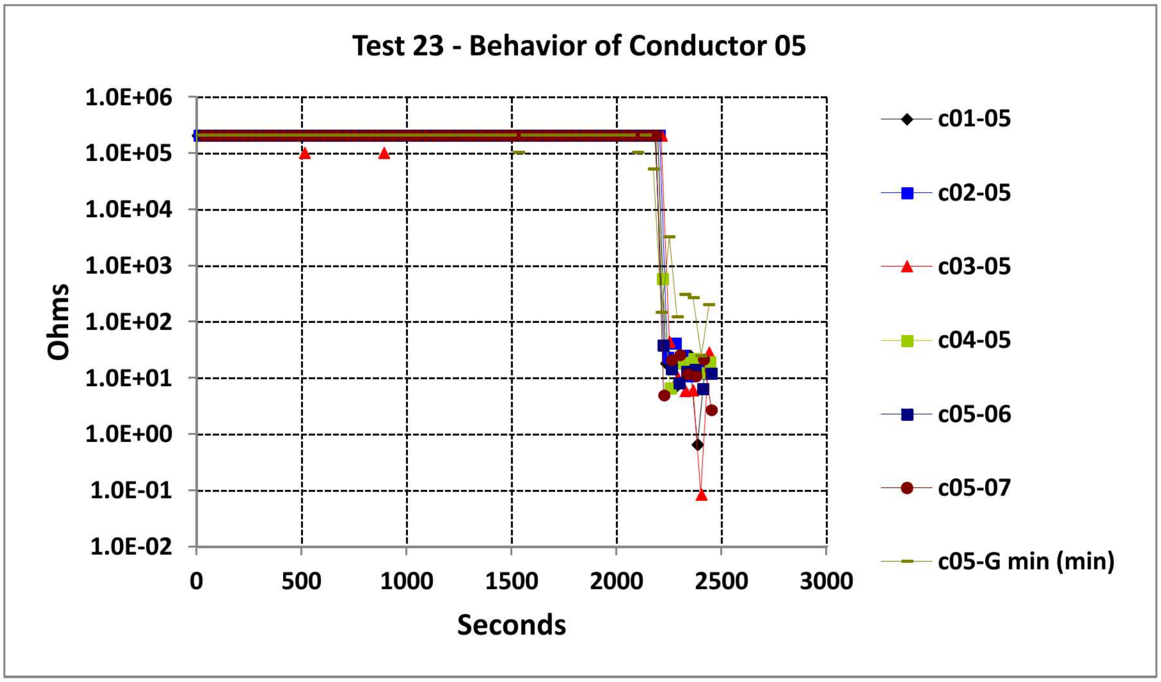

Figure E-17. Behavior of cable from the beginning to the end of test 23

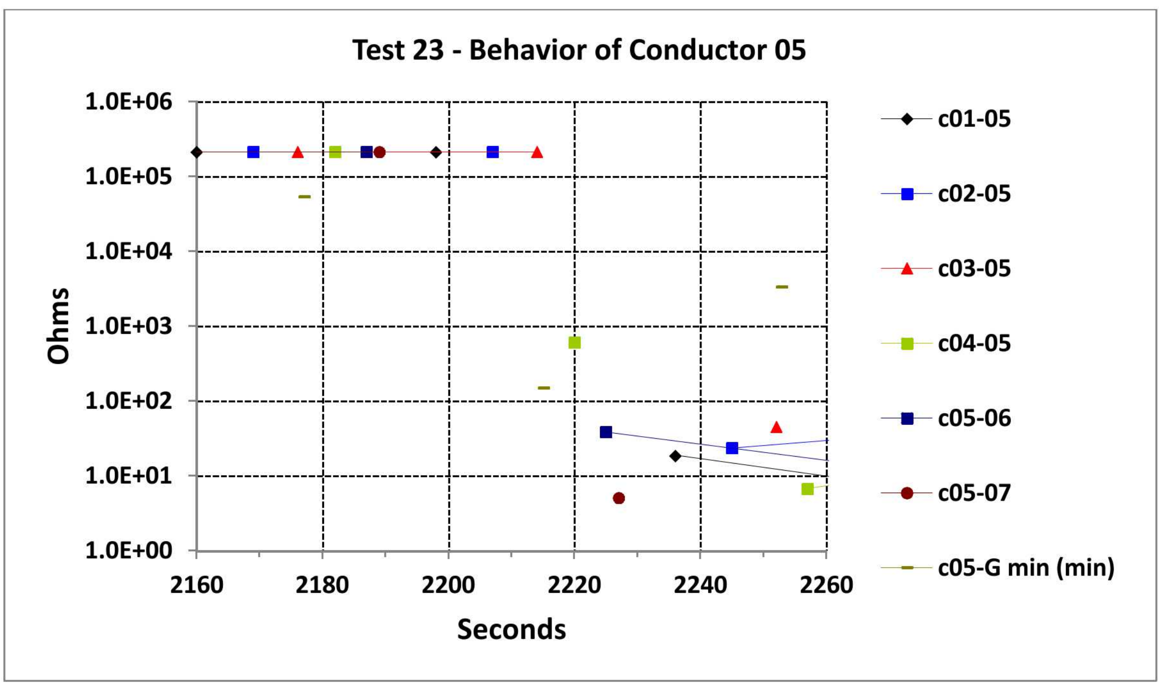

Figure E-18. Behavior of cable from the beginning to the end of test 23

E.11 **Cable Coating Test 24**

The test parameters and sequence of events for test 24 are shown below in Table E-10. This was a coated, single cable arrangement monitored electrically and thermally.

Table E-10. Test 24 parameters and sequence of events

Test Parameters	
Test Name	24
Test Date	11/3/11
Coating	Carboline Intumastic 285
Coating Thickness	0.1575"
Cable Type	PE/PVC
Thermally Monitored Cables	1
Circuit 1	IRMS
Penlight Starting Temperature	200 °C
Penlight Final Temperature	450°C
Sequence of events	
Time to Cable Ignition	50.83 min.
Time to Electrical Damage	31.32 min.

Figure E-19 displays the resistance measured by IRMS for the entire test and Figure E-20 shows a close up of the same data near the CC failure period. For this test, CC failure occurs between 1879–1917 seconds (31.3-32.0 minutes).

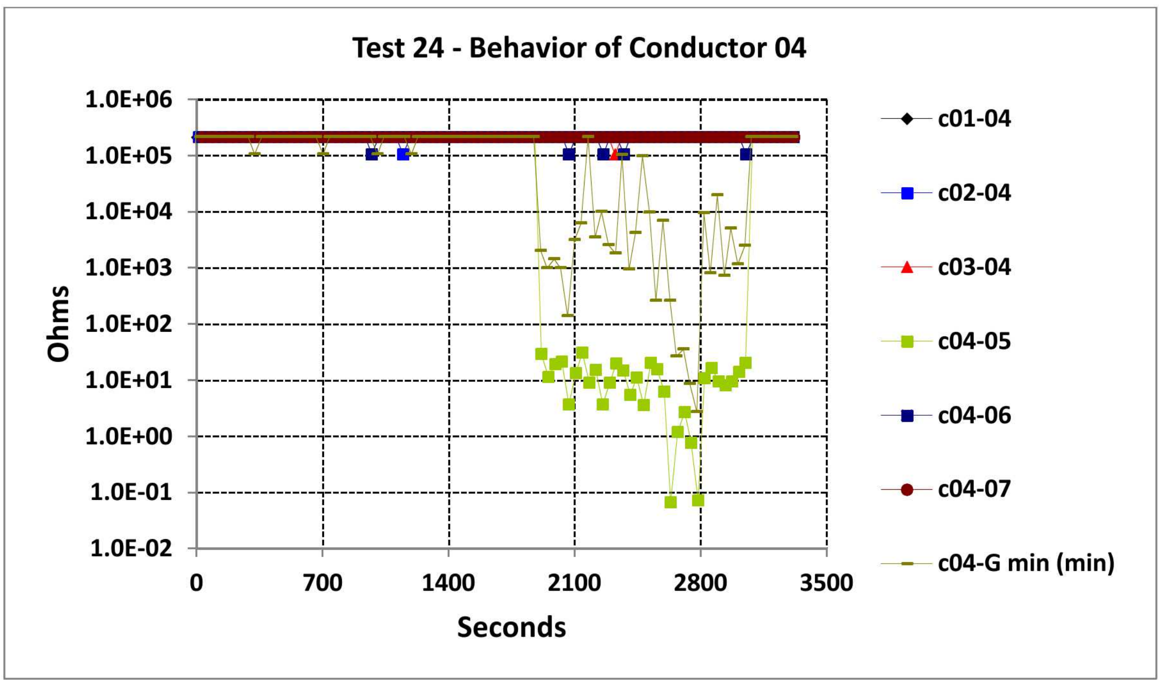

Figure E-19. Behavior of cable from the beginning to the end of test 24

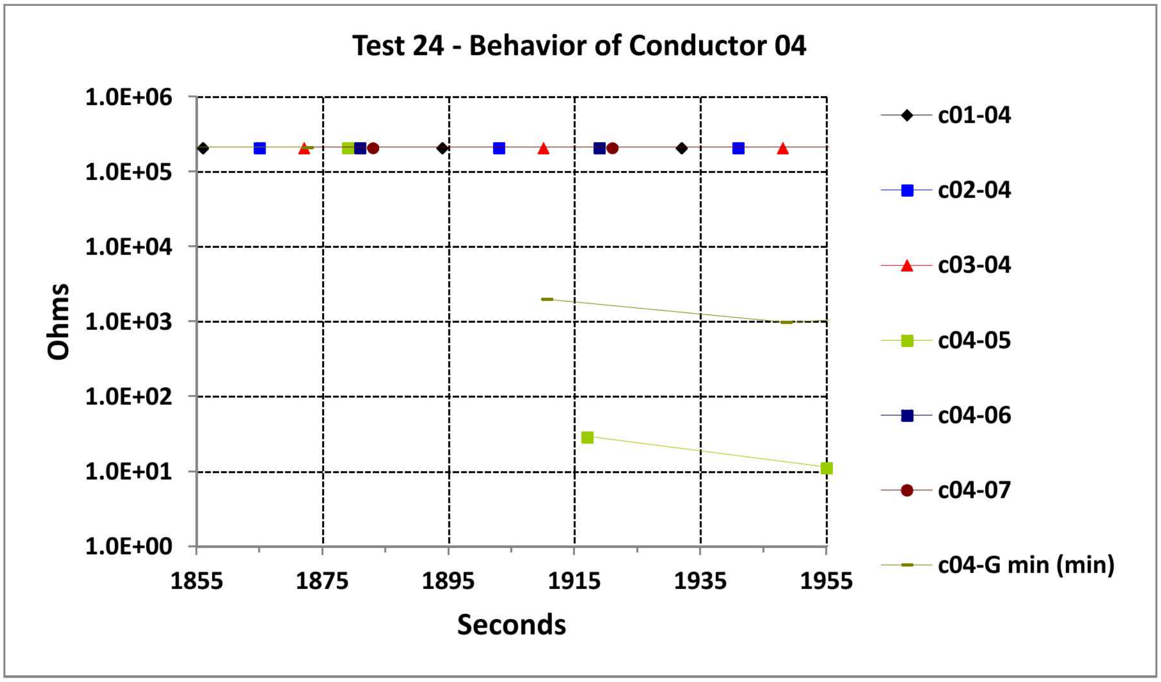

Figure E-20. Behavior of cable from near CC failure period in test 24

APPENDIX F. **Results for the Ten-Cable Bundle Tests**

APPENDIX F. Results for the Ten-Cable Bundle Tests

F.1 Introduction

The purpose of this Appendix is to provide the test results for each of the 14 ten-cable bundle tests performed. Test results include temperature plots and the SCDU data.

All of the ten-cable bundle tests involved thermoset cables and all used the same heating profile as documented in the main body of this report. All tests also involved the same arrangement of three electrical performance cables and seven thermal response cables.

Each section opens with a table that identifies the test name, test date and coating conditions. Also shown are key event times as follows: time to ignition ***in minutes*** and failure times ***in minutes*** for each SCDU module (SCDU 1-3).

Each thermal response cable, cables A-G, was instrumented with one centrally located sub-jacket thermocouple for a total of seven cable thermocouples. The temperature response data is comprised of the Penlight shroud temperature and the temperatures for each of the seven cable thermocouples. One figure is presented for each test illustrating these data. There were SCDU – thermocouple interference issues during the latter stages of most tests. The artifacts of this interference have not been removed from the data plots; rather, the data is plotted exactly as it was recorded.

Each of the three electrical performance cables, S1, S2 and S3 were connected to one module of the SCDU and has a respective data plot. Three plots are presented for each test, one for each SCDU module, and each plot shows the source (S#V1) and target (S#V5) voltages and source (S#A1) and target (S#A5) currents as measured over the course of each test. Failure is indicated either by an increase in the target voltage (V5) to that of the energized source, or in the event of a short to ground, a drop in the source voltage to zero. Given the SCDU – thermocouple interference issues, for most tests the SCDU was cycled on-off to maximize the data collection. Times when the SCDU are off are obvious in the plots. Once a source conductor shorts to ground it will not recover even if SCDU is cycled.

F.2 Uncoated 1

Table F-1. Uncoated 1 - parameters and sequence of events

Test Parameters	
Test Name	Uncoated 1
Test Date	4/15/2014
Coating	None
Sequence of events	
Time to Cable Ignition	24.2
Time to SCDU 1 failure	29.9
Time to SCDU 2 failure	29.2
Time to SCDU 3 failure	DNF*

* DNF indicates circuit did not fail. See main body for discussion.

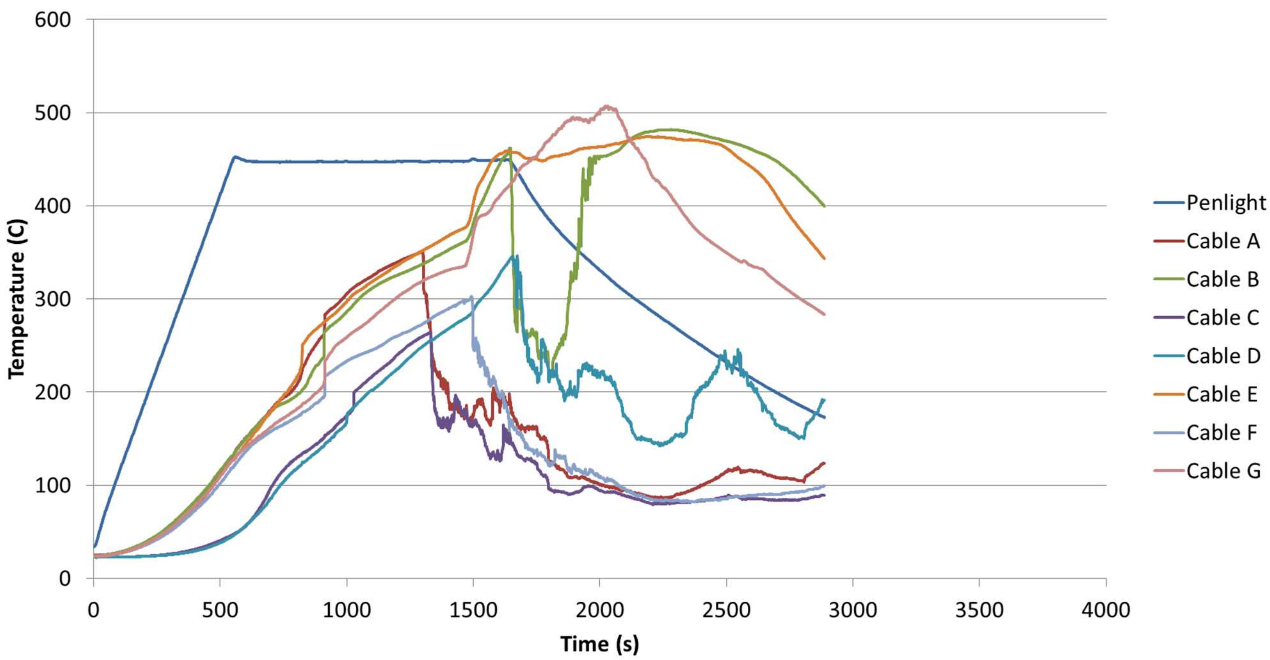

Figure F-1: Thermal response data for test Uncoated 1.

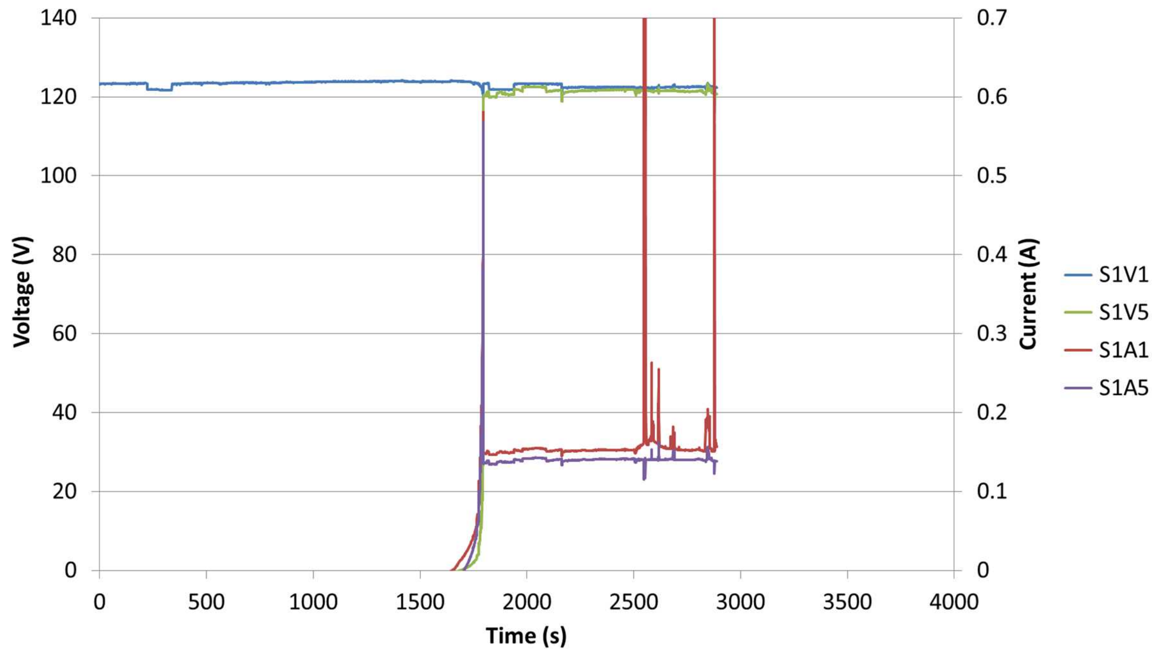

Figure F-2: SCDU module 1 response data for test Uncoated 1.

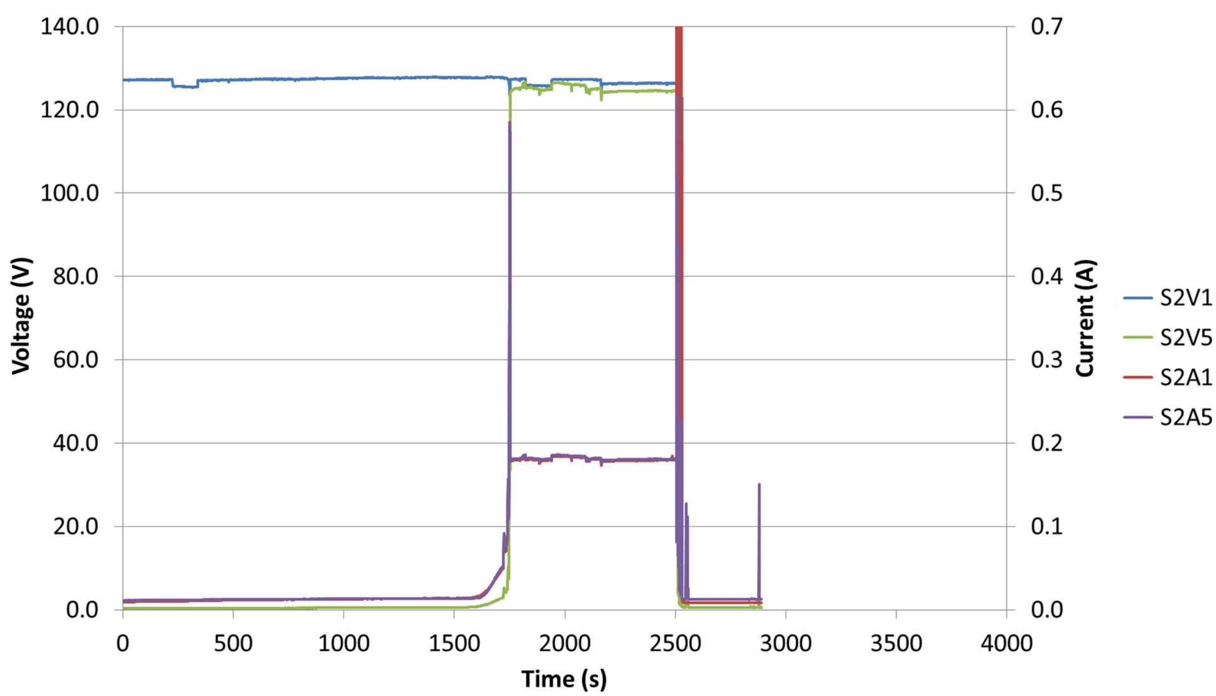

Figure F-3: SCDU module 2 response data for test Uncoated 1.

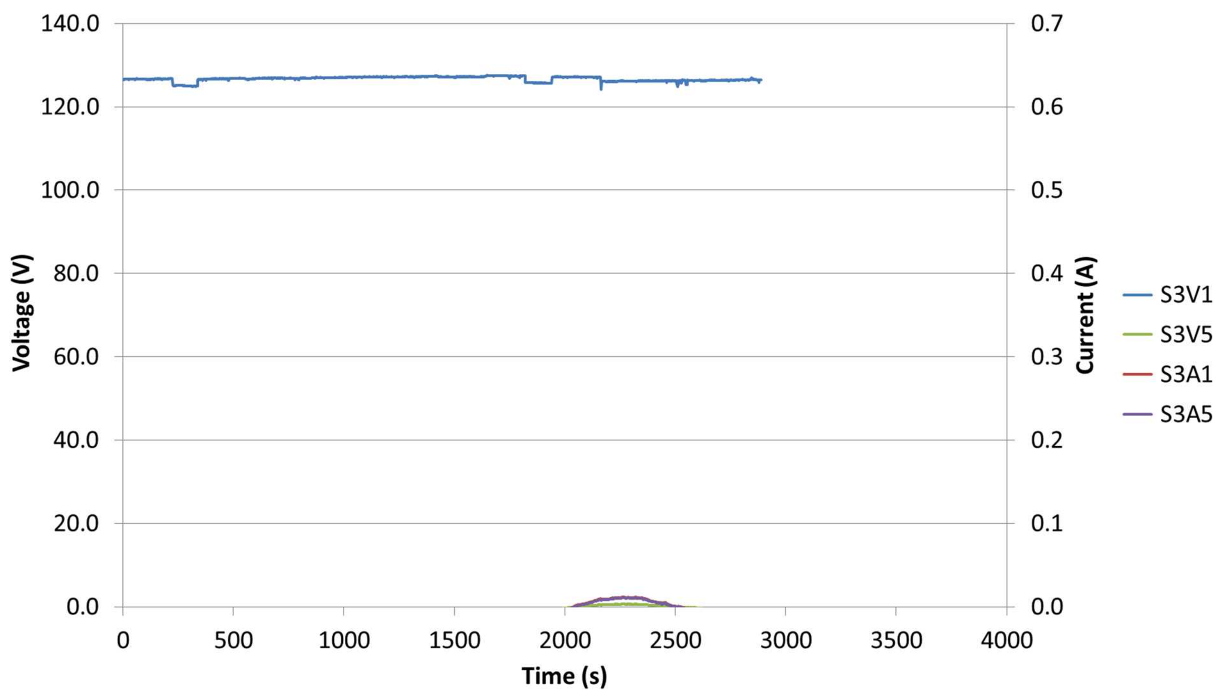

Figure F-4: SCDU module 3 response data for test Uncoated 1.

F.3 Uncoated 2

Table F-2. Uncoated 2 - parameters and sequence of events

Test Parameters	
Test Name	Uncoated 2
Test Date	4/15/2014
Coating	None
Sequence of events	
Time to Cable Ignition	25
Time to SCDU 1 failure	29.3
Time to SCDU 2 failure	29.8
Time to SCDU 3 failure	34.2

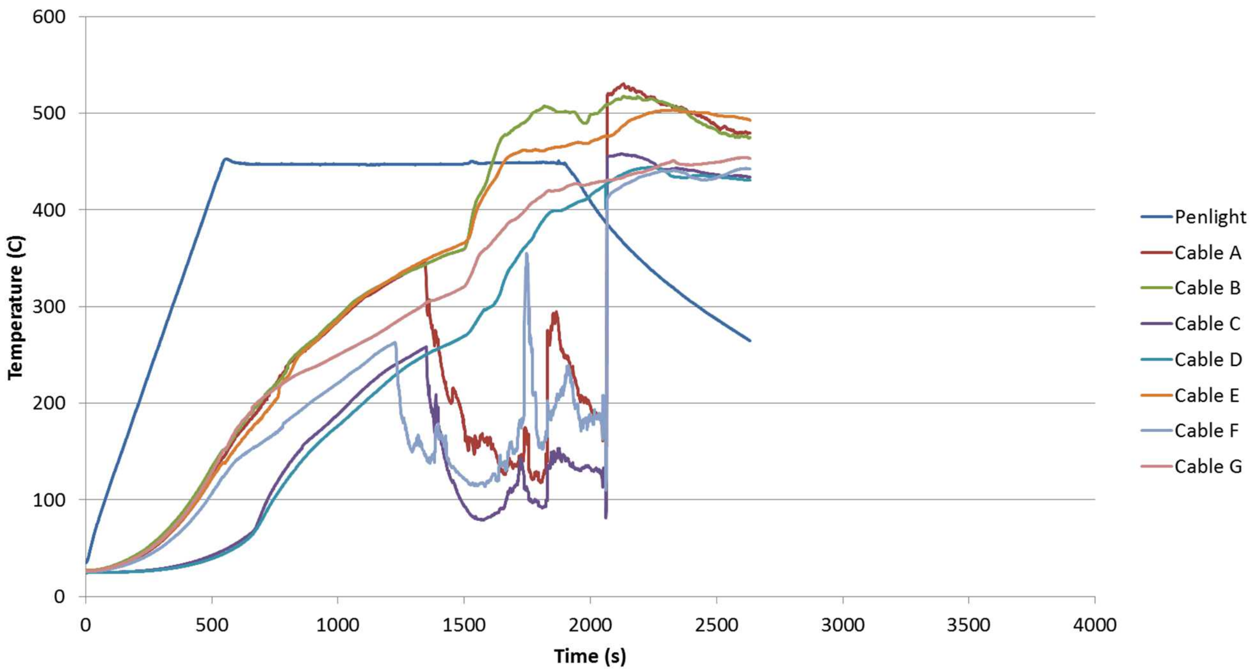

Figure F-5: Thermal response data for test Uncoated 2.

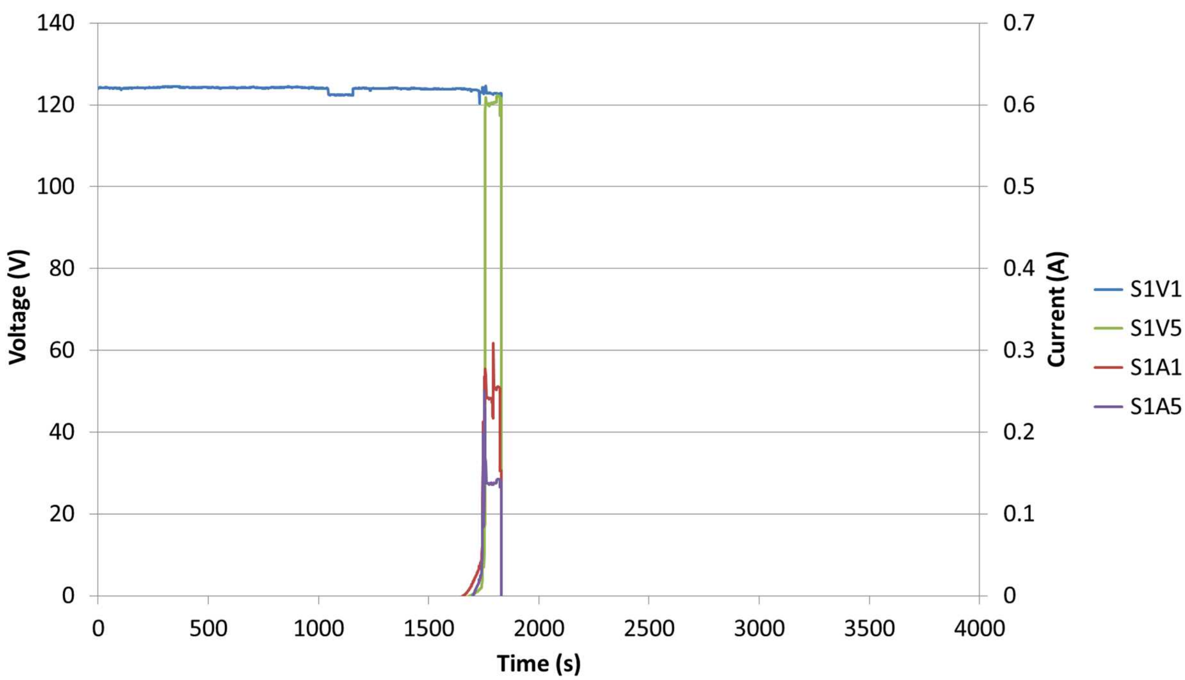

Figure F-6: SCDU module 1 response data for test Uncoated 2.

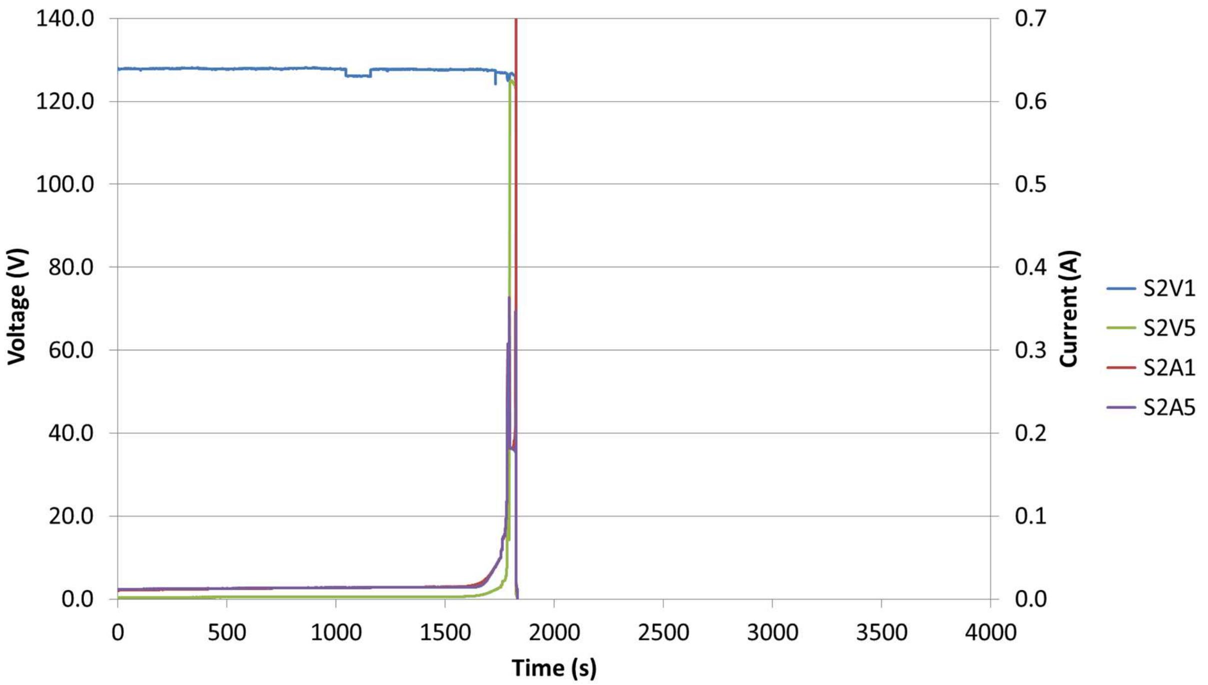

Figure F-7: SCDU module 2 response data for test Uncoated 2.

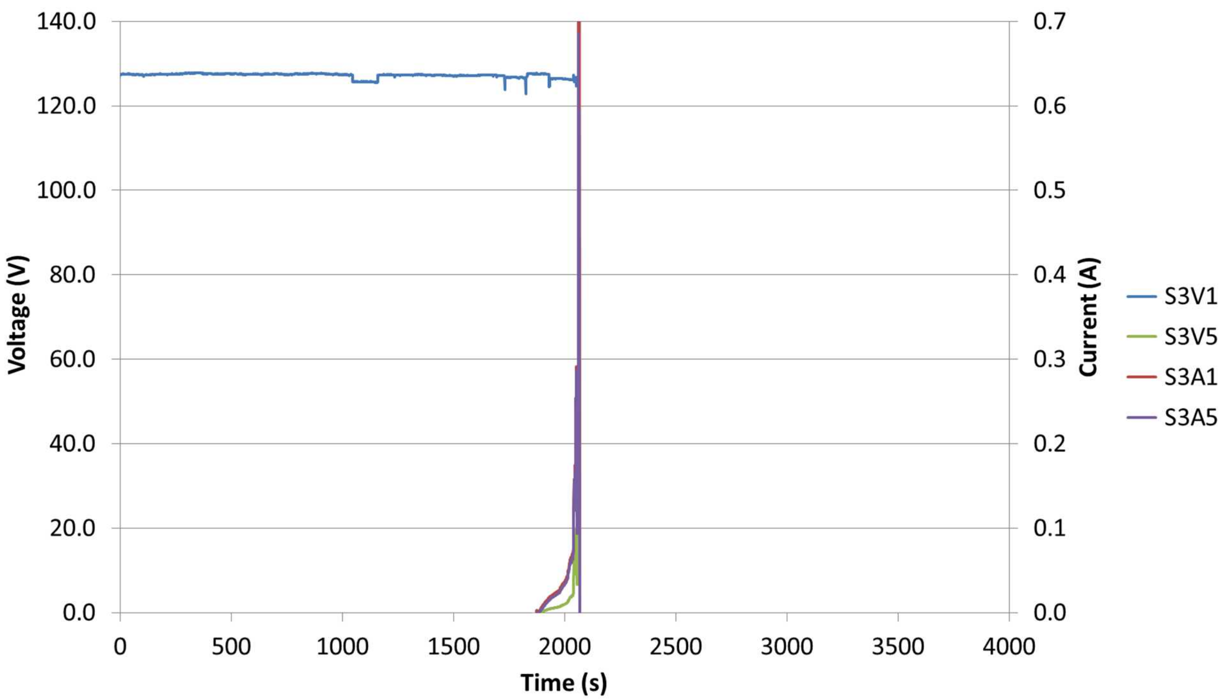

Figure F-8: SCDU module 3 response data for test Uncoated 2.

F.4 Uncoated 3

Table F-3. Uncoated 3 - parameters and sequence of events

Test Parameters	
Test Name	Uncoated 3
Test Date	4/21/2014
Coating	None
Sequence of events	
Time to Cable Ignition	24.1
Time to SCDU 1 failure	30.3
Time to SCDU 2 failure	29.7
Time to SCDU 3 failure	33.8

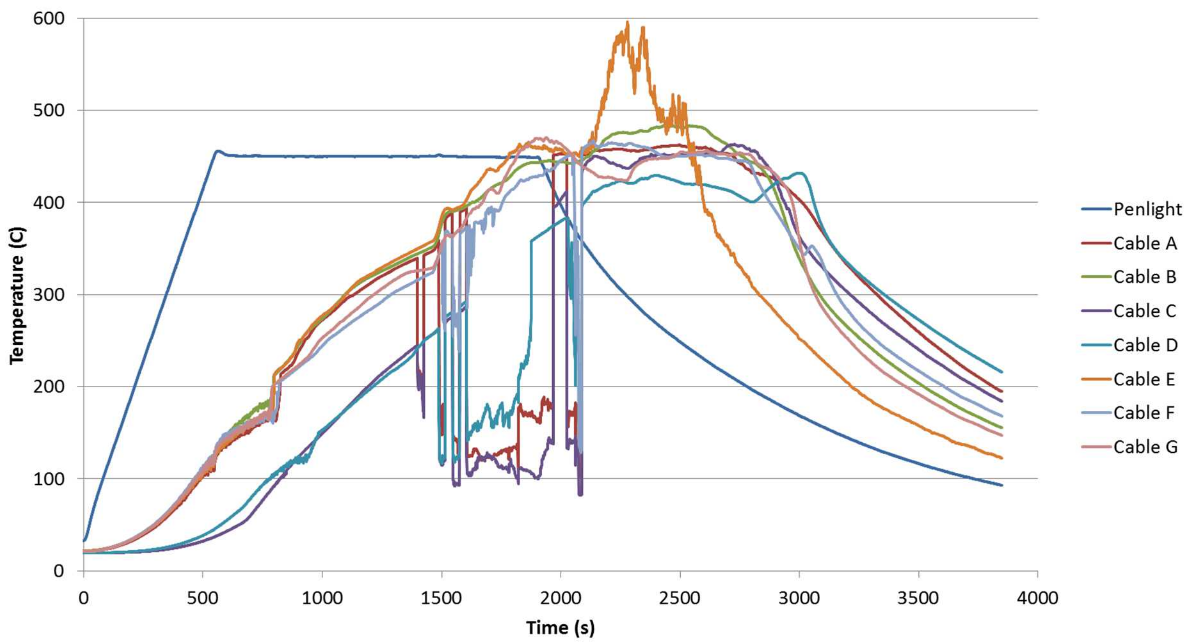

Figure F-9: Thermal response data for test Uncoated 3.

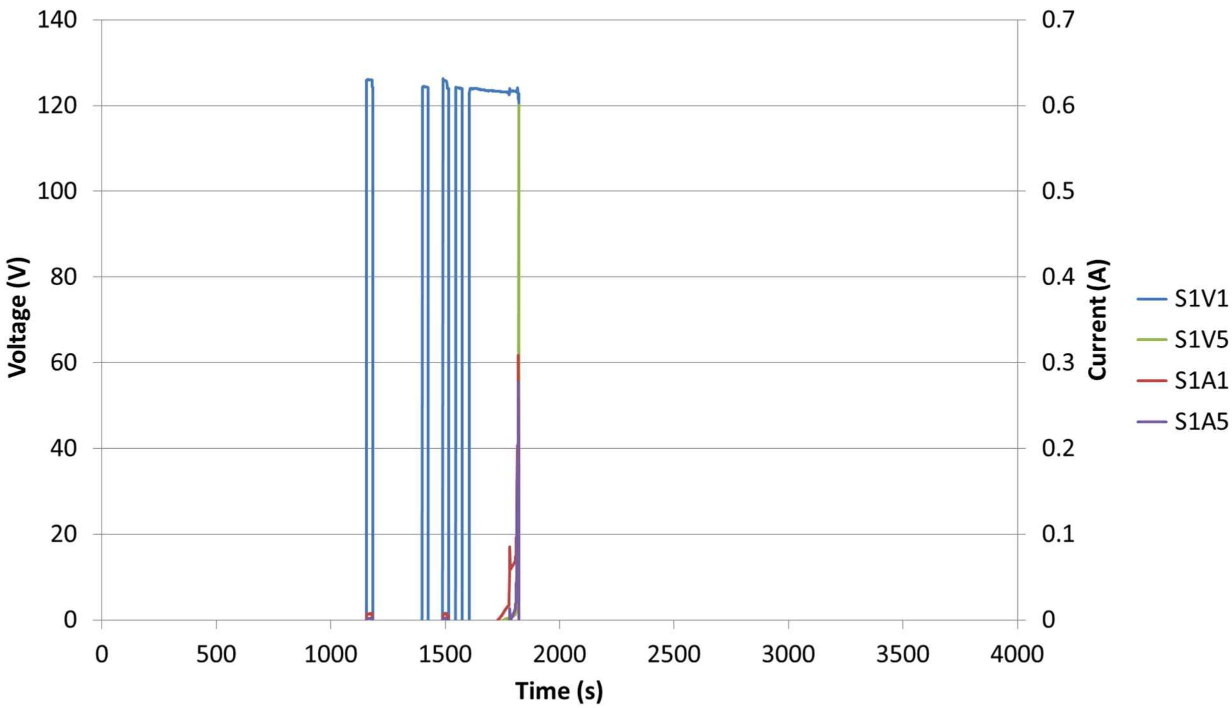

Figure F-10: SCDU module 1 response data for test Uncoated 3.

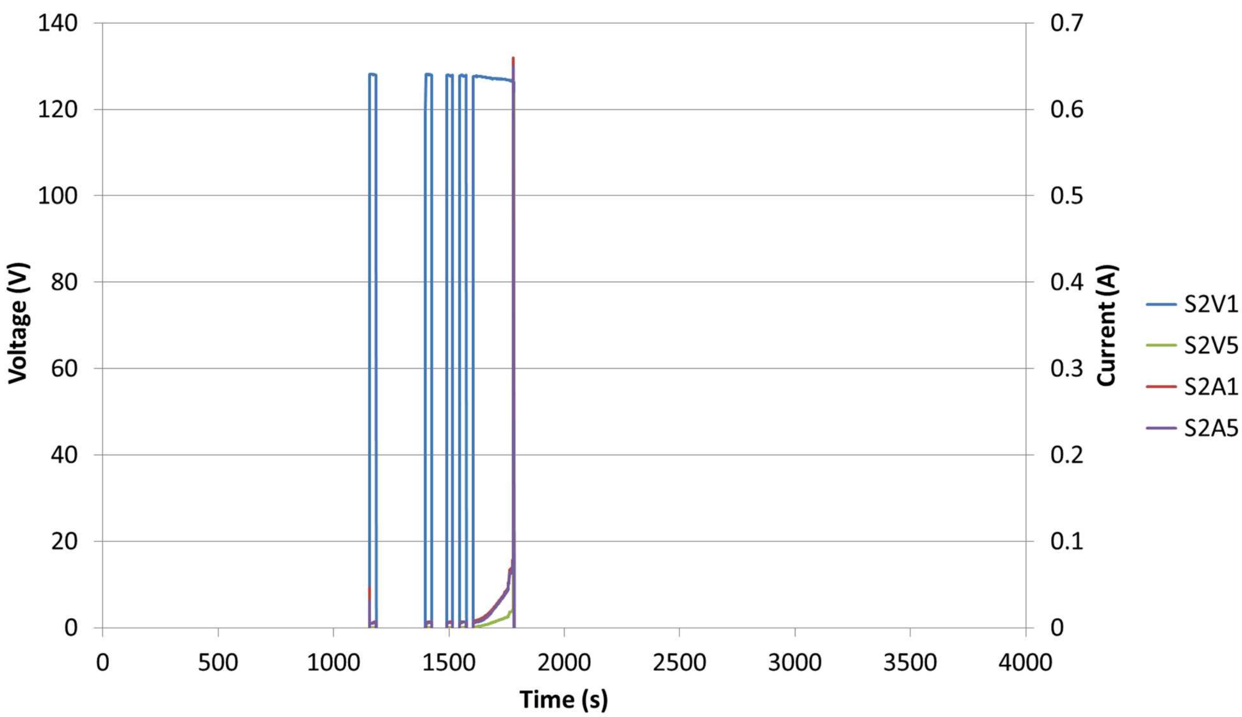

Figure F-11: SCDU module 2 response data for test Uncoated 3.

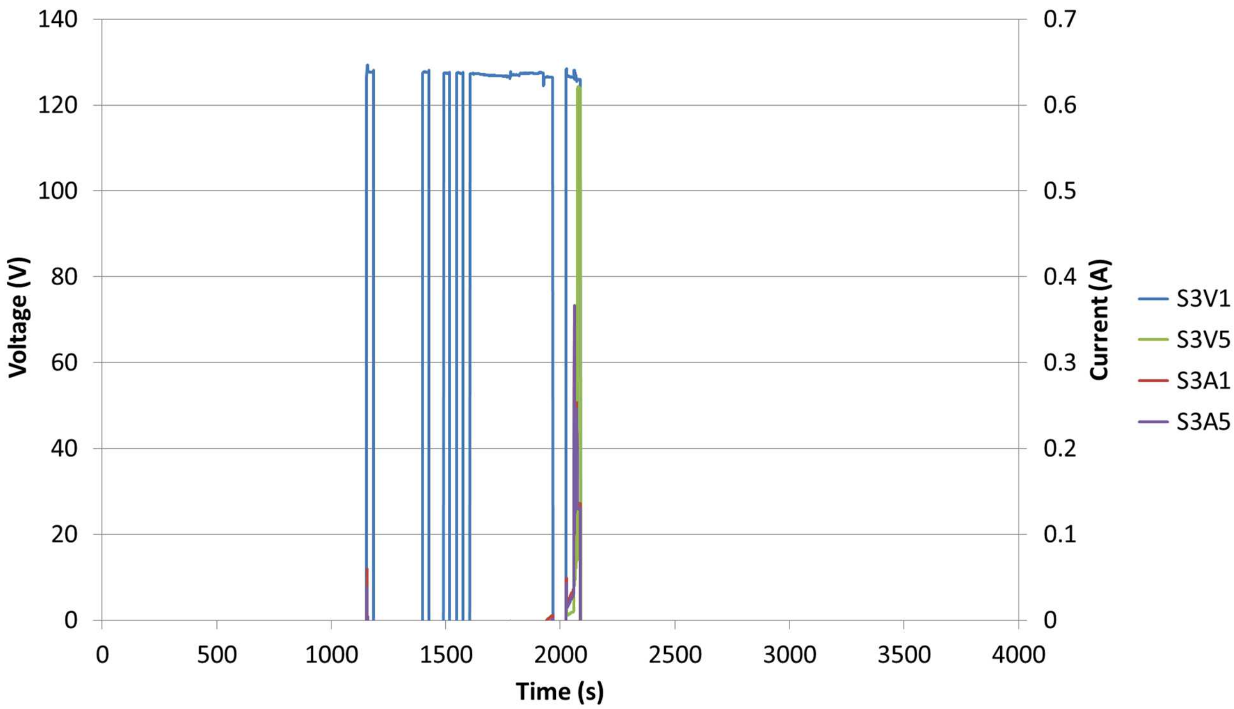

Figure F-12: SCDU module 3 response data for test Uncoated 3.

F.5 Uncoated 4

Table F-4. Uncoated 4 - parameters and sequence of events

Test Parameters	
Test Name	Uncoated 4
Test Date	4/23/2014
Coating	None
Sequence of events	
Time to Cable Ignition	24.0
Time to SCDU 1 failure	32.9
Time to SCDU 2 failure	30.2
Time to SCDU 3 failure	36.4

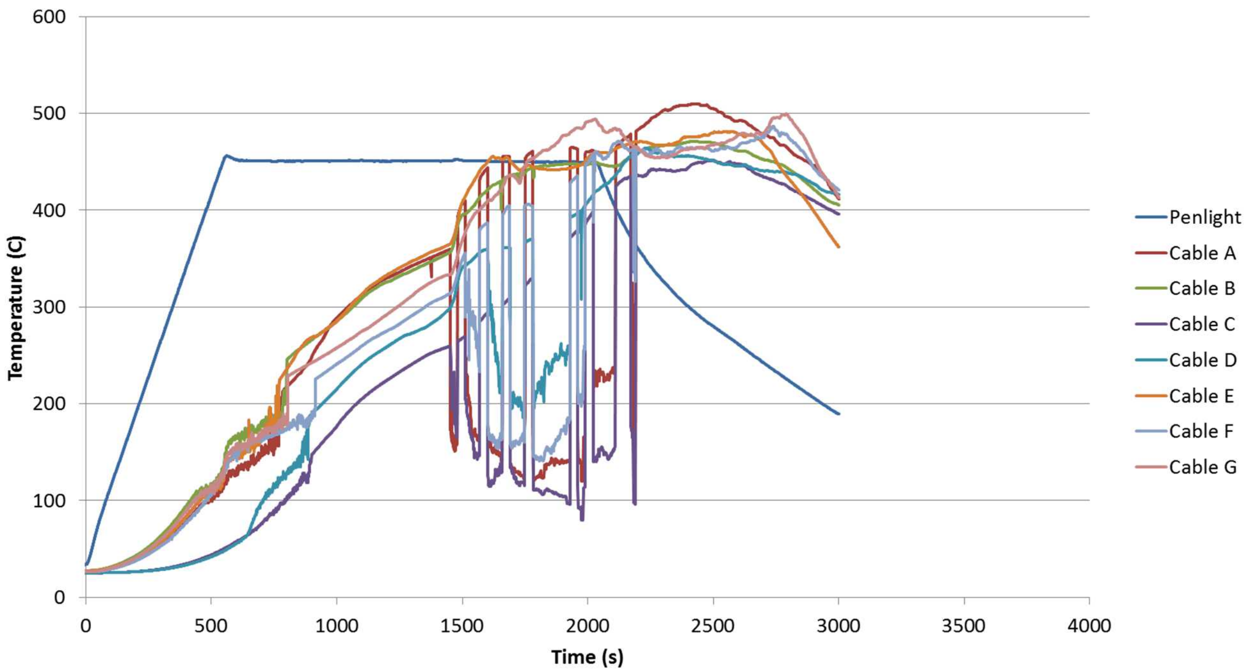

Figure F-13: Thermal response data for test Uncoated 4.

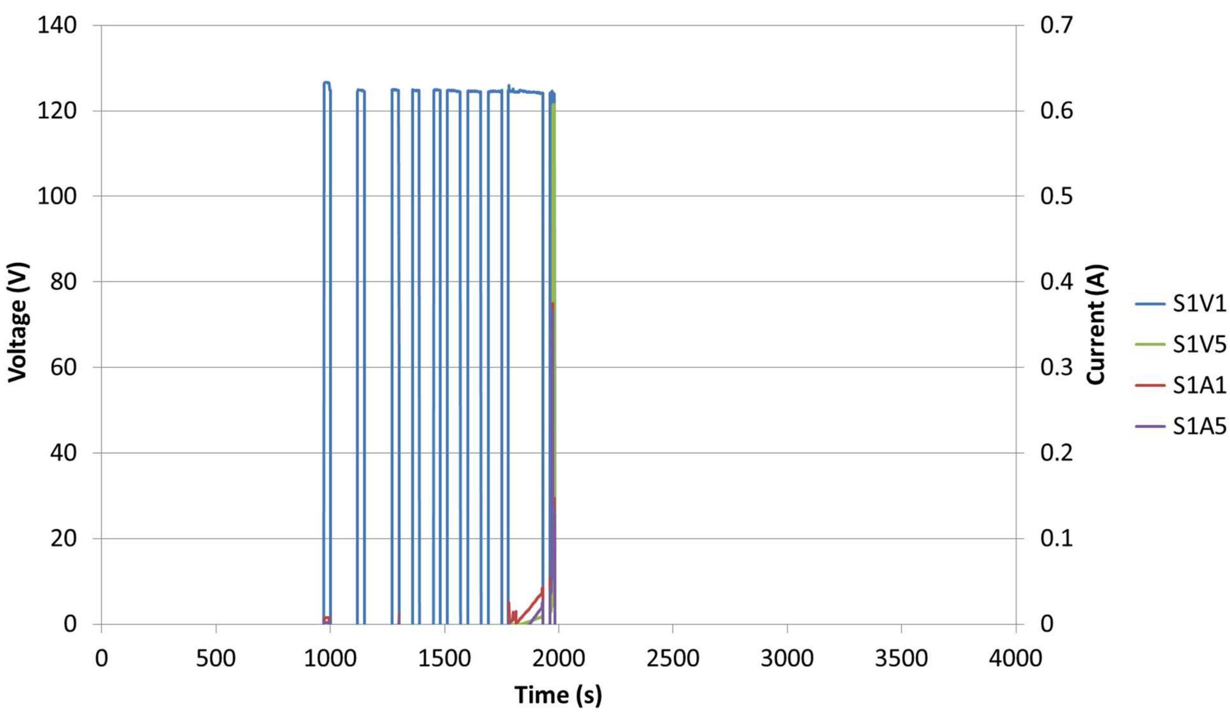

Figure F-14: SCDU module 1 response data for test Uncoated 4.

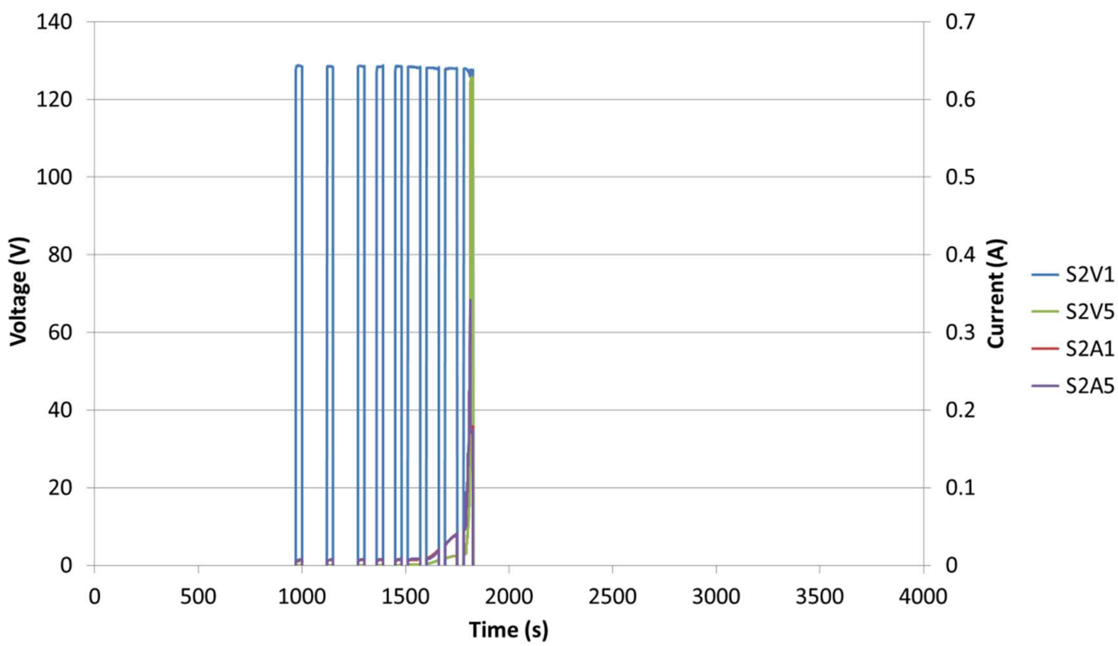

Figure F-15: SCDU module 2 response data for test Uncoated 4.

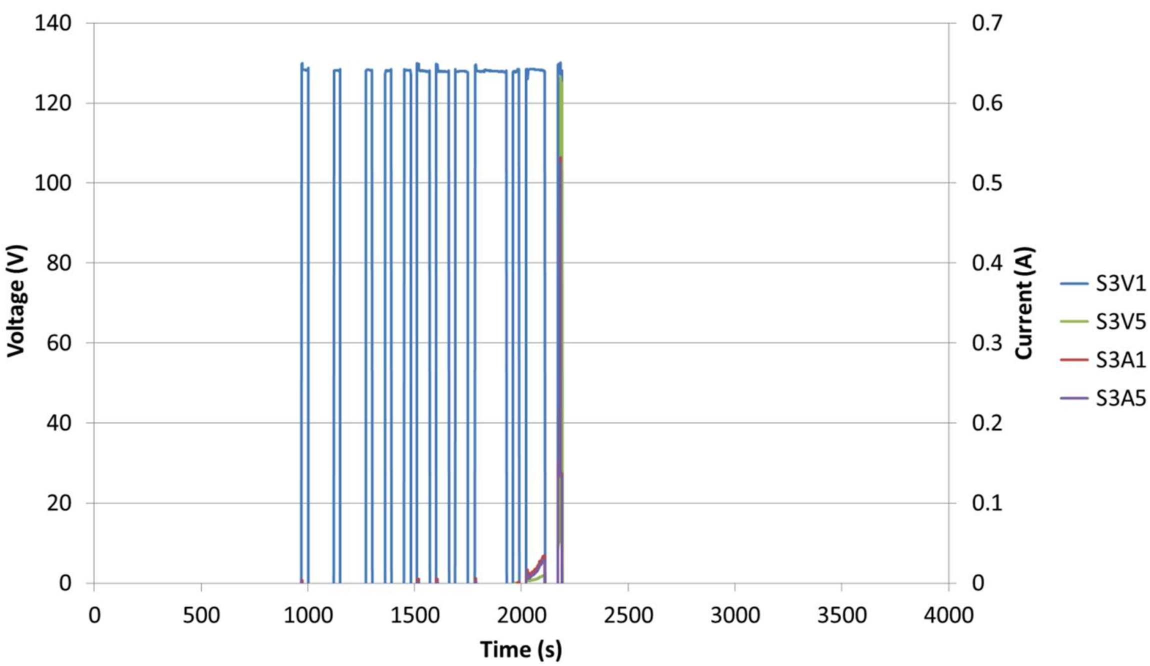

Figure F-16: SCDU module 3 response data for test Uncoated 4.

F.6 Uncoated Wire Bound

Table F-5. Uncoated Wire Bound - parameters and sequence of events

Test Parameters	
Test Name	Uncoated wire bound
Test Date	4/23/2014
Coating	None
Sequence of events	
Time to Cable Ignition	28.9
Time to SCDU 1 failure	35.2
Time to SCDU 2 failure	36.6
Time to SCDU 3 failure	38.3

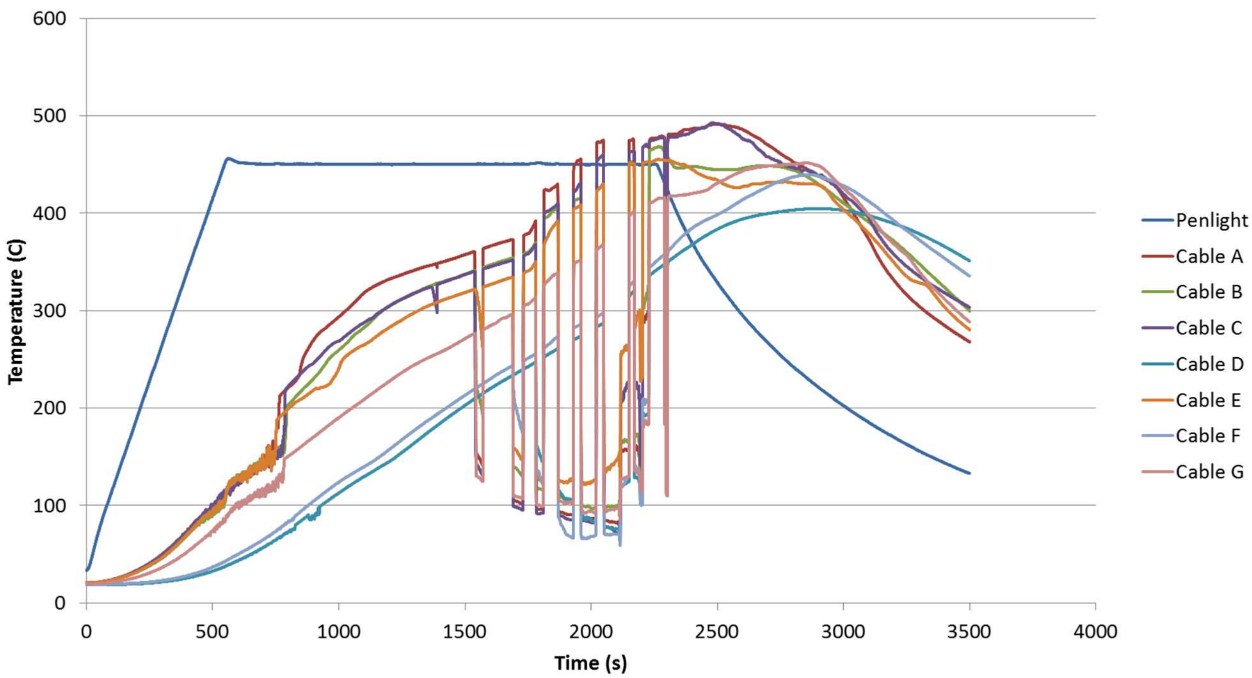

Figure F-17: Thermal response data for test Uncoated Wire Bound.

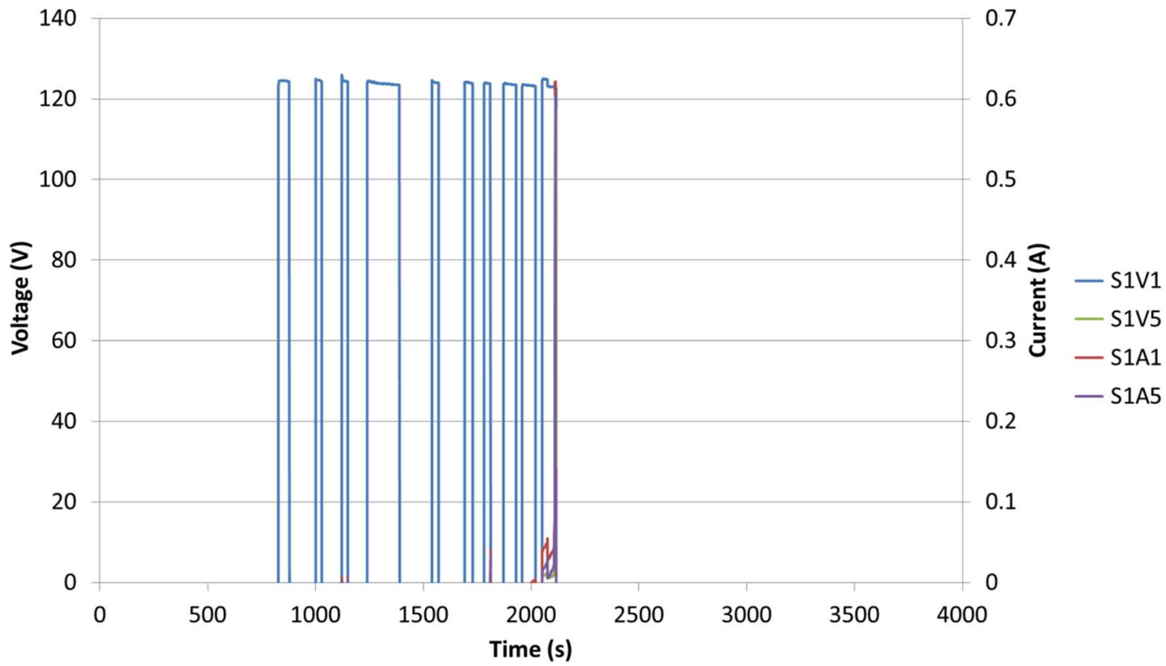

Figure F-18: SCDU module 1 response data for test Uncoated Wire Bound.

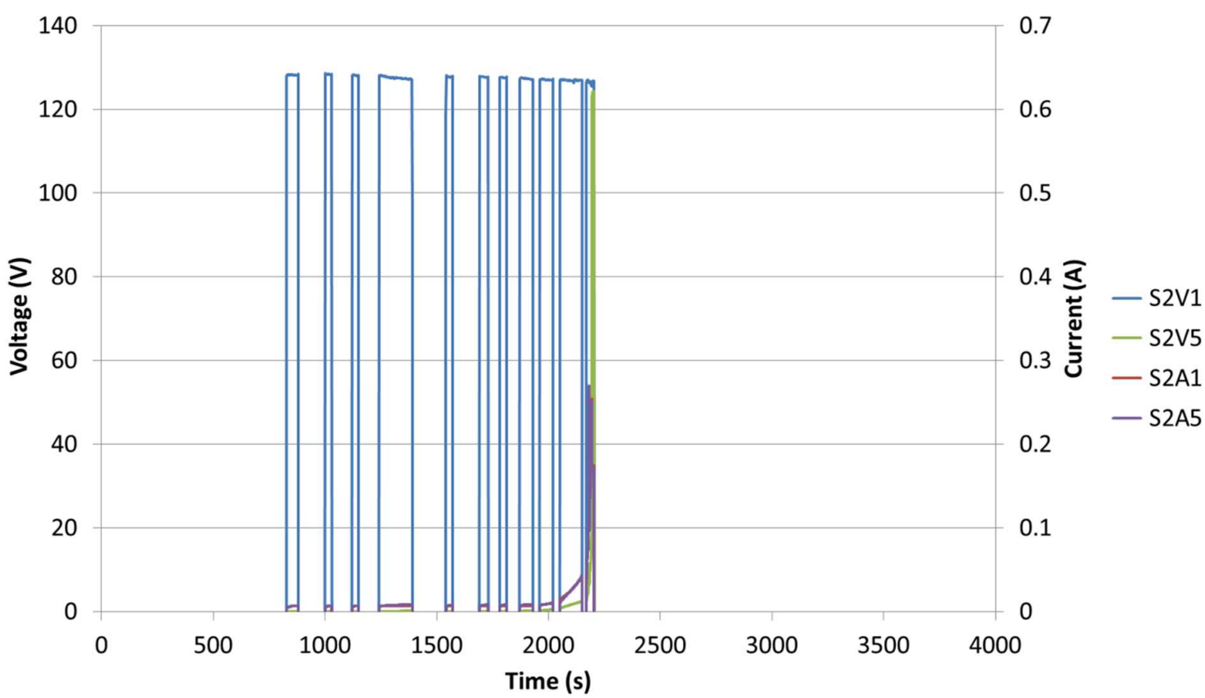

Figure F-19: SCDU module 2 response data for test Uncoated Wire Bound.

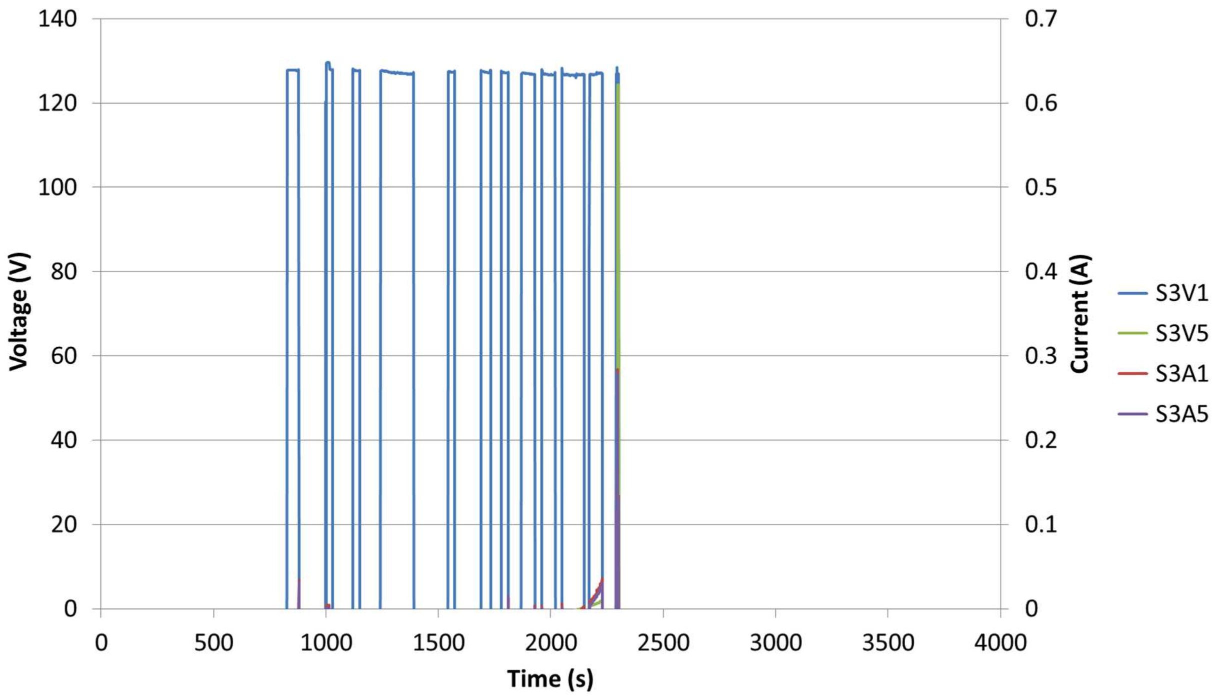

Figure F-20: SCDU module 3 response data for test Uncoated Wire Bound.

F.7 Vimasco 1

Table F-6. Vimasco 1 - parameters and sequence of events

Test Parameters	
Test Name	Vimasco 1
Test Date	4/16/2014
Coating	Vimasco
Sequence of events	
Time to Cable Ignition	n/a
Time to SCDU 1 failure	n/a
Time to SCDU 2 failure	n/a
Time to SCDU 3 failure	n/a

Note: While thermal response data was gathered for test Vimasco 1, the test was terminated prior to ignition or failure of the cables due to the extreme interference issues observed on the thermocouples. It was after this test that the SCDU cycling strategy was developed and implemented. No SCDU circuit response data is presented for this test.

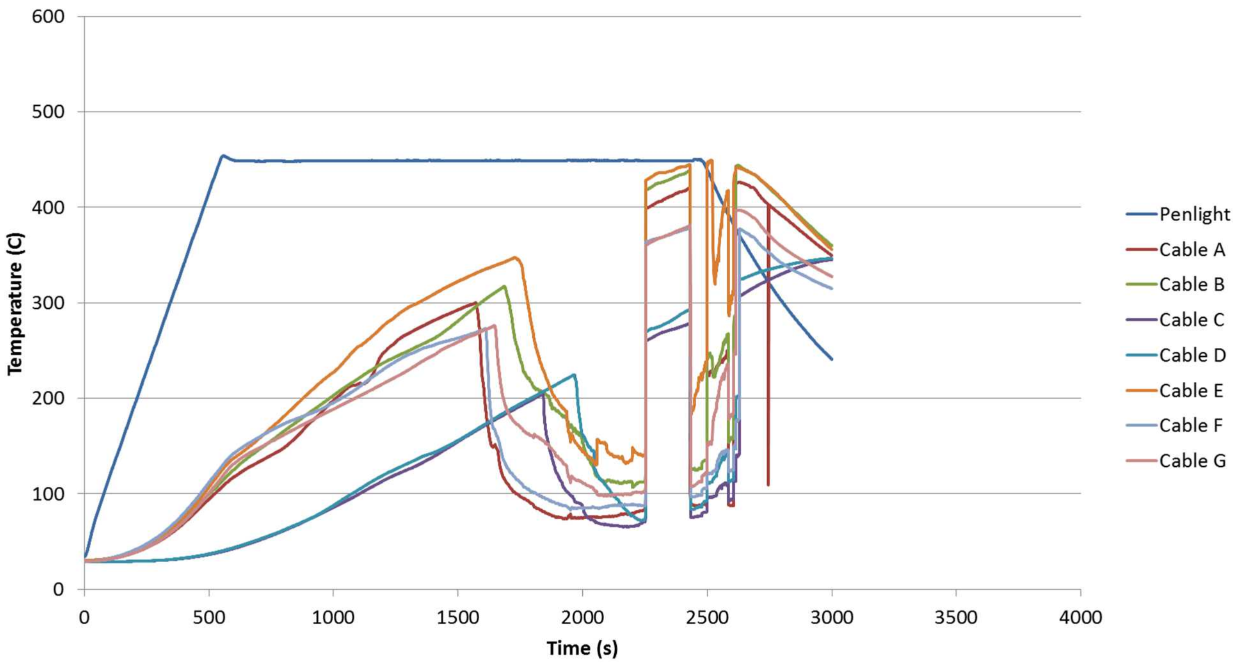

Figure F-21: Thermal response data for test Vimasco 1.

F.8 **Vimasco 2**

Table F-7. Vimasco 2 - parameters and sequence of events

Test Parameters	
Test Name	Vimasco 2
Test Date	4/17/2014
Coating	Vimasco
Sequence of events	
Time to Cable Ignition	40.3
Time to SCDU 1 failure	50.3
Time to SCDU 2 failure	47.1
Time to SCDU 3 failure	50.3

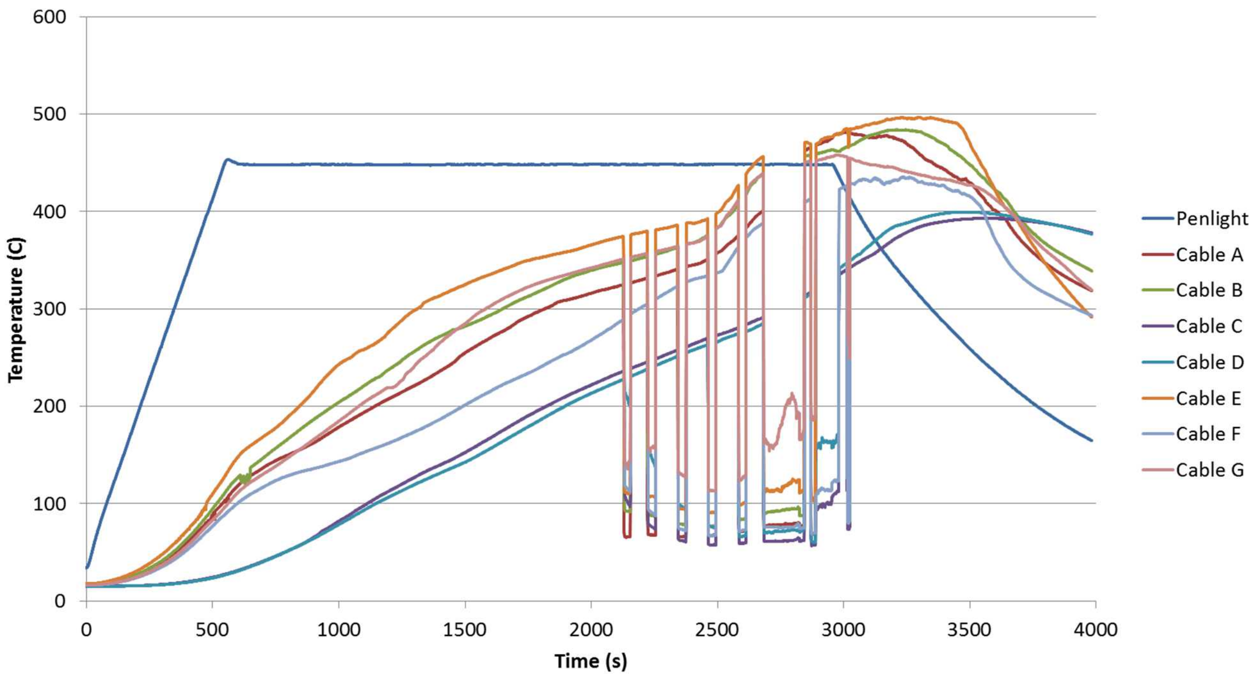

Figure F-22: Thermal response data for test Vimasco 2.

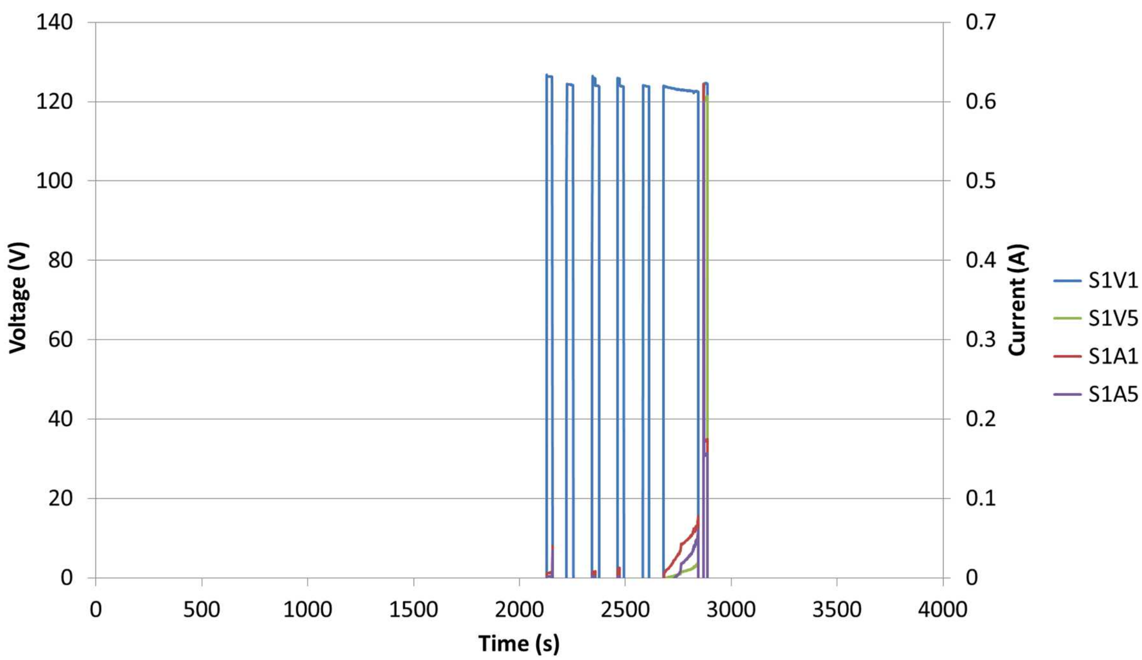

Figure F-23: SCDU module 1 response data for test Vimasco 2.

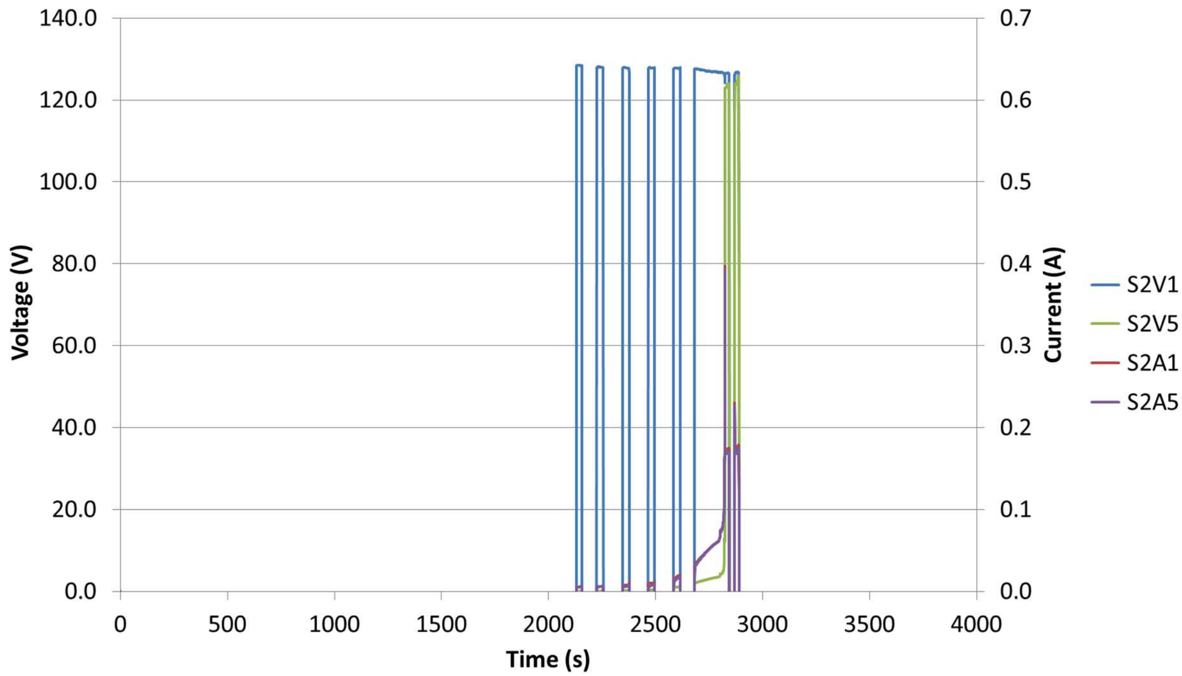

Figure F-24: SCDU module 2 response data for test Vimasco 2.

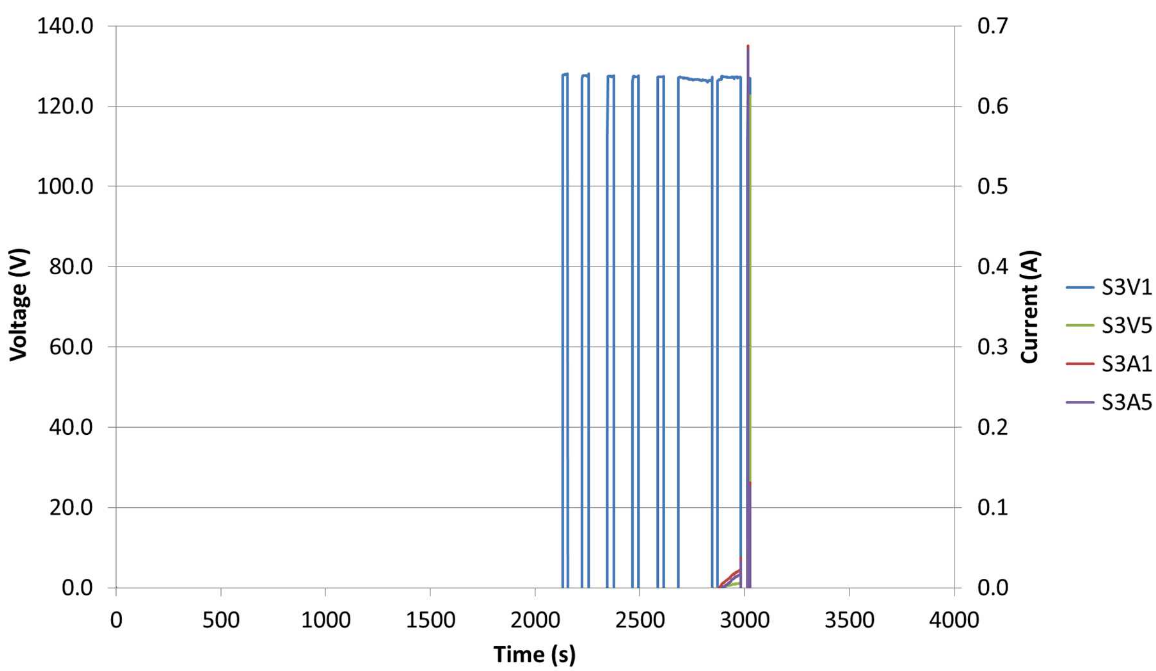

Figure F-25: SCDU module 3 response data for test Vimasco 2.

F.9 Vimasco 3

Table F-8. Vimasco 3 - parameters and sequence of events

Test Parameters	
Test Name	Vimasco 3
Test Date	4/17/2014
Coating	Vimasco
Sequence of events	
Time to Cable Ignition	37.5
Time to SCDU 1 failure	43.5
Time to SCDU 2 failure	44.3
Time to SCDU 3 failure	DNF*

* SCDU 3 did not fail (DNF)

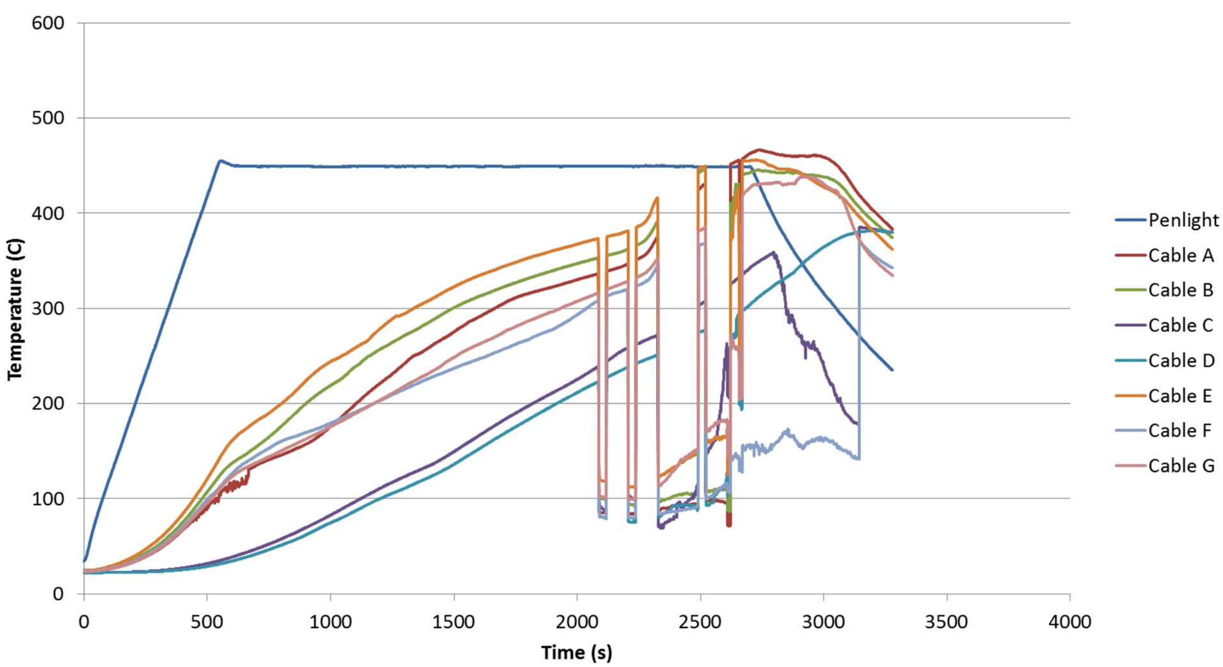

Figure F-26: Thermal response data for test Vimasco 3.

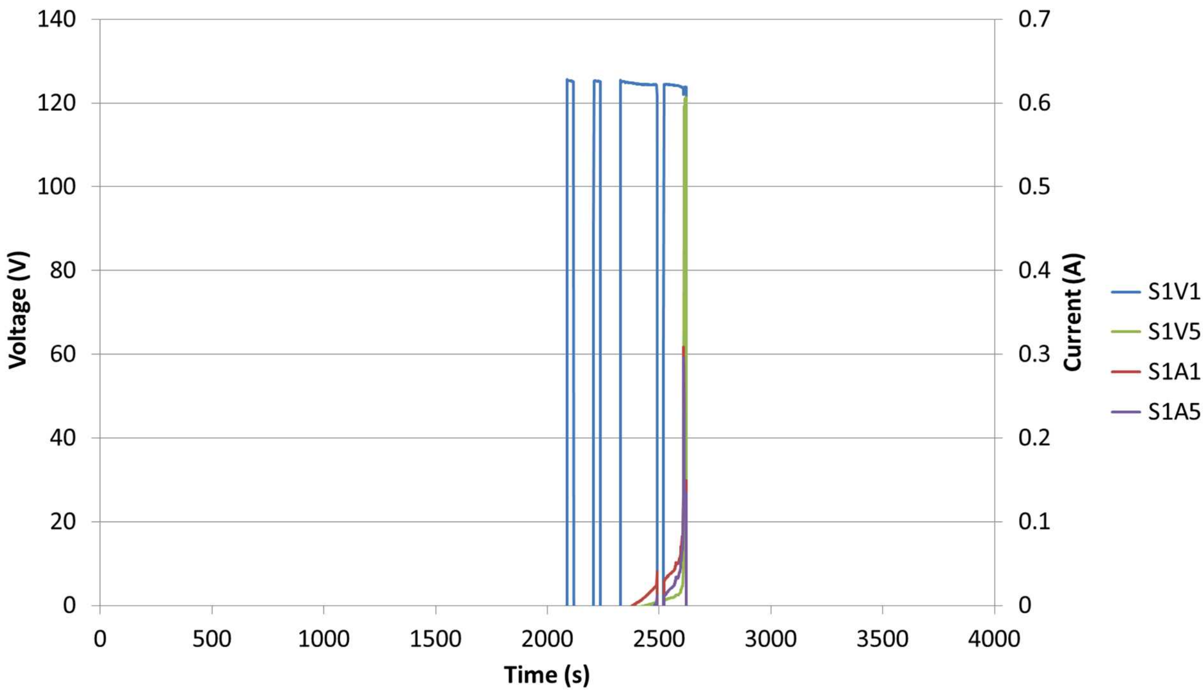

Figure F-27: SCDU module 1 response data for test Vimasco 3.

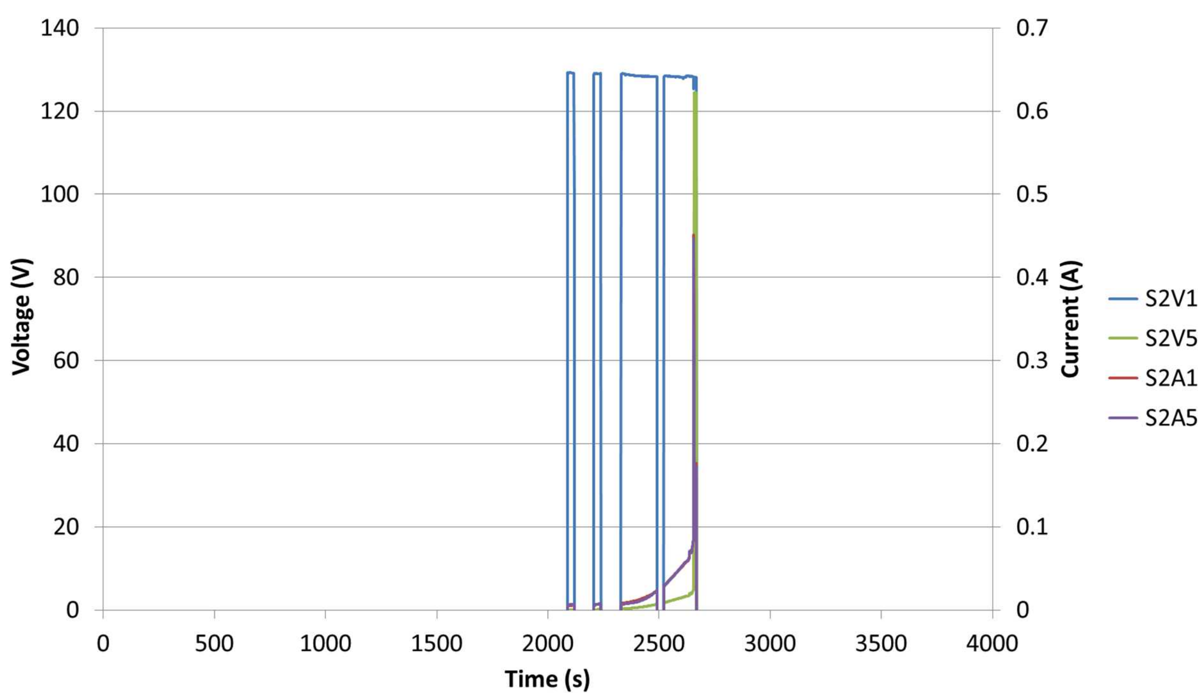

Figure F-28: SCDU module 2 response data for test Vimasco 3.

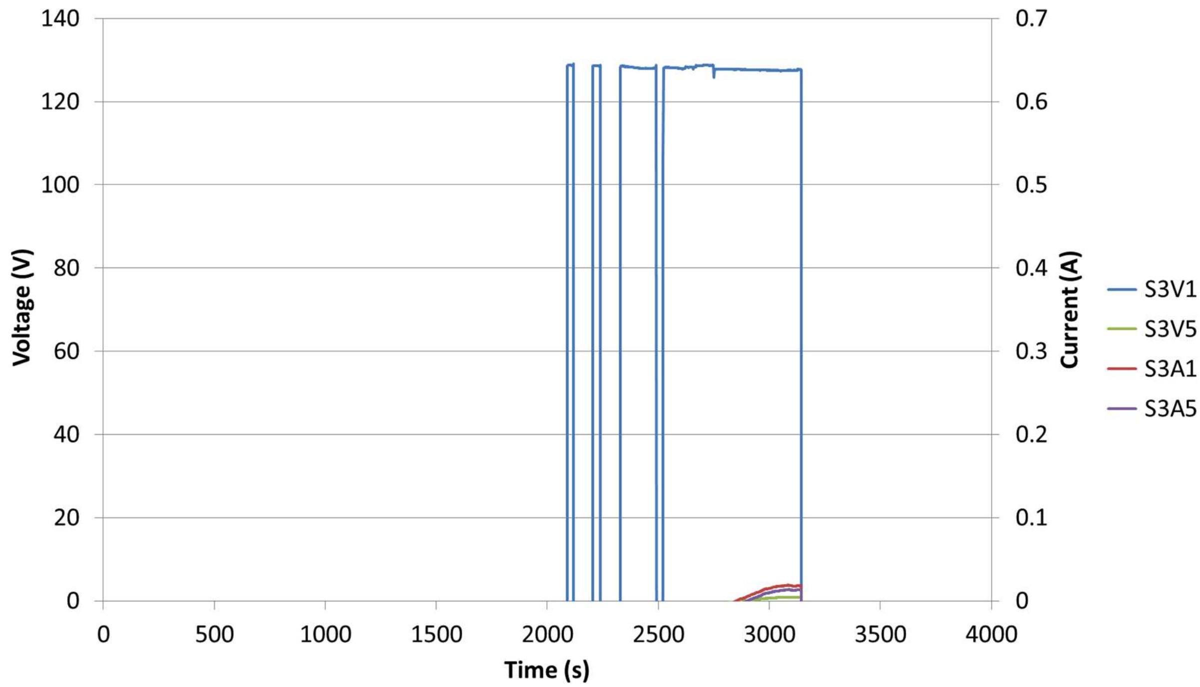

Figure F-29: SCDU module 3 response data for test Vimasco 3.

F.10 **Flamemastic 1**

Table F-9. Flamemastic 1 - parameters and sequence of events

Test Parameters	
Test Name	Flamemastic 1
Test Date	4/17/2014
Coating	Flamemastic
Sequence of events	
Time to Cable Ignition	35.6
Time to SCDU 1 failure	42.5
Time to SCDU 2 failure	41.9
Time to SCDU 3 failure	DNF

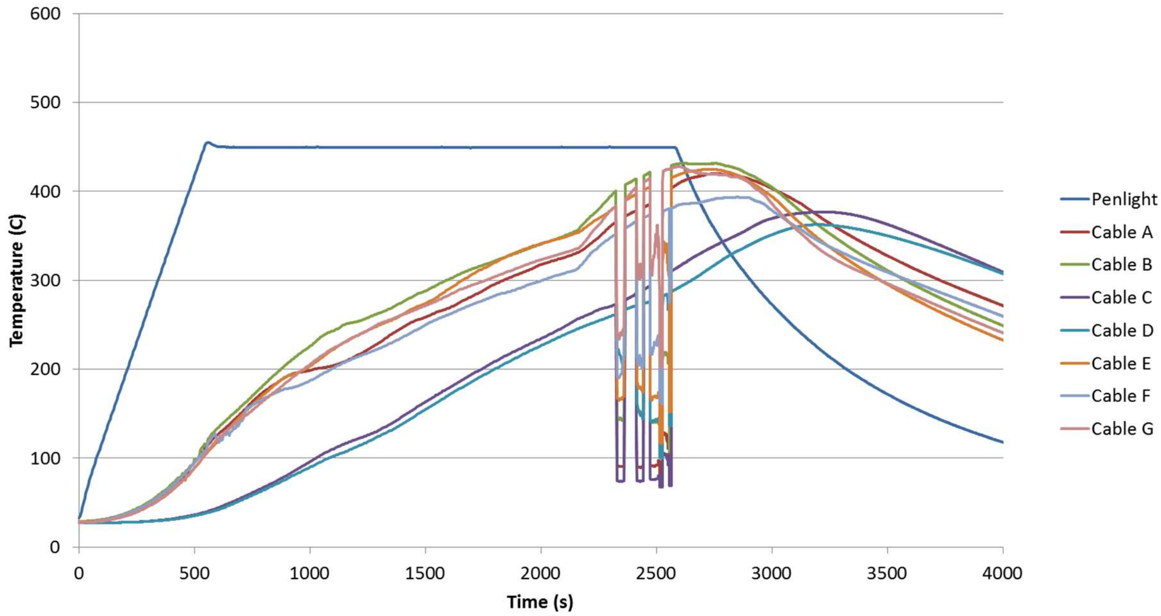

Figure F-30: Thermal response data for test Flamemastic 1.

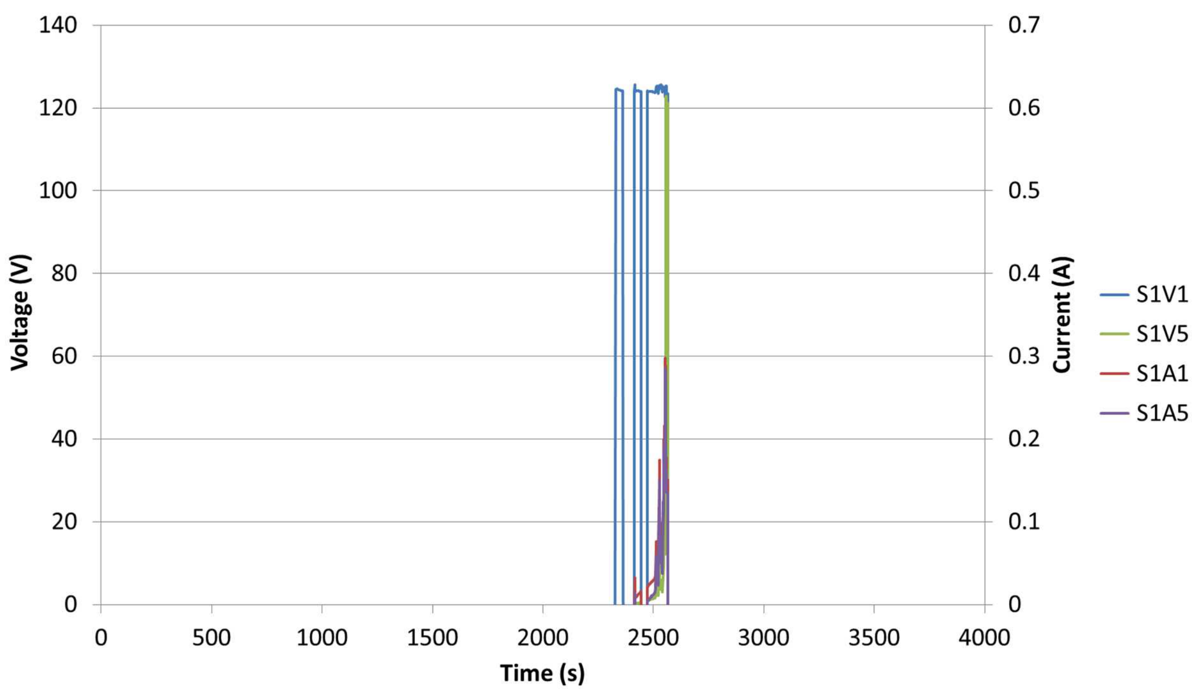

Figure F-31: SCDU module 1 response data for test Flamemastic 1.

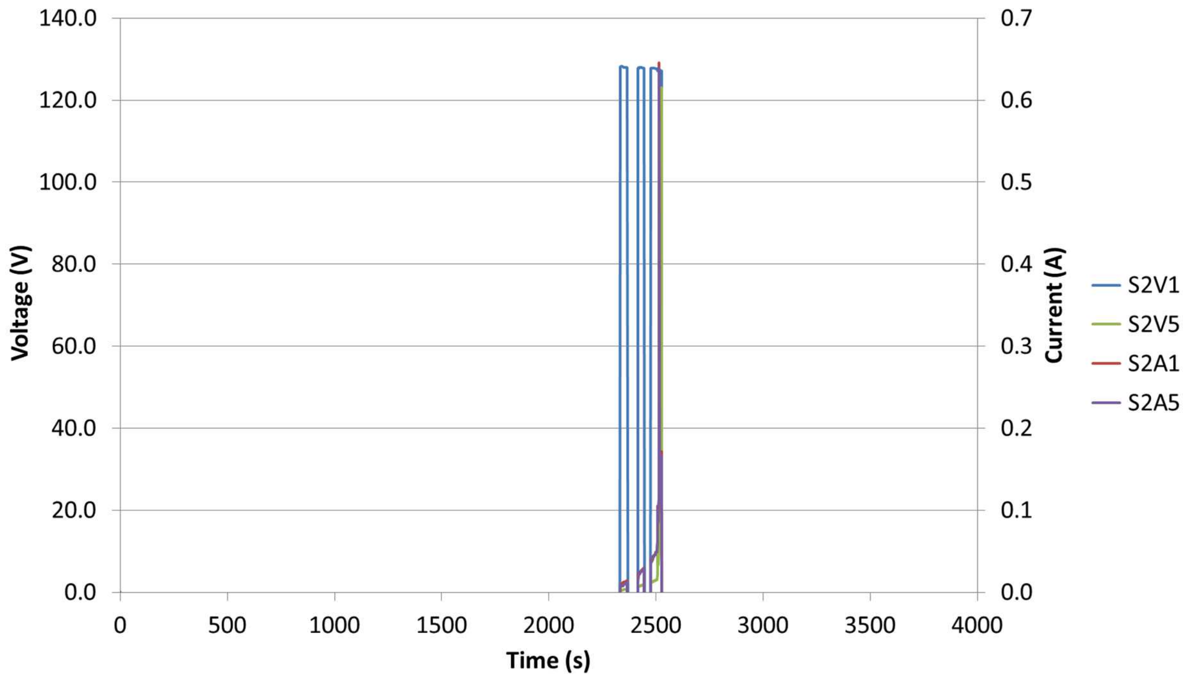

Figure F-32: SCDU module 2 response data for test Flamemastic 1.

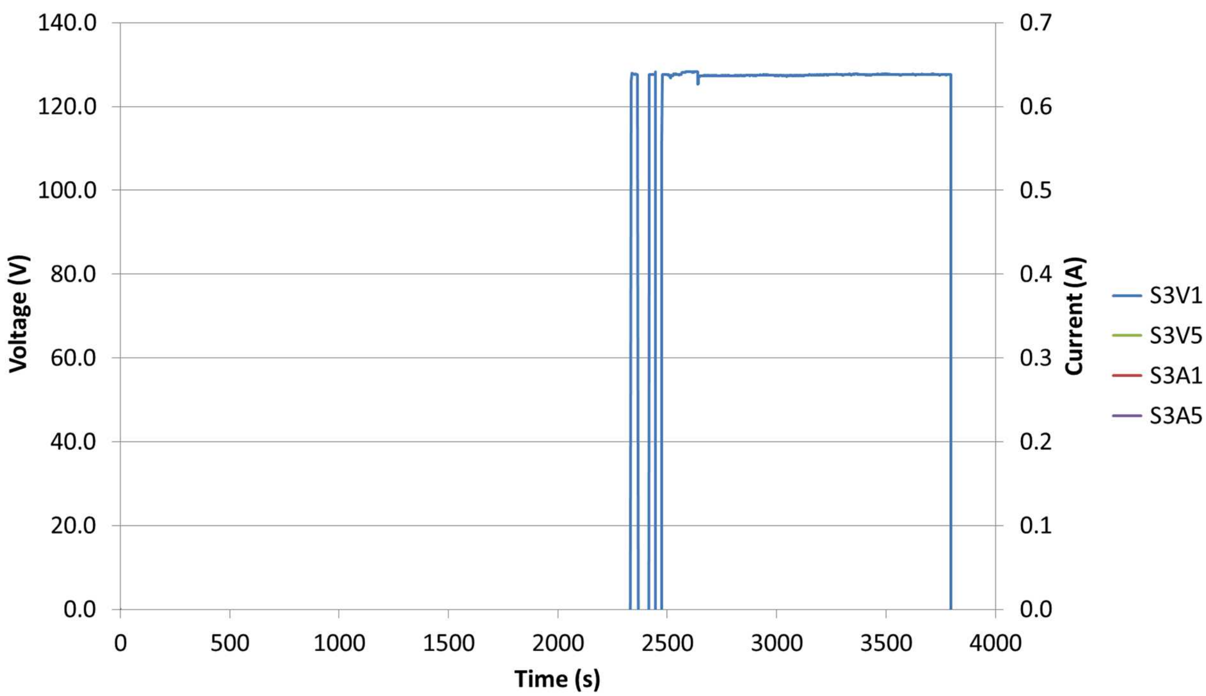

Figure F-33: SCDU module 3 response data for test Flamemastic 1.

F.11 **Flamemastic 2**

Table F-10. Flamemastic 2 - parameters and sequence of events

Test Parameters	
Test Name	Flamemastic 2
Test Date	4/22/2014
Coating	Flamemastic
Sequence of events	
Time to Cable Ignition	36.6
Time to SCDU 1 failure	41.5
Time to SCDU 2 failure	42.9
Time to SCDU 3 failure	47.1

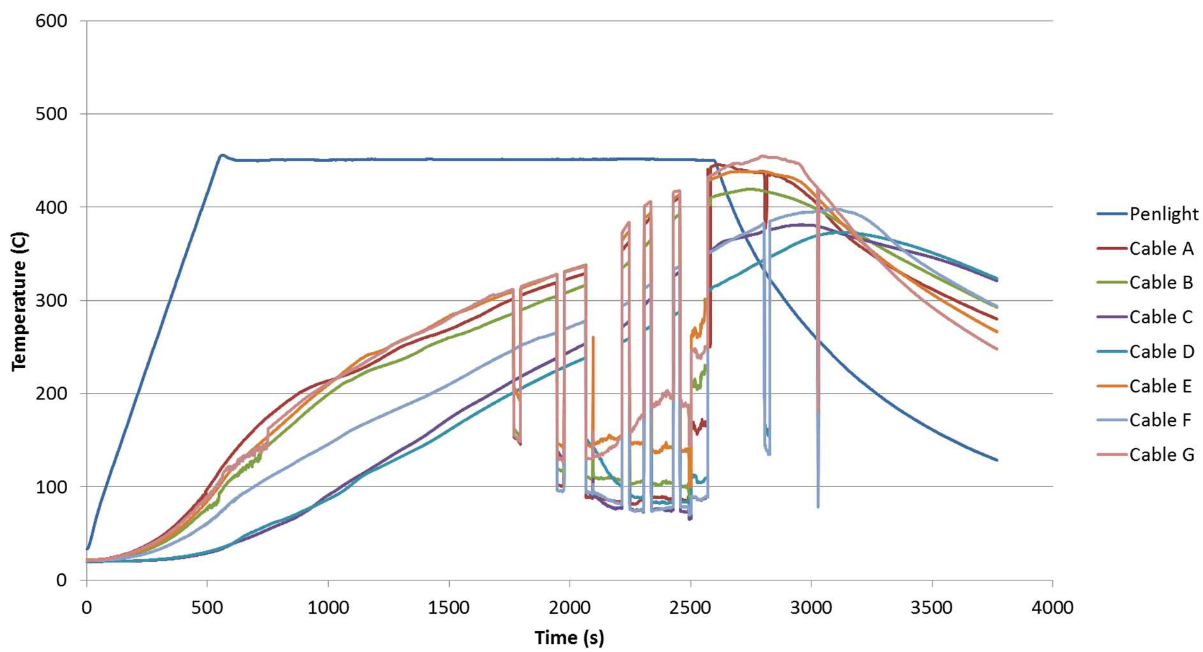

Figure F-34: Thermal response data for test Flamemastic 2.

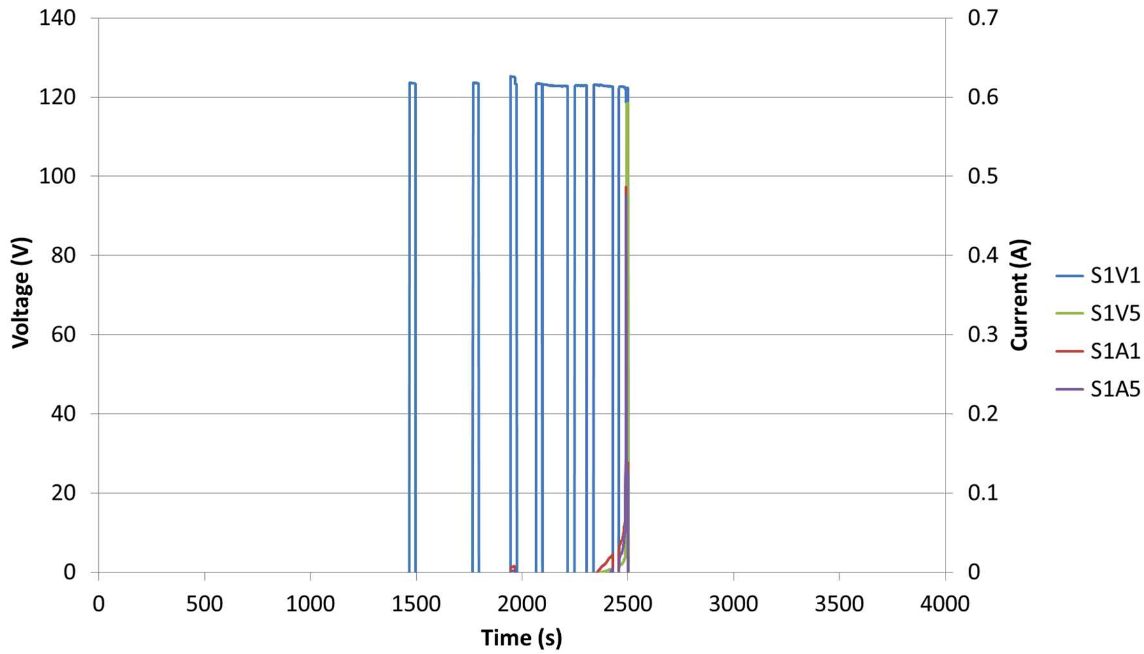

Figure F-35: SCDU module 1 response data for test Flamemastic 2.

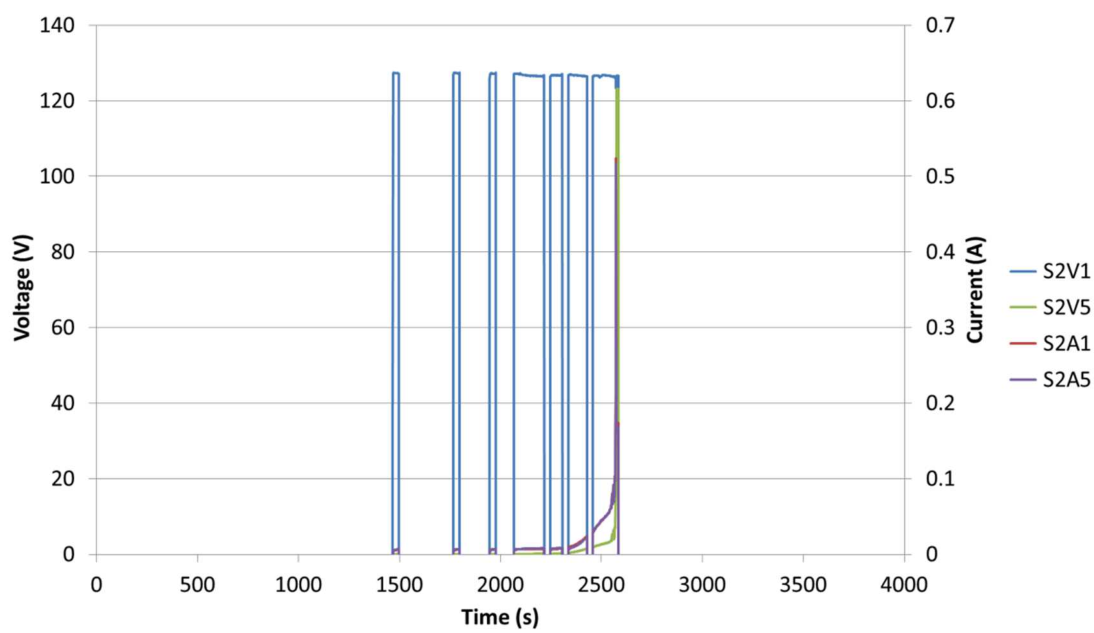

Figure F-36: SCDU module 2 response data for test Flamemastic 2.

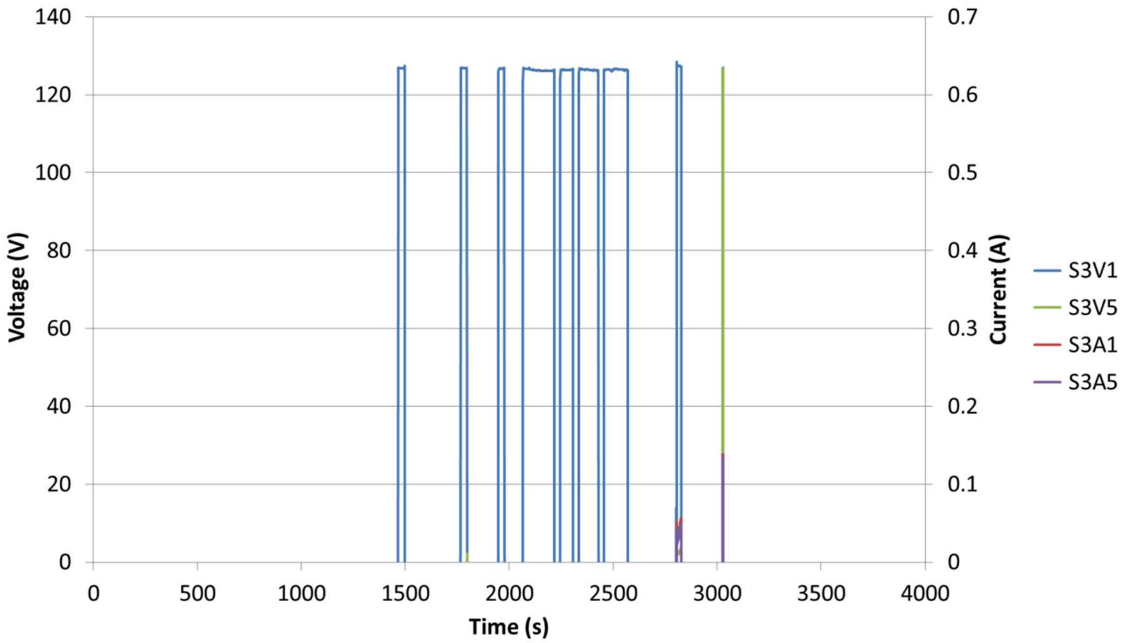

Figure F-37: SCDU module 3 response data for test Flamemastic 2.

F.12 **Flamemastic 3**

Table F-11. Flamemastic 3 - parameters and sequence of events

Test Parameters	
Test Name	Flamemastic 3
Test Date	4/22/2014
Coating	Flamemastic
Sequence of events	
Time to Cable Ignition	35.7
Time to SCDU 1 failure	39.7
Time to SCDU 2 failure	41.7
Time to SCDU 3 failure	48.7

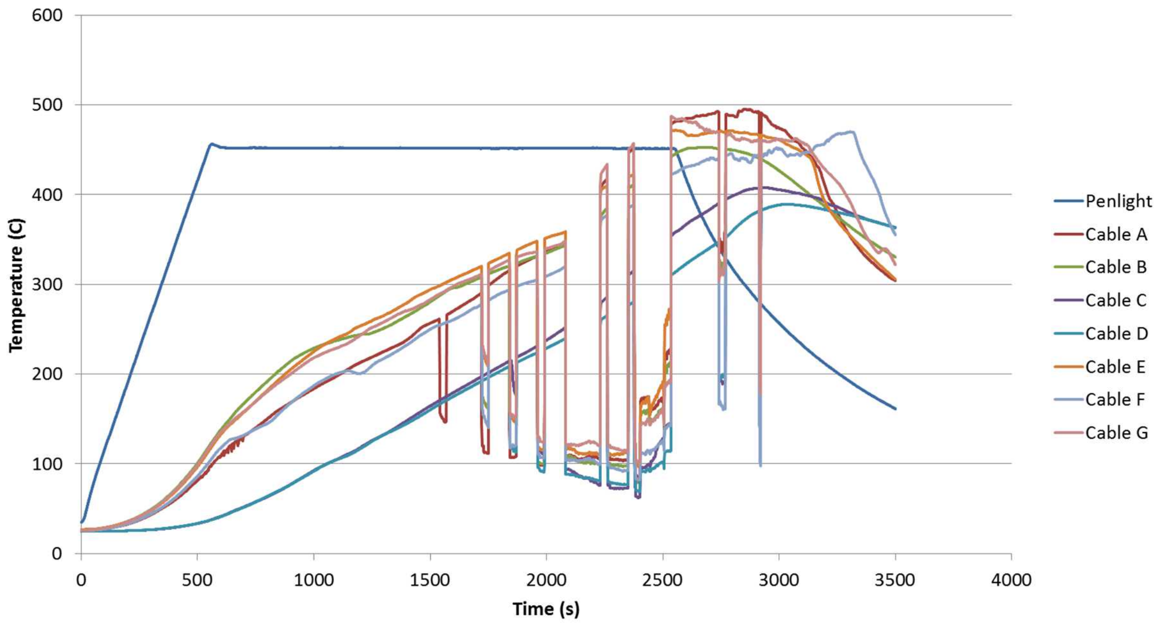

Figure F-38: Thermal response data for test Flamemastic 3.

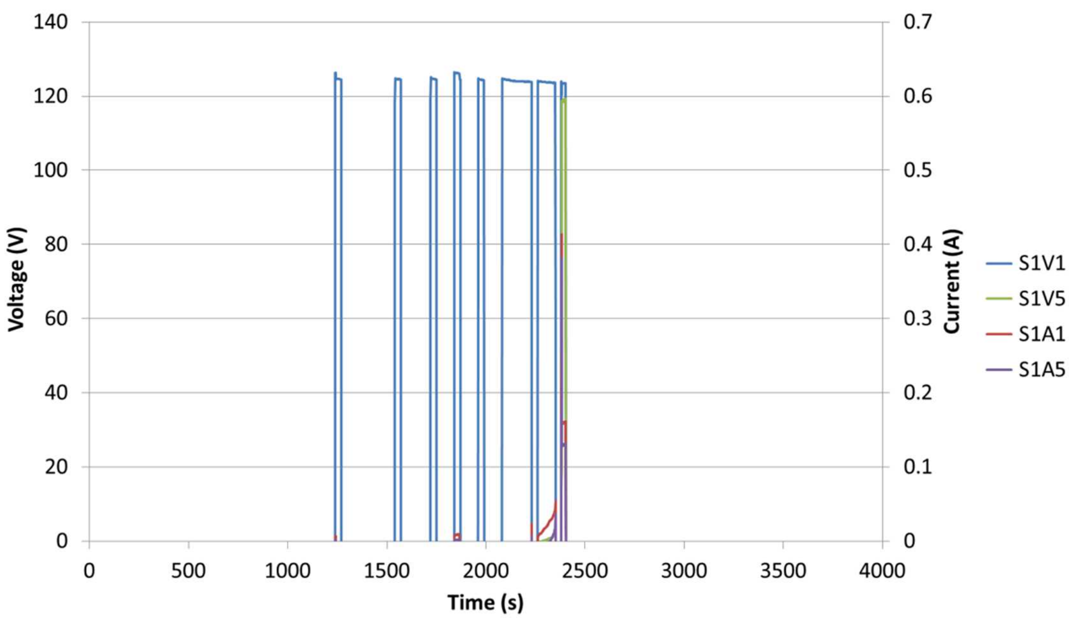

Figure F-39: SCDU module 1 response data for test Flamemastic 3.

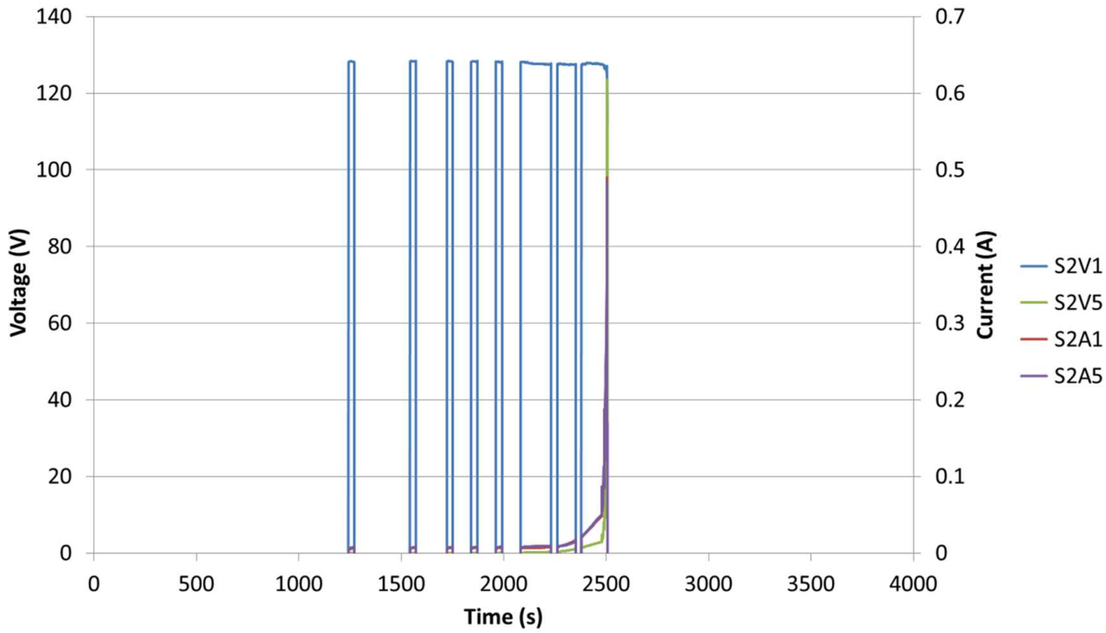

Figure F-40: SCDU module 2 response data for test Flamemastic 3.

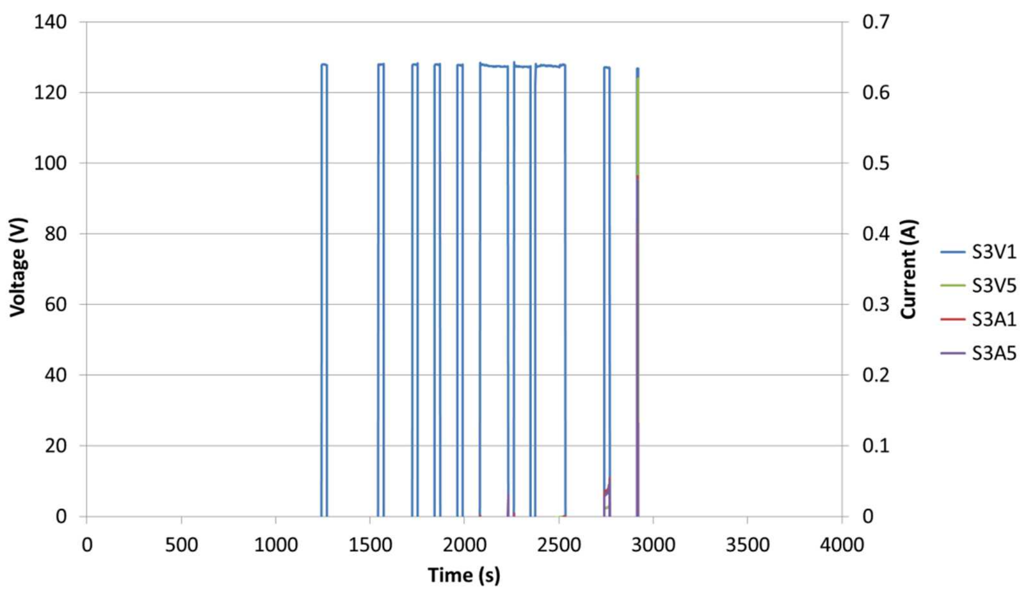

Figure F-41: SCDU module 3 response data for test Flamemastic 3.

F.13 **Carboline 1**

Table F-12. Carboline 1 - parameters and sequence of events

Test Parameters	
Test Name	Carboline 1
Test Date	4/21/2014
Coating	Carboline
Sequence of events	
Time to Cable Ignition	69.3
Time to SCDU 1 failure	69.3
Time to SCDU 2 failure	70.4
Time to SCDU 3 failure	DNF

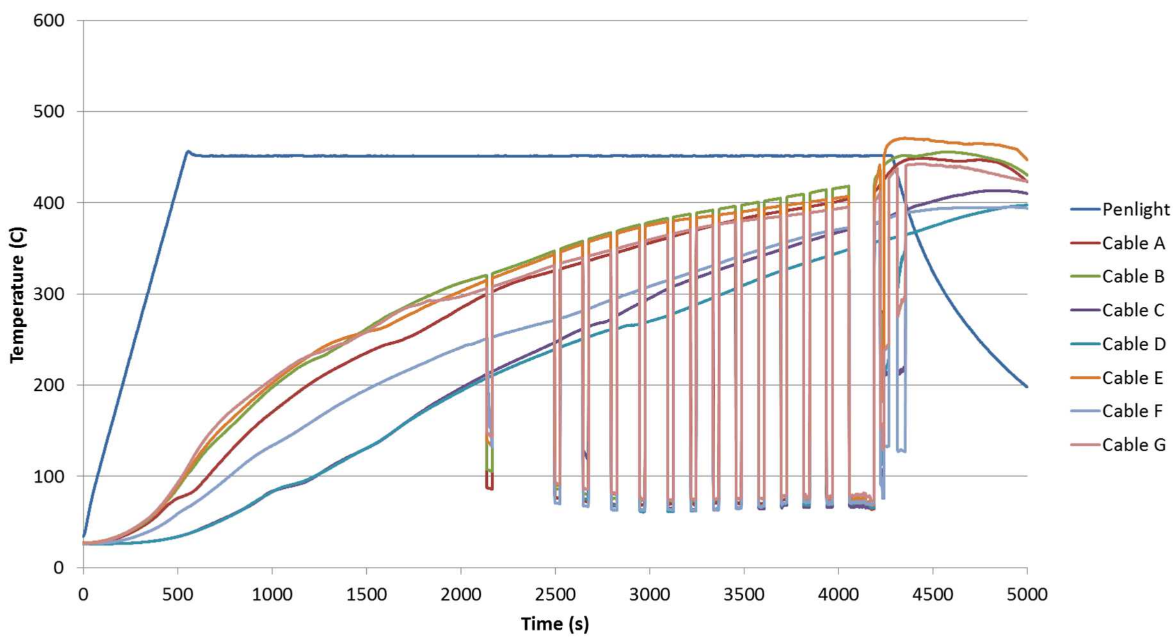

Figure F-42: Thermal response data for test Carboline 1.

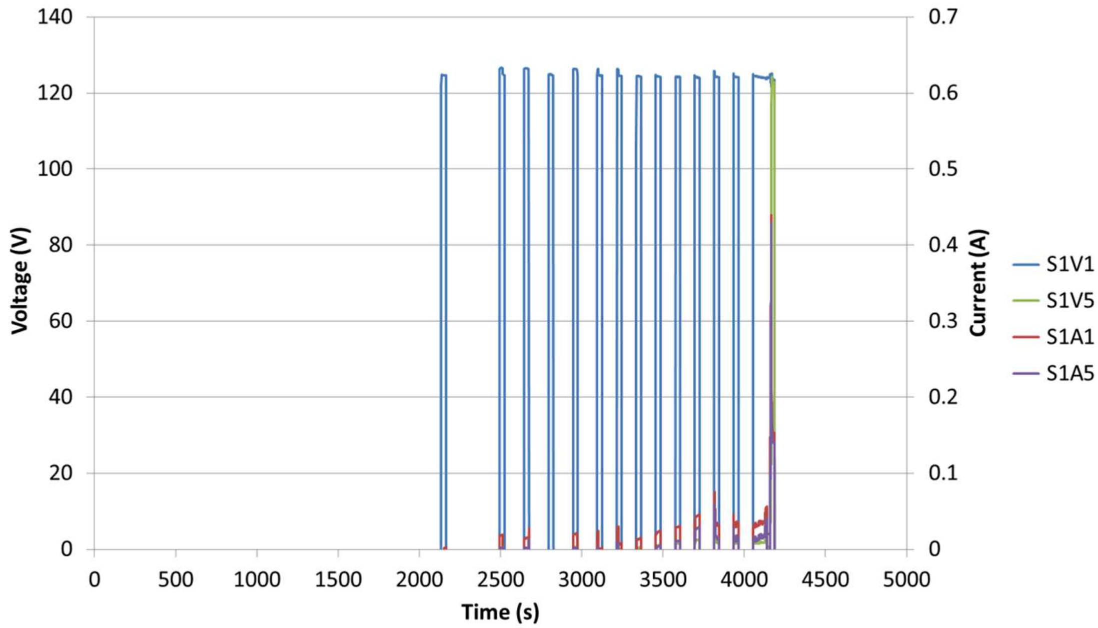

Figure F-43: SCDU module 1 response data for test Carboline 1.

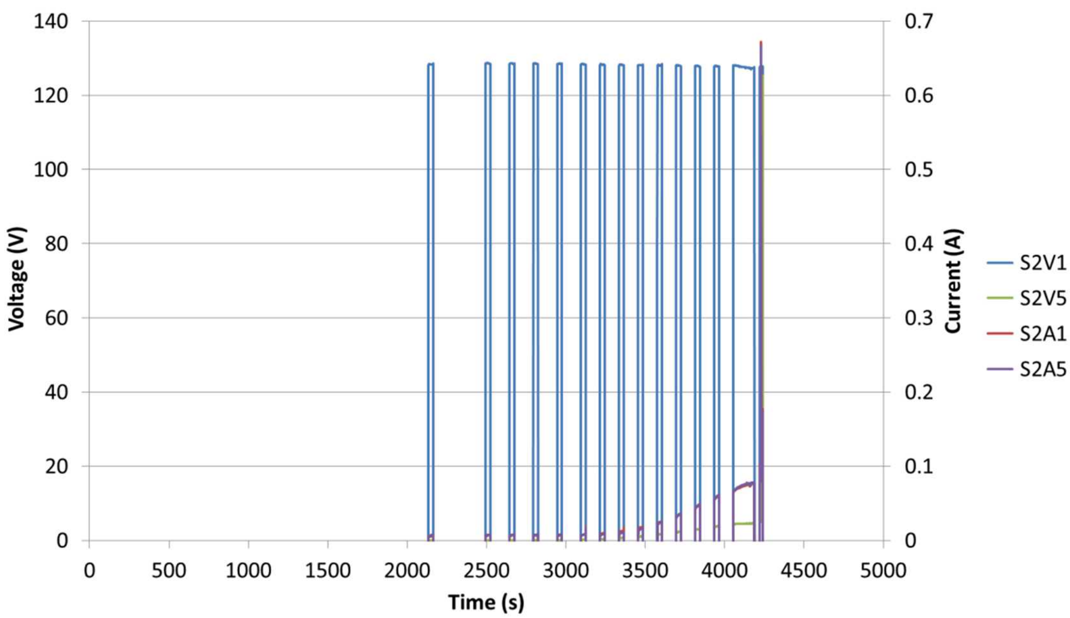

Figure F-44: SCDU module 2 response data for test Carboline 1.

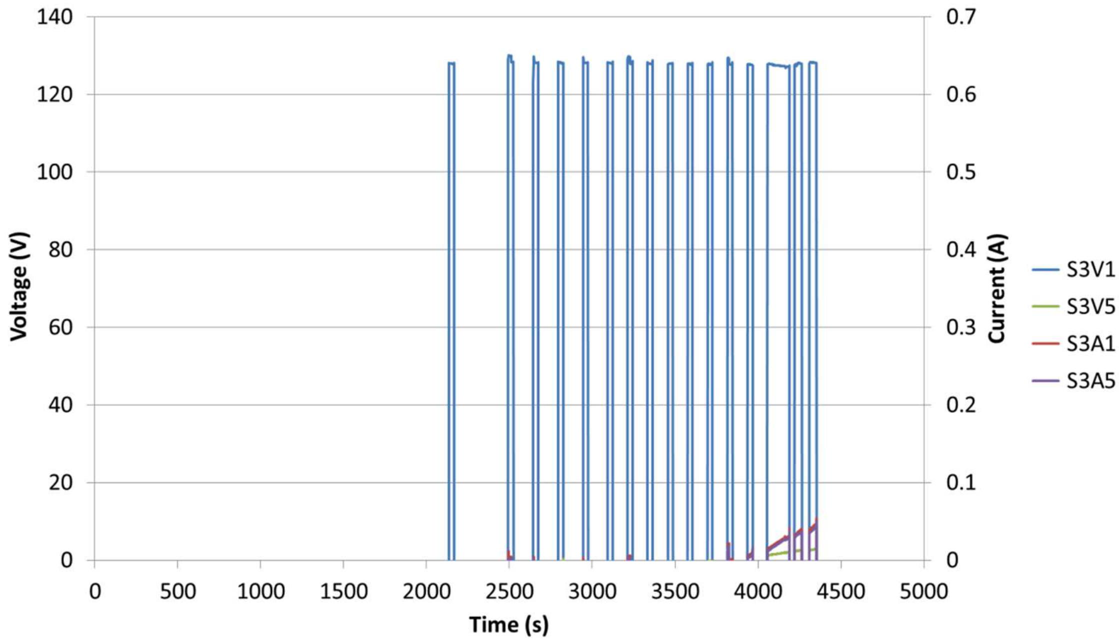

Figure F-45: SCDU module 3 response data for test Carboline 1.

F.14 Carboline 2

Table F-13. Carboline 2 - parameters and sequence of events

Test Parameters	
Test Name	Carboline 2
Test Date	4/22/2014
Coating	Carboline
Sequence of events	
Time to Cable Ignition	57.2
Time to SCDU 1 failure	59.0
Time to SCDU 2 failure	62.0
Time to SCDU 3 failure	76.2

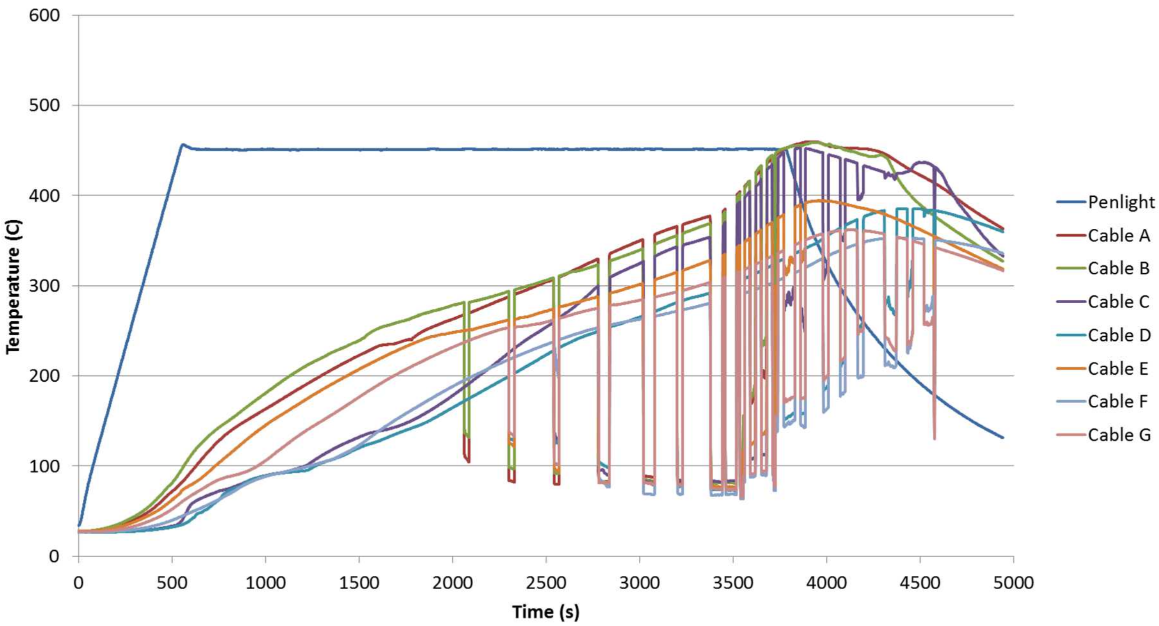

Figure F-46: Thermal response data for test Carboline 2.

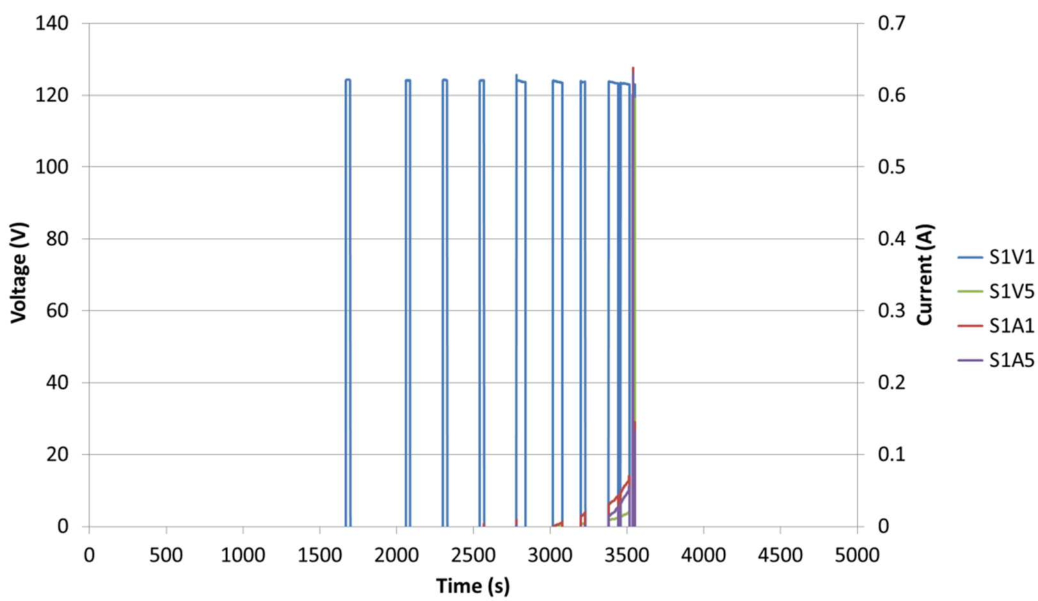

Figure F-47: SCDU module 1 response data for test Carboline 2.

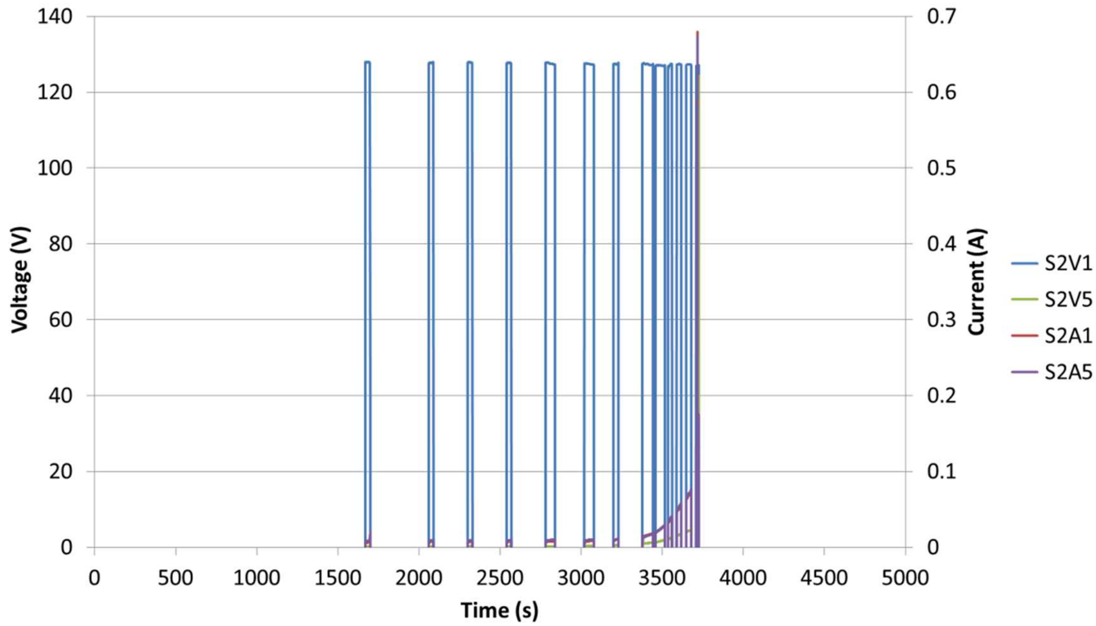

Figure F-48: SCDU module 2 response data for test Carboline 2.

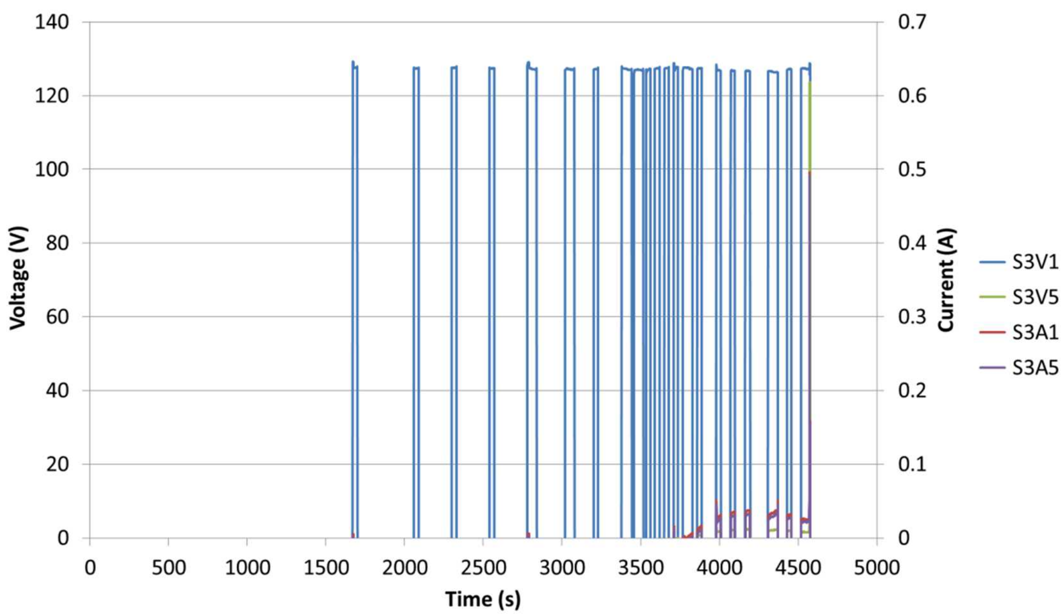

Figure F-49: SCDU module 3 response data for test Carboline 2.

F.15 **Carboline 3**

Table F-14. Carboline 3 - parameters and sequence of events

Test Parameters	
Test Name	Carboline 3
Test Date	4/21/2014
Coating	Carboline
Sequence of events	
Time to Cable Ignition	53.2
Time to SCDU 1 failure	60.1
Time to SCDU 2 failure	66.0
Time to SCDU 3 failure	DNF

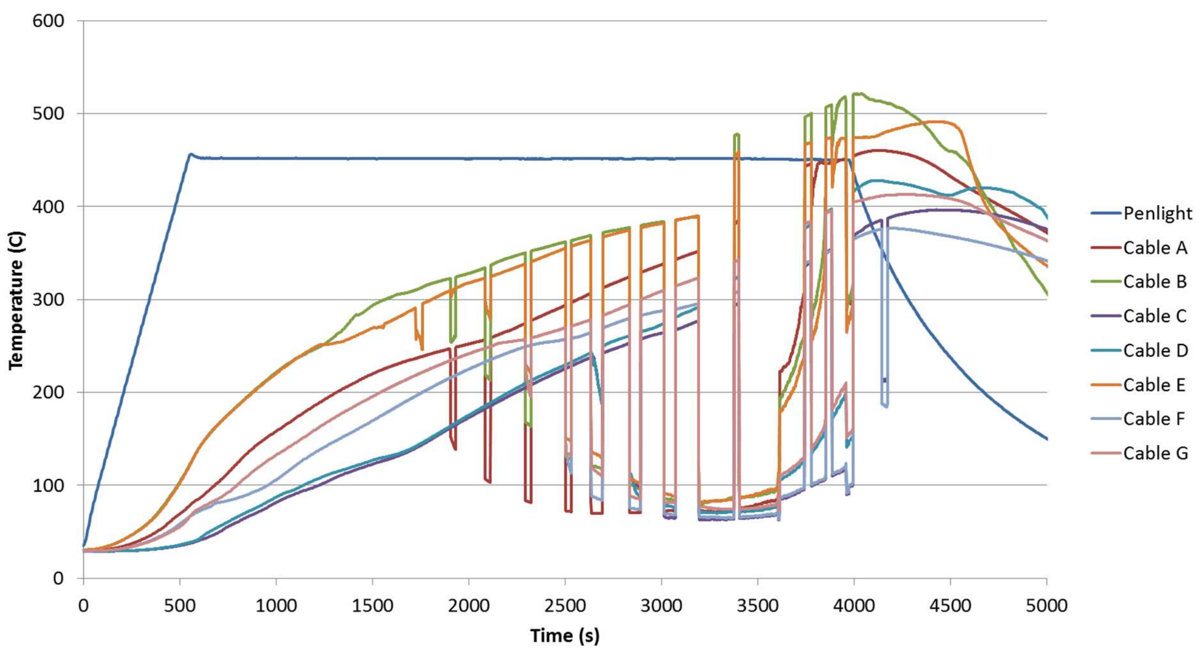

Figure F-50: Thermal response data for test Carboline 3.

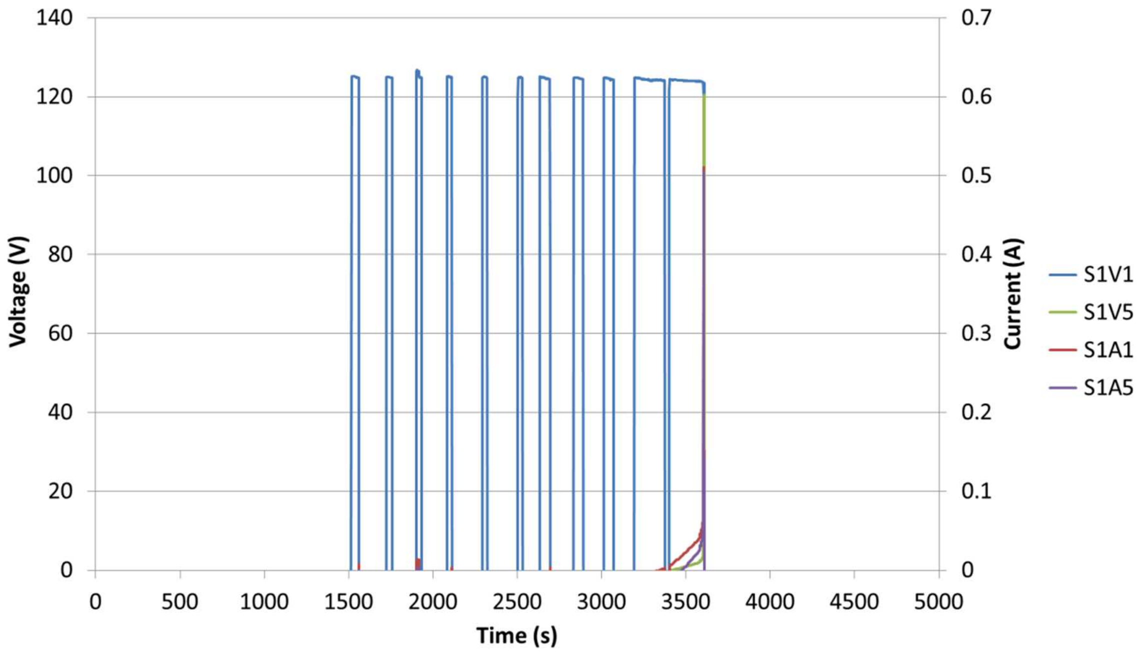

Figure F-51: SCDU module 1 response data for test Carboline 3.

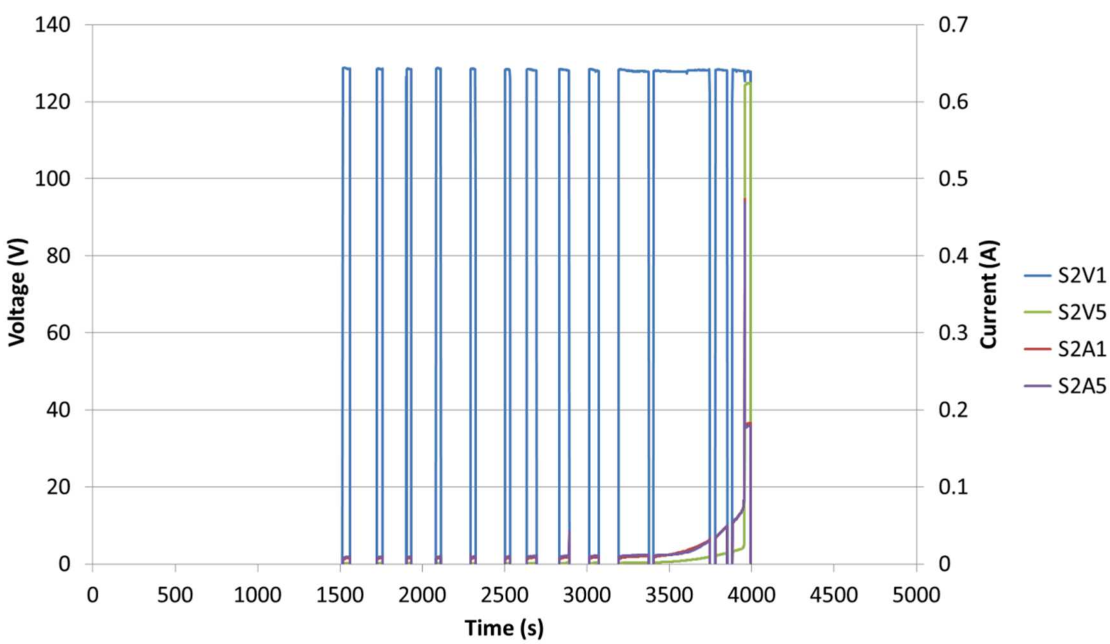

Figure F-52: SCDU module 2 response data for test Carboline 3.

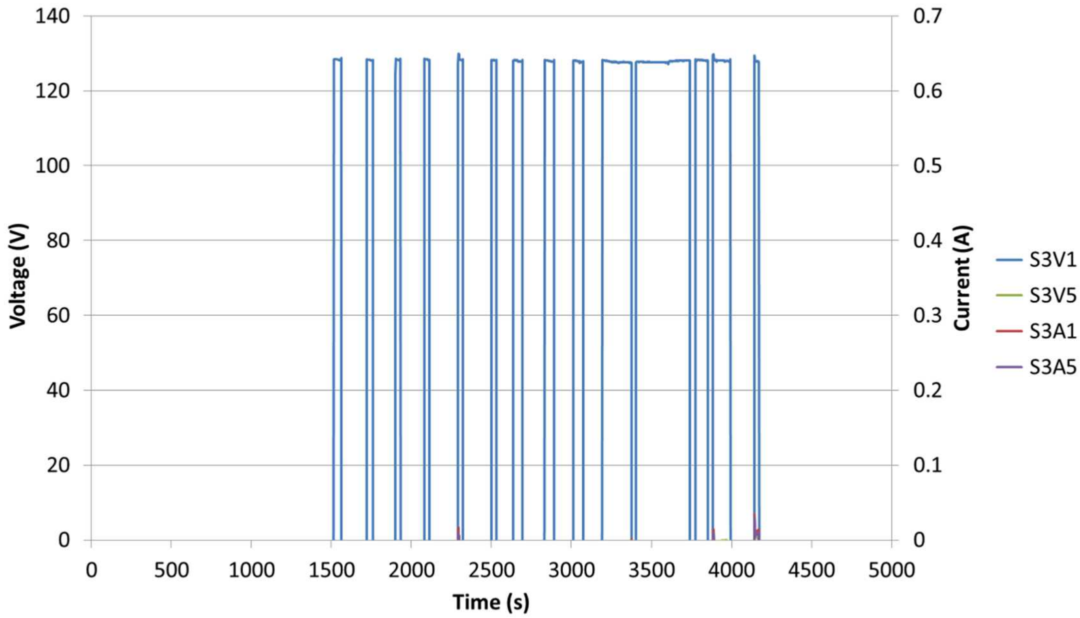

Figure F-53: SCDU module 3 response data for test Carboline 3.