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A Preliminary Look at the Fire-Induced Electrical Failure Behavior of Kerite® FR Insulated Electrical Cables

A Letter Report to the U.S. NRC/RES

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A Preliminary Look at the Fire-Induced Electrical Failure Behavior of Kerite® FR Insulated Electrical Cables

A Letter Report to the U.S. NRC/RES

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Abstract

This report presents the preliminary results of cable functionality tests conducted on the cable product marketed under the trade name Kerite FR. Kerite® FR is a thermosetting polymer, but prior testing had included at least one fire barrier fire endurance test that documented cable failure at relatively low temperatures compared to other known thermoset insulation materials. Hence, the actual performance limits of this material under fire exposure conditions were uncertain. The tests described here were conducted as a part of a much larger test program sponsored by the U.S. Nuclear Regulatory Commission. This preliminary assessment is based on small-scale radiant heating tests conducted in an apparatus known as Penlight. The results are considered preliminary and follow-up testing has already been scheduled. A more complete report on the material's performance will be prepared on completion of the planned follow-up tests.

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List of Acronyms

ac	alternating current
AWG	American Wire Gage
CAROLFIRE	Cable Response to Live Fire
CPT	Control Power Transformer
dc	direct current
DESIREE-Fire	Direct Current Electrical Shorting in Response to Exposure Fire Project
EPRI	Electric Power Research Institute
EQ	Equipment Qualification
JCN	Job Code Number
Kerite FR	A product trade name
Kerite HT	A product trade name
MOV	Motor Operated Valve
NEMA	National Electrical Manufacturer Association
NOS	New Old Stock
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
PORV	Power Operated Valve
PRA	Probabilistic Risk Assessment
SCDU	Surrogate Circuit Diagnostic Units
SCE&G	South Carolina Electric & Gas
SDP	Significance Determination Process
SOV	Solenoid Operated Valve

Executive Summary

This report describes the small-scale tests of Kerite® FR insulated cables that were completed as a part of the Direct Current Electrical Shorting in Response to Exposure Fire (DESIREE-Fire) test program. Previous tests have given conflicting results relative to the material's thermal failure threshold. The preliminary results from the DESIREE-Fire program were also inconsistent, but have led to a working hypothesis that could explain the observed behavior.

Kerite® FR is identified by the manufacturer as an "extruded thermosetting vulcanized flame retardant synthetic rubber" [1]. Kerite® FR is considered a thermosetting material as opposed to a thermoplastic material. Thermosetting materials generally provide a higher degree of thermal resistance (i.e., higher thermal failure limits) than do thermoplastic materials.

At least one prior test program [1] reported Kerite® FR cable failures at relatively low temperatures during raceway fire barrier certification tests. In one case Kerite® FR insulated cables failed during a test where the maximum temperature recorded within the protected raceway was just 184ºC. In a second case cable failures were recorded where the maximum temperature measured was 329ºC. Failure at temperatures this low would be considered unusual for a thermosetting cable insulation material [1]. In contrast, other prior tests [2] have indicated acceptable performance of Kerite® FR cables during equipment qualification tests (superheated steam exposures) to far higher temperatures; that is, cable temperatures of 372ºC or more which is more consistent with the typical behavior of thermosetting cable insulation materials.

Based largely on evidence of fire damage at relatively low temperatures as cited in Reference 1, the recommended current practice for fire Probabilistic Risk Assessment (PRA) applications, including the Nuclear Regulatory Commission's (NRC's) Significance Determination Process (SDP), is to treat Kerite® FR cables using the damage criteria associated with thermoplastic cables. The lower bound failure temperature for thermoplastic cables as recommended by the consensus fire PRA methodology [3] is 205ºC. Questions have been raised as to whether this recommended treatment is overly conservative or truly reflective of the material behavior.

The preliminary Kerite® FR cable tests described in this report also gave varied results. In one test the sample cable experienced outright failure of the test circuit at relatively low temperatures (i.e., 285-287ºC). During other tests the sample cables showed varying degrees of electrical degradation at the lower temperatures (i.e., in the 250-300ºC range), but did not experience outright failure until much higher temperatures (i.e., 390ºC or higher). A working hypothesis that still needs to be validated has been developed that would explain these results. Follow-on testing has already been scheduled that will seek to resolve the remaining uncertainties (see NRC JCN N6959).

First, it should be noted that the recent tests demonstrate that, in a purely physical sense, Kerite® FR is a thermosetting polymer, not a thermoplastic. There were no signs in any of the tests that the Kerite® FR material melts, which is the defining behavior of a thermoplastic polymer. The Kerite® FR material behaved much like a typical thermoset material in terms of its physical response – no melting but rather charring and ignition at higher temperatures.

Second, the testing showed no evidence of substantive cable degradation below cable temperatures of about 250ºC. Hence, this value can likely be taken as a lower-bound estimate of the cable's failure threshold (i.e., in lieu of the generic 205ºC thermoplastic failure threshold from the consensus methodology). Above 250ºC, the cable performance remains uncertain.

These two points aside, the material's electrical performance is more complicated than simply classifying the material as a thermoset and assuming corresponding performance. Thermoset insulation materials are generally expected to provide adequate electrical performance to

temperatures of at least 330°C [3]. Many of the common thermoset insulation materials show failure thresholds of 380ºC or higher [3]. In contrast, even the more robust thermoplastics (e.g., Tefzel®, a Teflon-based insulation material) will fail at temperatures of about 288-295ºC [4]. Based on the test described here two distinct fire-induced failure modes may be active for the Kerite® FR cables:

- A low temperature failure mode appears to be active when the cable temperature is 250-300°C. This was reflected in the tests by an outright circuit failure (spurious actuation) in one test and as signs of substantive electrical degradation that fell short of outright failure in all of the other ac-based circuit tests performed.
- A higher temperature failure mode is clearly active at temperatures at 390°C or higher. This second failure mode parallels the behavior of many other thermosetting materials which experience a gross breakdown of material electrical insulating properties at these temperatures including the onset of open flaming or smoldering combustion.

The working hypothesis is that the low temperature failure mode is caused by the formation of cracks in the conductor insulation which then fill with an internal liquid material that also forms during the heating process. Both elements of this hypothesis are based on direct observations. The presence of insulation cracks in cable samples heated to about 320ºC was verified during post-test examination of various cable samples including the one cable sample that had experienced an outright lower-temperature circuit failure (i.e., at 285-287ºC). A liquid material was seen oozing from the cable ends during the heating process for all of the tested cable samples. Assuming that the liquid material is electrically conductive, it could easily form conductive paths between conductors with cracked insulation. The properties of the liquid material have not yet been evaluated but will be investigated during the planned follow-up testing.

The lower temperature failure mode will likely be associated with some degradation of electrical performance for any exposed Kerite® FR insulated cable, but may or may not cause gross circuit failures. If the cable passes through this low temperature failure mode without experiencing enough degradation to cause circuit failure, then the second high temperature failure mode would remain active and electrical failure would occur when the cable exceeds about 390°C.

For the lower temperature failure mode, the active factor determining whether the cable experiences outright failure or some degree of degradation short of outright failure may be a somewhat random aspect of the cracking behavior; namely, the relative proximity of the cracks formed in the insulation of different conductors. Two possible cases are as follows:

- If two conductors experience cracks that are in close proximity to each other (i.e., along the cable length) then outright circuit failure would be likely. This was, in fact, the case for the early circuit failure observed in test 13-qual. During post-test inspection, two adjacent conductors were found with co-located circumferential through-cracks in their insulation.
- If two conductors develop insulation cracks, but those cracks are not in close proximity, then some electrical degradation would be experienced, but the resistance of the short circuit path may not be low enough to induce an outright circuit failure. This appeared to be the case for the cable from Test 15 which also went through a post-test examination. For that cable, numerous cracks through the insulation of various conductors were observed, but none were in close proximity to each other.

1 Introduction

1.1 Background

The Nuclear Regulatory Commission (NRC) sponsored Direct Current Electrical Shorting in Response to Exposure Fire (DESIREE-Fire)[1] project was an effort to examine cable failure modes and effects for dc-powered control cables. The program included limited testing of Kerite® FR insulated cables. This trade name product is no longer available on the electrical cable market, but was used by some U.S. nuclear power plants during their original construction and remains present in an undetermined fraction of the U.S. commercial nuclear power plant (NPP) fleet.

There has been uncertainty relative to this material's performance at fire-induced elevated temperature conditions. At least one industry fire barrier test [1] noted Kerite® FR cable failures at relatively low temperatures (i.e., at or below 184ºC for one test sample and 329ºC for another). In contrast, equipment qualification (EQ) tests [2] have shown adequate performance up to 372°C or higher.

Kerite® FR is identified by the manufacturer as an "extruded thermosetting vulcanized flame retardant synthetic rubber" [1]. The designation "FR" is thought to stand for either "fire resistant" or "flame retardant" depending on the source consulted. Kerite® FR is a thermosetting material and, in general, thermosetting cable insulation materials are expected to provide adequate electrical performance to temperatures of at least 330ºC [3]. Hence, evidence of potential Kerite® FR failures at lower temperatures is unexpected.

Also note that a second relatively common Kerite cable product called Kerite® HT (or HTK) has also been used by industry. The designator "HT" is thought to refer to "high temperature." There have been no corresponding indications of unexpected behavior with the Kerite® HT products.

1.2 Purpose and Scope

This report provides a preliminary look at the Kerite cable failure tests performed as a part of the DESIREE-Fire project. The discussions focus on the fire-induced electrical failure behavior observed for three vintage Kerite® FR insulated and jacketed cables. One sample of a Kerite® HT insulated cables has also been tested and those results will be discussed briefly.

All of the tests used multi-conductor cables. All of the Kerite® FR cables were control cable type configurations. The Kerite® HT insulated sample was a light power cable. Samples for testing were all provided by industry from available stocks of unused cable. Preliminary conclusions relating to material performance are provided.

While both small- and intermediate-scale tests have been performed, this report is based on the small-scale tests only because processing of the intermediate-scale tests has not yet been completed. The NRC has already established a follow-on testing program (JCN N6959) to further investigate the Kerite® FR failure behaviors. That program will include testing of at least five Kerite cable samples and will specifically investigate the behaviors noted during the preliminary tests described here. The follow-up test report will provide detailed descriptions for all of the Kerite tests including additional details for the tests described here.

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[1] NRC Job Code Number N6579.

2 The Kerite Cable Samples

2.1 Overview

As noted in Section 1, it is no longer possible to procure Kerite® FR cables from the manufacturer. Fortunately, the DESIREE-Fire project was performed in collaboration with industry as represented by the Electric Power Research Institute (EPRI) and its member utilities. It was through this collaboration that samples were obtained for testing. It is common practice for U.S. NPPs to retain unused excess cable stocks left over from the original plant construction for use in ongoing plant maintenance activities (e.g., for new cable routings or as replacement cables in the event of some cable damage). Vintage unused (new old stock or NOS) cables originally procured in the late 1970's and early 1980's were provided by two EPRI member utilities; namely, South Carolina Electric & Gas (SCE&G) and Progress Energy.

Note that after completion of the small-scale DESIREE-Fire testing, several additional cable samples were made available by industry. These other cables will be included in the follow-up testing, but were not included in the small-scale DESIREE-Fire tests described in this report.

2.2 Cables Provided by SCE&G

SCE&G initially provided Kerite cables in three configurations; namely:

- **10-conductor, 12 AWG[2] (or 10/C-12AWG – Item 1):** This cable is a Kerite® FR insulated and jacketed control cable. The jacket is approximately 2 mm thick with a spiral-wound zinc tape directly beneath the jacketing material. Two counter-wrapped spiral-wound fabric strips separate the insulated conductors from the zinc tape. Eight insulated conductors surround a center bundle of two conductors with filler materials in the gaps created by this geometric configuration. The center bundle also has a separate fabric wrap. The conductor insulation is approximately 1 mm thick. Kerite® FR insulated and jacketed control cable with shield wrap (item 1)[3],
- **5/C-12AWG cable (item 2):** This cable is a Kerite® FR insulated and jacketed control cable. The jacket that is approximately 1.65 mm thick. Similar to item 1, a zinc tape is spiral-wound directly beneath the jacketing material and two fabric wraps separate the insulated conductors from the zinc material. The five insulated conductors surround a central core of filler material. The conductor insulation is approximately 1 mm thick.
- **3/C-6AWG cable (item 3):** This cable is a Kerite® HT insulated, Kerite® FR jacketed light power cable. The jacket is approximately 1.65 mm thick. Unlike the first two cables, this cable did not have a zinc wrap and had only one wrap of fabric between the outer jacket and the insulated conductors. The Kerite® HT conductor insulation was approximately 1.4 mm thick. Filler materials were similar to those used in both the 10/C and 5/C cables.

Note that the first two cables use the Kerite® FR insulation and the third, the 3/C-6AWG cable, uses Kerite® HT insulation. The cable specification information provided in Table 1 was derived from the SCE&G "Bill of Material" sheets. Figure 1 provides a cross-sectional view of the three Kerite cables from SCE&G and Figure 2 illustrates the layers of cloth wrap, zinc tape, and other filler materials for each of the three cables.

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[2] AWG – American Wire Gage

[3] For convenience, the cables tested are identified using an "item number"; i.e., "item 1" through "item 4"

Table 1: Kerite cables supplied by SCE&G and tested in Penlight.

ITEM	DESCRIPTION	QTY (ft)	DESCRIPTION OF MATERIAL
1	12 AWG, 10/C, Zinc Wrap, Outer Diameter 1.06" max	150	10/C, 12 AWG stranded, 40 mils FR insulation (printed colors), cabled, zinc tape, 80 mils FR jacket Class B stranding, copper tin-coated conductor.
2	12 AWG, 5/C, Zinc Wrap, Outer Diameter 0.74" max	100	5/C, 12 AWG (7 strands), 40 mils FR insulation (printed colors), cabled, zinc tape, 65 mils FR jacket Class B stranding, copper-tin coated conductor.
3	6 AWG, 3/C, Outer Diameter 0.87" max	100	3/C, 6 AWG, stranded 55 mils HT Kerite insulation, (printed colors), cabled, 65 mils FR jacket (printed), Class B stranding, copper conductor.

Figure 1: Cross sectional view of the first three SCE&G Kerite® cables.

Figure 2: Exploded view of the sub-jacket materials for the first three Kerite® cable samples.

2.3 Cable Provided by Progress Energy

Near the end of the DESIREE-Fire small-scale testing efforts, two additional Kerite® cables were provided by Progress Energy through the EPRI collaboration. Small-scale tests were included at the end of the DESIREE-Fire small-scale matrix for one of these two cables. These were, again, NOS cables that in this case were originally procured in 1975. The configuration of the tested cable is summarized as follows:

- **9/C-14AWG control cable (item 4):** This cable is a Kerite® FR insulated and jacketed control cable. The jacket is approximately 1.65 mm thick and is red in color. Beneath this jacketing material is one layer of fabric wrap which surrounds the eight outermost conductors. There is one center conductor that is surrounded by filler material which stabilizes the circular pattern. The conductor insulation is approximately 1.27 mm thick.

Table 2 provides cable specification information as provided by Progress Energy. Figures 3 and 4 provide a cross-sectional view and an exploded view of cable respectively.

Table 2: Kerite cables provided by Progress Energy.

ITEM	DESCRIPTION	QTY (ft)	DESCRIPTION OF MATERIAL
4	14 AWG, 9/C, Outer Diameter 0.85" max	150	9/C cable: Kerite Cable, Control, 600V, 9/C#14 AWG, 50 mils FR insulation, 65 mils red FR jacket, max. O.D. 0.85"FPD code EK19J, Certified to Franklin Institute Report #F-C4020-2, DTD 3/75.

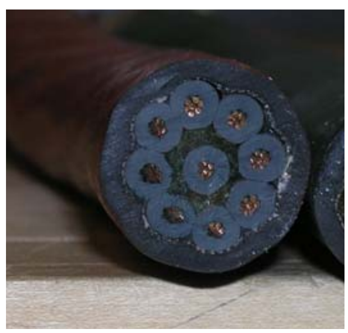

Figure 3: Cross-section of the tested Kerite sample cable from Progress Energy.

Figure 4: Exploded view of the tested Kerite cable from Progress Energy.

3 Test Conditions

The equipment and physical test configurations used for the Kerite® FR tests are essentially identical to those used during the *Cable Response to Live Fire (CAROLFIRE)* project [4], an NRC-sponsored experimental program investigating ac-powered control circuits and their response to fire-induced cable failure. As in CAROLFIRE, two scales of testing were conducted. Volume 2 of the CAROLFIRE report [4] provides a detailed description of both the small-scale and intermediate-scale tests facilities and the general test protocols applied. This report only discusses the small-scale Kerite tests because data processing for the intermediate-scale tests is not yet complete.

Most of the small-scale Kerite tests used the ac-powered surrogate circuit diagnostic units (SCDUs) developed as a part of the CAROLFIRE project. The last three tests used the dc-powered surrogate motor operated valve (MOV) control circuits developed for DESIREE-Fire.

The following three subsections provide a brief overview of the small-scale test facility and the diagnostic instrumentation used. The reader should refer to the CAROLFIRE report [4] and to the DESIREE test plan[4] for more complete descriptions.

3.1 Small-Scale Radiant Heating Apparatus

The small-scale tests for DESIREE-Fire were conducted at the Thermal Test Complex at Sandia National Laboratories in Albuquerque, NM using a radiant heating apparatus known as "Penlight." The Penlight apparatus is placed beneath a ventilation hood within the Adverse Thermal Environments Laboratory, as shown in Figure 5.

Figure 5: The Penlight apparatus.

Penlight uses computer-controlled, water-cooled quartz lamps to heat a stainless steel shroud. The shroud is painted flat-black and acts as a grey-body radiant heating source, re-radiating heat

[4] The test plan has not been published but is available as an NRC public document and can be obtained through the ADAMS system at http://adamswebsearch.nrc.gov/scripts/securelogin.pl by searching for ML082520518 (the ADAMS accession number).

to a test sample located within the shroud. The exposure temperature is controlled and monitored based on thermocouples mounted on the inner surface of the shroud. Penlight creates a, primarily, radiant heating environment which is analogous to that seen by an object enveloped in a fire-induced hot gas layer. 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.

All of the small-scale Kerite tests were conducted using paired cable lengths supported on a 12" (30 cm) wide 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. For each cable pair in each test, one length of cable was instrumented with type-K thermocouples inserted just below the outer cable jacket to measure the cable temperature response. Additional lengths of cable were routed in symmetric positions on the tray (relative to the shroud) and were connected to energized electrical integrity test circuits. This cable pairing approach allows for a direct correlation of temperature response and electrical performance without compromising the electrical integrity of the energized cable. The electrical integrity test circuits used varied between tests and test samples as described further below.

In most of the Kerite tests, the shroud temperature control set point was varied through the course of the test. That is, a test would be started at a particular set point value, but that value would be increased as the measured cable temperature approached equilibrium. Step-wise increases were continued at, typically, 10-15 minute intervals until cable failure was observed. The actual test profile is unique for each test.

3.2 AC Circuit Testing

One of the electrical performance monitoring systems used in testing is the Surrogate Circuit Diagnostic Units (SCDUs) originally built for use in CAROLFIRE [4]. The basic SCDU circuit diagram is shown in Figure 6.

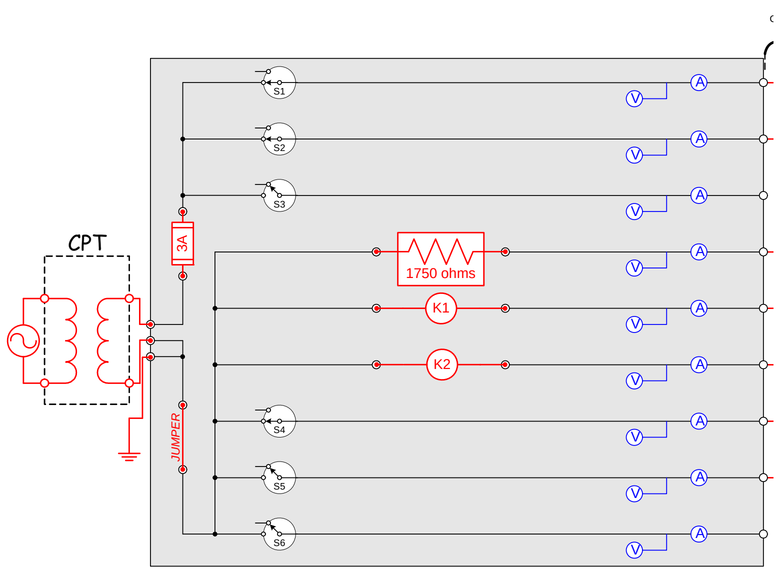

Figure 6: SCDU circuit diagram.

The SCDUs were nominally designed to simulate an ac-powered reversing MOV control circuit although an alternate configuration was used in the tests described here. All of the small-scale tests performed using the SCE&G cables utilized the SCDUs.

Four units were constructed, but only two were used during the Kerite tests. Each SCDU allows for the following circuit paths to be used:

- One, two or three (switch selectable) energized source circuit paths: These are generally referred to as ‘S1’ through ‘S3’ and are represented by the top three circuit paths in Figure 6.
- One passive target path: This target is a 1750Ω resistor nominally simulating an indicator lamp and is represented by the fourth circuit path from the top in Figure 6. This circuit path is generally referred to as ‘T4’ (for the target on circuit path 4).
- Two active target circuit paths: These are the two motor contactors shown as ‘K1’ and ‘K2’ in the circuit diagram. These are typically referred to as ‘T5’ and ‘T6’ (for the targets on circuit paths 5 and 6).
- One, two or three (switch selectable) circuit ground paths: These are represented by the bottom three circuit paths as shown in Figure 6. If one of these circuit paths is used in testing but with the selector switch open (not grounded) then the conductor on that circuit path would act as a monitored spare conductor (i.e., no circuit function but monitored for voltage and current).

All of the Kerite tests utilizing the SCDUs were run with a grounded ac power source with power provided through a 150Vac control power transformer (CPT).

One modification to the SCDU was made for these tests as compared to the CAROLFIRE tests. That is, the original motor starter relay sets used in CAROLFIRE were replaced by more representative Joslyn-Clark NEMA Class 0 motor starter relay sets. Other than this one change, the SCDU circuits and diagnostics are exactly as described in the CAROLFIRE report.

For the Kerite tests, the SCDUs were connected to allow for detection of either conductor-to-conductor or conductor-to-ground short circuit interactions. Details of each test are provided in Section 5.

In general, the test cable would be connected to either one or two energized source paths (S1 and/or S2) and to both of the active target circuit paths (T5 and T6). The wiring configuration was adjusted depending on the number of conductors present, but in general, the wiring resulted in adjacent conductors alternating between an energized source and an active target. Given this configuration, conductor-to-conductor shorting between any adjacent conductor pair would activate the associated target motor contactor. Conductor-to-ground shorting for any of the energized conductors would result in a fuse-blow failure.

In some tests one conductor was grounded. For these cases, a conductor-to-conductor short between and energized source and the grounded conductor would cause the circuit fuse to blow de-energizing the test circuit.

In all tests the cable tray and, if present, the zinc tape shield wrap (see cable descriptions above) were grounded. Grounding of the zinc tape is consistent with plant practice for SCE&G and is considered typical of general practice for cables of a similar construction (conductive shield wraps are generally grounded during installation). These grounded elements provided additional mechanisms for fuse-blow failure to occur; namely, shorts between any energized conductor and either the external cable tray or the zinc wrap.

3.3 The dc-Powered Surrogate Circuits

For DESIREE-Fire, several dc-powered surrogate control circuits were built specifically to support the testing of dc cable failure modes and effects. The test circuits are also described in detail in the DESIREE program test plan which is available through the NRC web site. Only the two dc-powered MOV control circuits were used in the small-scaled Kerite tests (referred to as MOV1 and MOV2). The other circuits were used during the intermediate-scale tests, but the analysis of those tests has not been completed and they are not covered by this report. Details of the test configurations used are provided in Section 5.

Figure 7 provides the wiring diagram for the MOV test circuit. The circuit is based on an actual pair of Joslyn-Clark NEMA Class 0 motor contactors that are mechanically and electrically interlocked.[5] The two contactors are identified in the diagram as red circles with the letter "C" for the "close" contactor and "O" for the "open" contactor. As shown in the diagram, the battery power supply is ungrounded. A ground fault detection system (not shown in this diagram) was installed in the battery system and all circuit voltages are measured relative to a common earth-ground. The wiring of the "cable under test" as shown on the right side of this figure is generally consistent with the Kerite tests, although the Kerite tests involved a 9/C cable (rather than a 7/C cable as illustrated here). The remaining two conductors were not connected to the test circuit. See Section 5 for additional details on the cable wiring configuration.

The dc-powered circuits receive their power from a bank of 60 lead-acid battery cells connected in series and producing a nominal 125Vdc output. The battery bank is shown in Figure 8. Power to the control circuits is nominally limited only by the short-circuit current output of the battery bank, but each circuit is also protected, in order, by a pair of 200A primary battery output fuses (one each on the plus and minus legs of the battery bank), a 30A dc double pole output feed breakers, and paired (plus/minus) circuit fuses. The breakers and fuses were coordinated so that the individual circuit fuses represented the primary fault protection for each circuit. The individual circuit fuse sizes were chosen based on typical industry practice for each of the circuit types tested (as provided via the EPRI collaboration). The two MOV circuits used 10A fuses.

[5] Note that it was determined after completion of testing that the "close" contactor on MOV2 was not functional. The contactor as supplied by the manufacturer was missing the moving core assembly against which the contactor coil acts to close the contacts. The coil itself was in place and functional (i.e., when energized the coil drew power consistent with normal operation), but the contactor was not capable of closing. As a result, there was no interlock active given actuation of the close contactor. The open contactor was fully functional and its activation would lock out the close contactor coil.

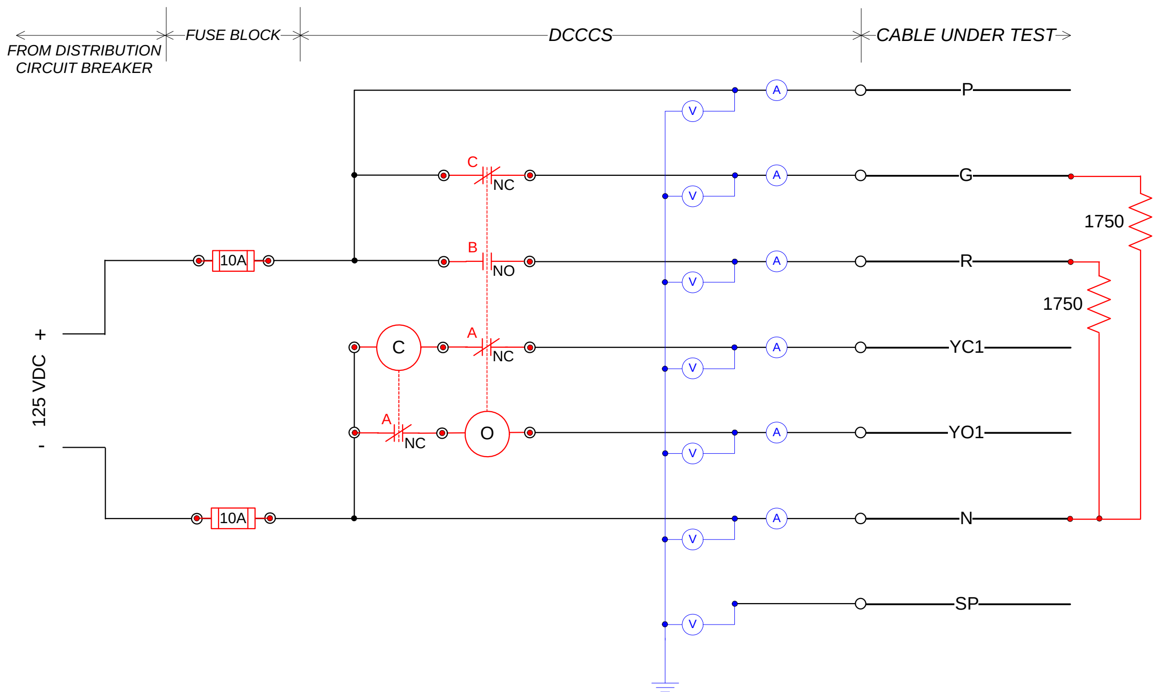

Figure 7: Wiring diagram for the dc-powered MOV circuits.

Figure 8: Photo of the battery assembly

4 The Matrix of Small-Scale Kerite Tests

Each of the Kerite sample cables is associated with a cable item number as described in Section 2. The cable conductor configuration and corresponding item numbers for the four cable types that were used in the small-scale tests performed to date are summarized in Table 3 for convenience. A total of 11 small-scale Kerite tests were performed as a part of DESIREE-Fire. A matrix summarizing these tests is presented in Table 4.

The small-scale tests were performed in two parts. The first eight tests ("13-qual" through 18) used the ac-powered SCDU system and the SCG&E cables. The last three tests (44, 49 and 50) were performed using the dc-powered surrogate MOV circuits and the Progress Energy cables.

Table 3: Summary of the Kerite cable configurations item numbers.

Item #	Conductor configuration	Insulation/Jacket type	Cable source
Item 1	10/C-12AWG	FR / FR	SCE&G
Item 2	5/C-12AWG	FR / FR	SCE&G
Item 3	3/C-6AWG	HT / FR	SCE&G
Item 4	9/C-14AWG	FR / FR	Progress Energy

Table 4: Kerite tests from the DESIREE-Fire small-scale test matrix.

Test ID	Tested Cable				Circuits Used
	Item 1	Item 2	Item 3	Item 4	
13-qual	X				SCDU 1
13		X			SCDU 1
	X				SCDU 2
14		X			SCDU 1
	X				SCDU 2
15		X			SCDU 1
	X				SCDU 2
16		X			SCDU 1
	X				SCDU 2
17-qual			X		SCDU 1
17			X		SCDU 1
			X		SCDU 2
18			X		SCDU 1
			X		SCDU 2
44				X	MOV1
				X	MOV2
49				X	MOV1
				X	MOV2
50				X	MOV1
				X	MOV2

5 Overview of Test Results

5.1 Overview

This Section provided an overview of the Kerite cable tests performed to date. The intent is not to provide a detailed description of every test performed, but rather, to highlight key aspects of the testing and test results as available. Again, this report is intended only to provides a preliminary look at the test results. A more complete treatment of the DESIREE-Fire data set, and a more complete investigation of the failure behavior including additional tests is planned as a part of follow-on activities to be performed under JCN N6959.

5.2 Test 13 - Qualification

Test 13 – Qualification (or more simply, 13-qual) was the first test performed with the Kerite® FR cables. The primary objective of test 13-qual was to explore the failure threshold of the first Kerite® FR cable sample in a relatively deliberate fashion. This test was staged with one cable pair (a thermal response cable and an electrical performance cable as described in Section 3), both taken from the 10/C-12AWG SCE&G cable (cable item 1). The numbering scheme for the conductors within the cable is illustrated in Figure 9 and the specific connections to the SCDU are described in Table 5.

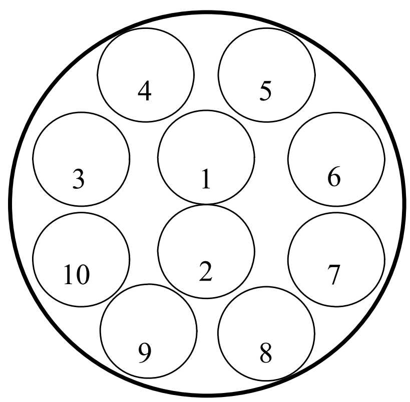

Figure 9: Conductor numbering scheme for the 10/C cable.

Table 5: Cable conductor connections to SCDU for Test 13-qual.

SCDU Circuit Path	Conductor Numbers (per Figure 9)
Energized Source (S1)	1
Energized Source (S2)	3, 5, 7, 9
Active Target (T5)	2
Active Target (T6)	4, 6, 8, 10

Note that conductors 1 and 2 (i.e., the two center conductors) as a pair were connected to a source and target circuit path pair on the SCDU. That is, conductor 1 is an energized source (S1) and conductor 2 is an active target (T5). The other conductors in the cable were connected in two groups of four, one group to the second energized source (S2) and the second group to active target (T6). With this wiring scheme, any two adjacent conductors represent a source-target pair. Hence, short circuits occurring between any two adjacent conductors would lead to a spurious operation of one of the two active targets. Although none of the conductors were grounded, the zinc wrap within the cable was grounded as was the cable tray. A short between a source conductor and ground would result in a fuse blow failure. The same wiring configuration was used for all small-scale tests of the 10/C cable (cable item 1).

The heating protocol began with a shroud temperature of 300°C which was increased twice in increments of 25°C (to a maximum of 350°C) over the course of approximately one hour. That is, as the cable temperature approached equilibrium conditions, the temperature of the shroud would be increased.

During this test, the cable experienced a conductor-to-conductor short circuit between two conductors on the outer ring resulting in actuation of the T6 target relay. A summary data plot is provided in Figure 10. Note in particular that the spurious actuation is indicated by the purple line in this plot which increases from zero to 120Vac suddenly at the time of failure. The data from the temperature response cable is also shown in Figure 10 including both the shroud temperature (black) and the two thermocouples inserted below the jacket of the thermal response cable (green "Top TC" and red "Side TC"). Note that the sub-jacket thermocouples were reading 285-287°C at the time of electrical failure.

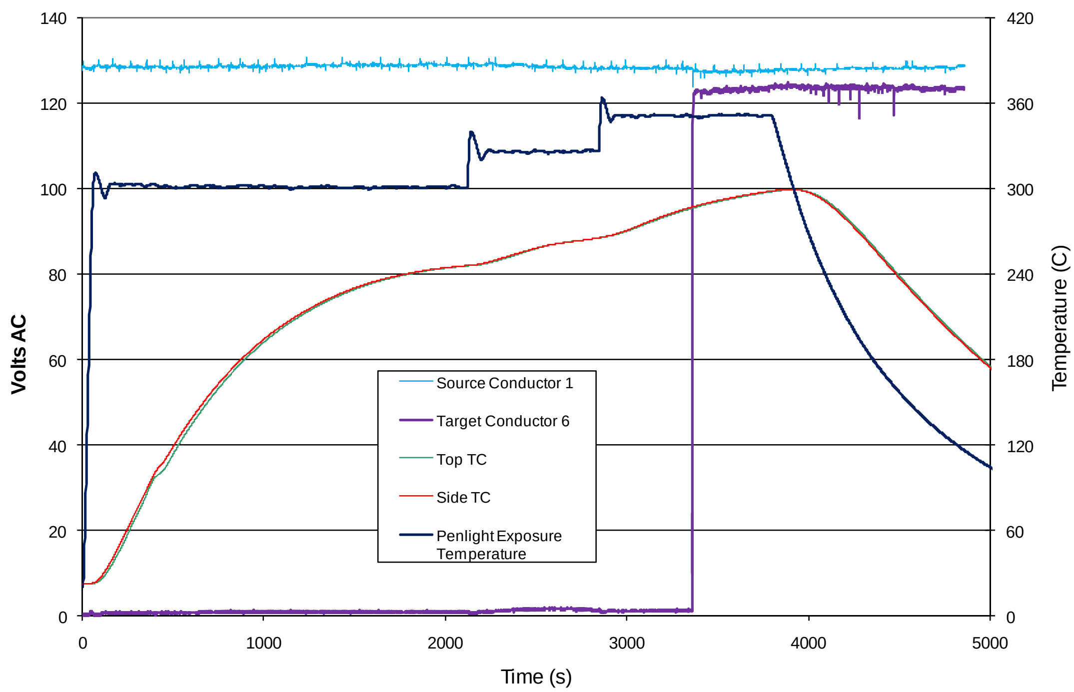

Figure 10: Electrical and temperature data for Test 13-qual.

The first signs of cable degradation were noted somewhat before the time of ultimate failure. This is best illustrated by the current data rather than by the voltage data for this case. The current for the S2 circuit path (C1A2) is shown in Figure 11. In order to emphasize the data trends, and to de-emphasize point to point variability, the raw current data have been plotted as a running average of five consecutive data points (i.e., the plot shows the simple average of the value at the actual time, the two previous values, and the two subsequent values). The first indications of a definite trend towards increasing leakage currents are seen at approximately 2200 s. At this point in the test, the measured cable temperature was 246-247ºC.

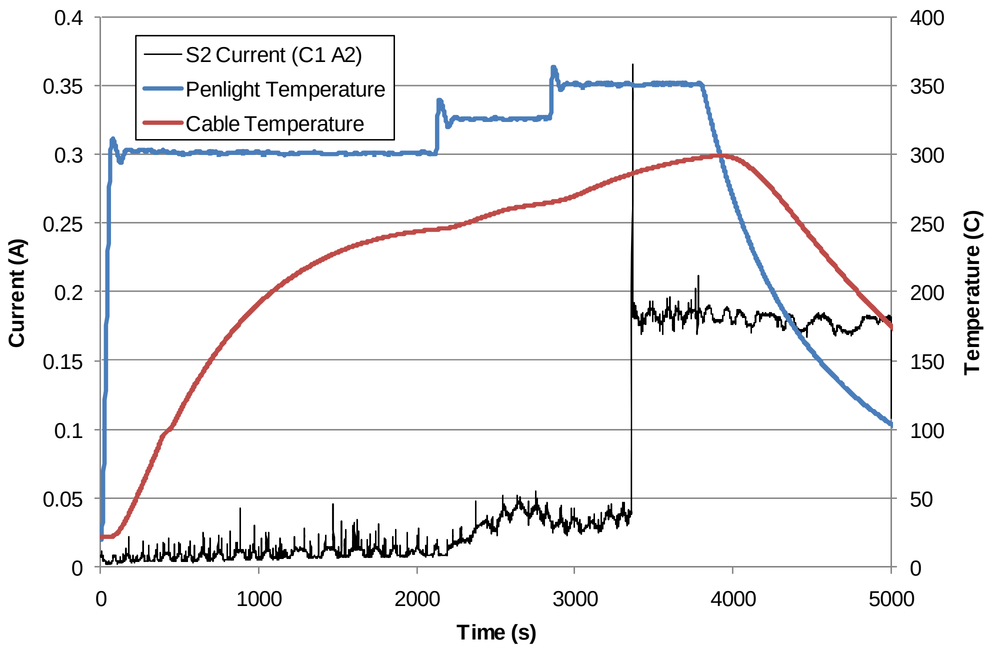

Figure 11: Source 2 Current data for Test 13-qual.

Figure 12 shows the paired test cables after completion of the test. The left-hand cable is the temperature response cable and the right-hand cable is the electrical performance cable. During this test, the cables did not ignite which allowed for a post-test examination to be performed.

Figure 12: Post-test photos of the Kerite cable in the initial experiment.

A post-test inspection of the electrical performance cable focusing on the center-most section of the tested cable was conducted. Given the geometry of the Penlight shroud, that part of the cable in that is located at the length-wise center of Penlight experiences the highest heat flux; hence, that is the most likely location for electrical failure.

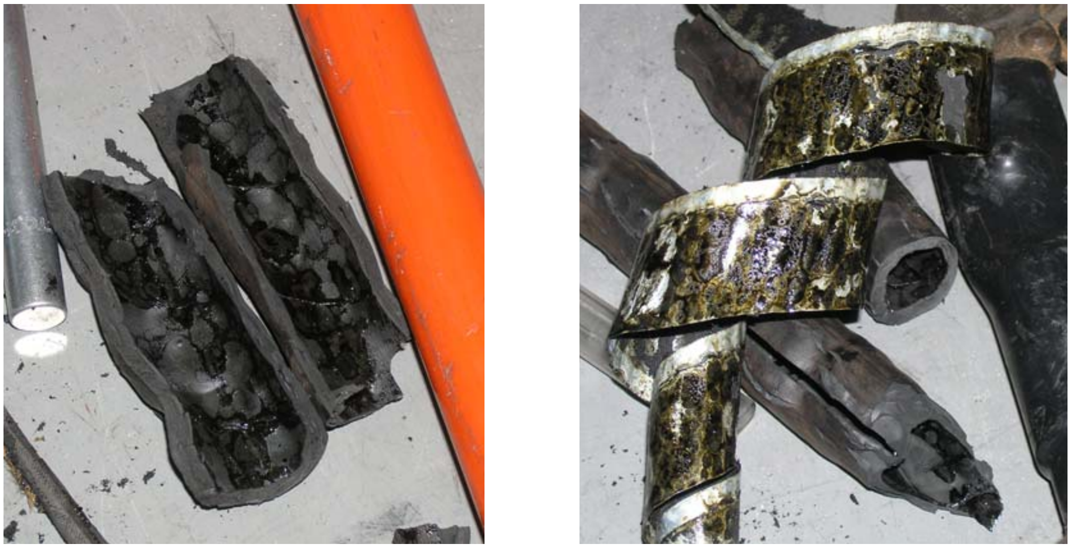

Figure 13: Oily residue found between the jacketing material and zinc wrap

As a first step, the jacket was separated from the cable. An oily residue was observed between the jacketing material and zinc wrap and again between the zinc wrap and the insulated conductor bundle. This is illustrated in Figure 13. Once the zinc wrap was removed, the cloth material over the conductor bundle was also removed. Throughout the heated portion of cable, conductors were observed to have both circumferential (Figure 14) and axial (Figure 15) cracking. In two conductors in particular, circumferential cracks through the insulation of both conductors were exactly aligned. The right-hand photo in Figure 14 shows these two adjacent conductors each with a circumferential crack at the same point along their length (visible below the edge of the razor knife in the center of the photograph). As discussed in Section 6, this alignment of insulation cracks in two adjacent conductors is thought to be an important aspect of the Kerite failure behavior.

Test 13-qual is important in that it is the only test performed to date that experienced an outright circuit failure at temperatures below 300ºC. However, as will be described further below other tests did show signs of substantive cable degradation, although not outright circuit failure, at very similar temperatures.

5.3 Other Penlight Tests using the SCDU

The second test of the Kerite cable, Test 13, was typical of the other small-scale Penlight tests performed using the ac-based SCDU system and will be used to illustrate the behavior observed in most of the other Penlight tests.

Figure 14: Circumferential cracking discovered during post-test analysis

Figure 15: Axial cracking observed during post-test analysis is visible as a dark line running along the right hand conductor near the center of the photo.

In Test 13, two sets of cable pairs were tested; namely, one pair of 10/C-12AWG cables (item 1) and one pair of 5/C-12AWG cables (item 2). The 10/C item 1 electrical performance cable was connected to SCDU unit 2 using the same wiring scheme used in test 13-qual (see Section 5.2). The conductor numbering scheme for the 5/C item 2 cable is shown in Figure 16 and the circuit corresponding circuit connections to SCDU unit 1 are identified in Table 6. Note that the wiring scheme for the 5/C cable creates source-target pairs between certain of the adjacent conductor pairs (i.e., conductor pairs 1&2, 2&3, 3&4) and it creates a source-ground pair between conductors 1&5. As is typical for all tests, the sub-jacket zinc wraps were grounded to the cable tray.

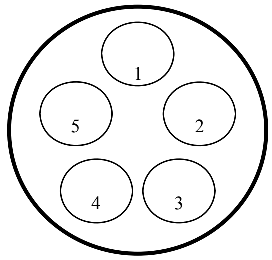

Figure 16: Conductor numbering scheme for the 5/C cable.

Table 6: 5/C conductor connections SCDU 1.

SCDU Circuit Path	Test Cable Conductor Numbers (per Figure 16)
Energized Source (S1)	1
Active Target (T5)	2
Energized Source (S2)	3
Active Target (T6)	4
Ground	5

Based on the results of Test 13-qual, the Penlight shroud was initially set to 350°C which was expected to induce electrical failure within 15-20 minutes. While the cable did not experience outright circuit failure (i.e., either a fuse blow or spurious actuation fault) at temperatures below 300ºC, as had the cable in Test 13-qual signs of electrical degradation were observed. The first signs of substantive degradation are again best indicated by the current trace for the S2 circuit path as illustrated in Figure 17. For reference, this figure also includes the measured voltage on T6. At approximately 1320s, both the voltage and current began notable trends of steady increase. At this time the corresponding temperature for the 10/C cable (item 1) was 264-265ºC. Also note that the S1 and T5 circuit paths show similar behavior.

The overall circuit fault and cable temperature data for 10/C cable in Test 13 are illustrated in Figure 18. At its peak, around 1471s, the voltage on the T6 conductor increased to approximately 12V (a bit less than 1/10 of the source voltage). In this case it is possible to estimate of the effective insulation resistance (IR) between the source and target conductor groups. The conductor-to-conductor electrical contact can be assumed to be purely resistive for this case. Hence, the effective IR can be calculated based on the voltage difference between the source and target cable and the corresponding current measurement for the target conductor.

The actual peak measured voltage on the T6 conductor was 12.4 V. Given a total source voltage of 128 V, the voltage drop between the source and target conductors was approximately 116 V. The corresponding current measured on the T6 circuit path was 0.19 A. Using these values[6], the effective insulation resistance can be estimated using Ohm's law as follows:

$$R \approx \Delta V / I = (116\text{ V}) / (0.19\text{ A}) = 610\ \Omega$$

[6] For reference, the cited voltage and current values are taken from the test data at the fire time 1571s.

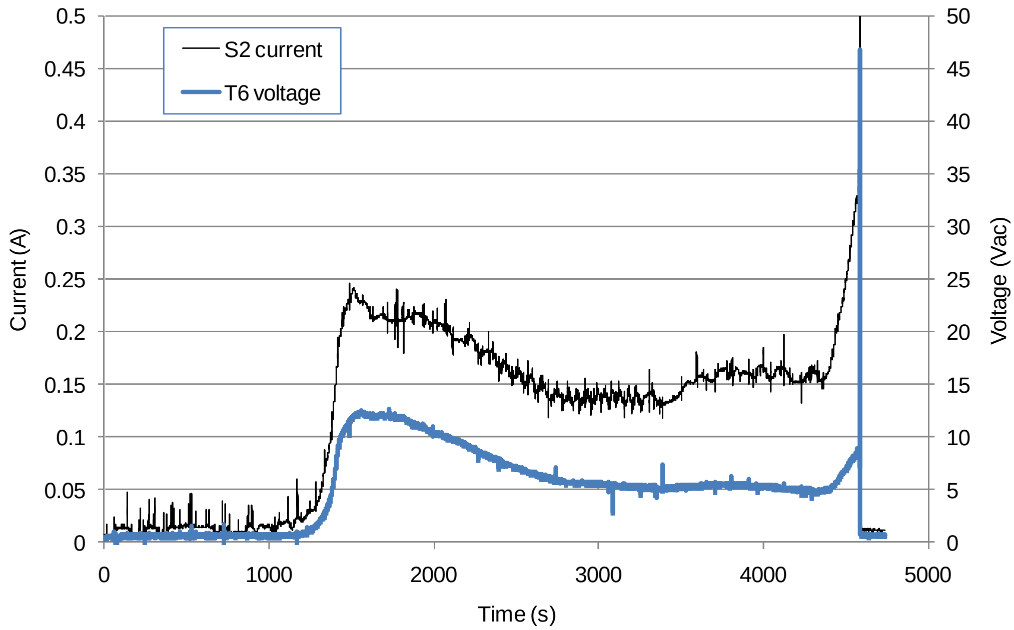

Figure 17: Source 2 (S2) current and Target 6 (T6) voltage data for Test 13.

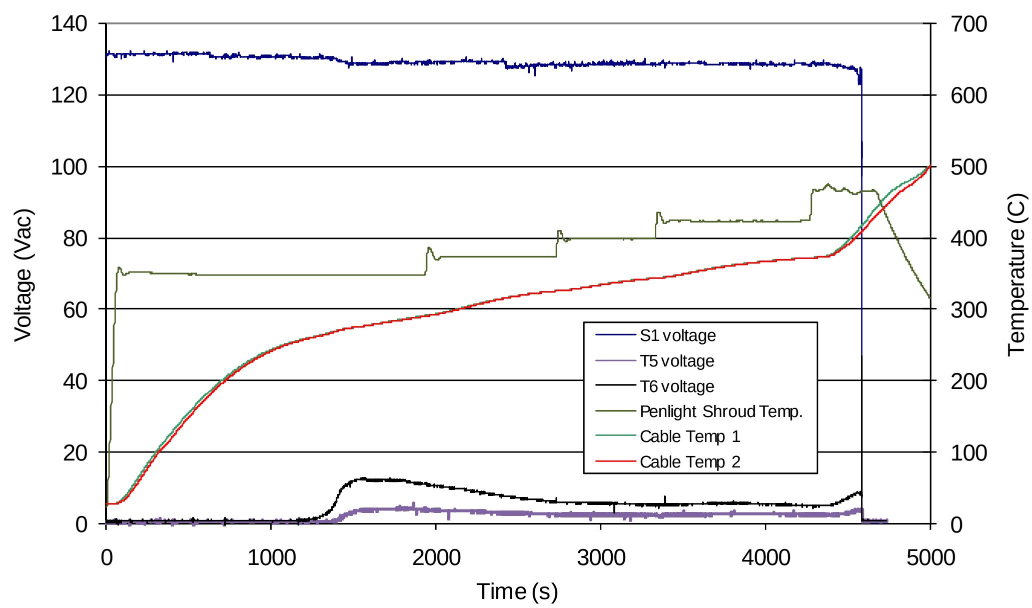

Figure 18: Test results for the 10/C cable in Test 13.

Note that this value represents the approximate resistance between the 4 conductors in the S2 source grouping and the four conductors in the T6 grouping (i.e., see the wiring configuration as specified in Table 5) rather than the IR between any two individual conductor pairs. It is not clear whether the IR behavior was dominated by interactions between one conductor pair or was reflective of a more general degradation of, and interactions between, multiple conductors in the two conductor groups.

The other source-target pair in the 10/C cable was conductors 1 and 2 which (connected to S1 and T5 respectively). These are the two conductors located at the center of the cable. During a similar time period the voltage on T5 rose as high as 4.4V with a corresponding current flow of 0.10A (fire time index = 1769s). Using the same approach, the approximate IR between these two conductors at that time can be estimated as follows:

$$R \approx \Delta V / I = (124\ V) / (0.10\ A) = 1240\ \Omega$$

For the CAROLFIRE tests, one of the systems used in testing was specifically designed to measure conductor-to-conductor insulation resistance. The test report makes the following statements relative to the interpretation of insulation resistance data (See NUREG/CR-6931, Volume 1, pg 32):

> "For purposes of analysis, a control cable was considered to have failed when any one of the monitored conductors shorts to ground (e.g., the cable tray or conduit) or to another conductor with an *(insulation resistance)* IR of less than or equal to 1000Ω. These particular insulation resistance limits were selected by the CAROLFIRE team as representative of expected failure onset conditions for control and instrument circuits. This value was also chosen because the typical behavior of a cable during fire exposure involved a fairly steady degradation of IR with rising temperature until the IR value reaches about 1000Ω. At this point, the cable will typically experience rapid degradation to IRs of typically less than 100Ω. Hence, the use of 1000Ω as a general failure criterion was representative of this behavior."

The CAROLFIRE project did not include the testing of any Kerite cables, and it would appear that the Kerite cables do not follow the same typical behavior as was described for other cable types in this discussion. However, an IR of less than 1000Ω is certainly indicative of substantive degradation for a cable whose baseline IR is measured in mega-ohms.

The 5/C cable in Test 13 also showed signs of degradation at roughly the same temperature range, although the degradation was less pronounced. The voltages on the two target conductors reached a peak of roughly 2.5V before retreating to 2V where they remained until gross failure was observed much later in the test. This behavior is illustrated in Figure 19. The first signs of current leakage from the two source conductors are noted at approximately 1020s. At this point in the test, the 5/C cable temperature was about 276ºC.

After about 1900s, the target conductor voltages had peaked and were beginning to drop, and the cable appeared to be approaching thermal equilibrium. Beginning at 1940s, the shroud temperature was increased in steps over the next 38 minutes to a maximum of 470°C. Shortly after the final increase to 470°C, the cables spontaneously ignited and failure occurred approximately 4 minutes after ignition. According to the data, the 5/C-12AWG cable failed roughly 12 seconds before the 10/C-12AWG cable.

Temperatures recorded for the cables after ignition are not considered reliable indicators of the actual insulation temperature due to exposure of the thermocouple to the flames. Note in the data plots that the ignition time is clearly evident from the departure of the measured temperature response data from its more general heating trends and towards sharply increasing temperature. The thermocouple temperatures rise above the shroud temperature rather quickly after ignition, again indicating exposure to the much hotter flames from the burning cable. However, the 5/C cable had reached a relatively stable temperature of approximately 385°C just prior to the final increase in shroud temperature and ignition of the cable. Hence, it can be concluded that the ultimate gross failures for the 5/C cables occurred at cable temperatures in excess of 385ºC. At about the same time, the 10/C cable thermocouples were reading about 370ºC.

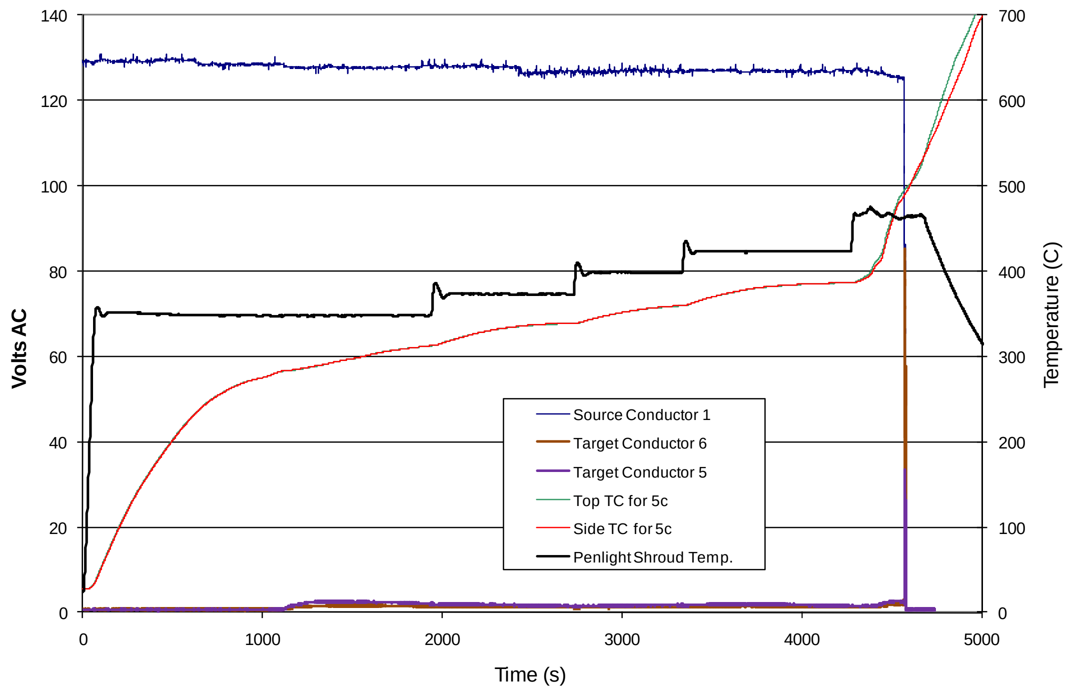

Figure 19: Test results for the 5/C cable in Test 13.

As noted, the cable samples burned during the test and that left little but char behind. Hence, no post-test examination was possible.

Overall, the behavior observed in Test 13 was quite typical of the remaining Penlight tests which used the ac-based SCDU systems and the Kerite FR-insulated cables. In each test, a period of cable degradation as indicated by increasing target conductor voltages would be observed as the cable temperature passed through the 250-300ºC range followed by some degree of recovery and ultimate gross cable failure at cable temperatures in excess of 380ºC. In no case, other than test 13-qual, was an early gross circuit failure (e.g., a spurious operation or fuse blow) observed while the cable temperature was below 380ºC. Section 6 below provides a summary table that includes the temperatures where the first signs of degradation were noted for each cable and the temperature at which ultimate failure occurred.

5.4 A Second Post-Mortem Examination - Test 15

Test 15 was an attempt to roughly repeat the heating profile from Test 13-qual in order to determine if the slower heating protocol might be responsible for the observed early failure during that test. The physical setup for Test 15 was the same at that used in Test 13 with both the 5/C and 10/C cables tested. The heating protocol, however, mirrored that of Test 13-qual.

During previous tests it had been observed that a liquid material leaked from the cut ends of the sample cables during testing. This was most noticeable for the temperature response cables in particular which were shorter than the electrical response cables and had blunt cut ends (since there was no need to make electrical connections to these cables). Particular attention was paid to this behavior during Test 15. As in the previous tests, liquid material was noticed leaking from the cut ends of the thermal response cables.

Figure 20 illustrates this liquid which can be seen as a yellow-green in color and transitioning to dark brown or black over the course of the test.

Figure 20: A pre-test view of the test cables (left) and a photo taken during the Test 15 (right) showing liquid leaking from the cut ends of the both of the thermal response cables (the 5/C and 10/C cables).

Once again, signs of lower temperature cable degradation were observed. The voltage increase during thermal exposure for the cables powering SCDU 1 (5/C-12AWG) and SCDU 2 (10/C-12AWG) are illustrated in Figure 21 and Figure 22, respectively. For the 5/C cable (item 2) the first signs of current leakage from the source conductors are noted at about 2200s when the cable temperature was about 255-256ºC. For the 10/C cable (item 1) the first signs of current leakage are noted at about 2300s. At this point the cable temperature was 251-254ºC.

Neither cable experienced outright circuit failure during the test. A decision was made to end the test prior to ignition of the cables. At the time the test was ended, the sub-jacket temperature of each cable was about 350°C. The intent was to preserve the cable samples for examination.

Upon removing the cable tray from the test apparatus, it was noted that a liquid material had leaked from cracks in the cable jacket at locations within the Penlight Shroud leaving behind hardened black lumps on the surface of the cable. This is illustrated in Figure 23. Nominally, this may indicate that some portion of the observed liquid material might be comprised of thermoplastic materials.

Post-test examination initially focused on, but was not solely limited to, the areas where the liquid residue had seeped from the jacket as pictured in Figure 24. As was the case for the cable from Test 13-qual, an oily residue was observed beneath the jacketing material. The investigation also identified circumferential and axial cracking of the conductor insulation similar to that noted in Test 13-qual. This is illustrated in Figure 25. In this particular case, no areas were noted where the cracks in one conductor were in direct alignment with cracks in an adjacent conductor.

Overall, test 15 and the post-test inspection revealed very similar levels of physical damage (cracking) as had been observed in the case of Test 13-qual. Inspection of the 5/C cable also revealed similar cracks in the conductor insulation. When inspecting these cracks, it was also common that the actual copper conductor was visible indicating that the cracks were not limited to the insulation surface, but rather, went all the way through the insulation. These observations will be discussed further in Section 6.

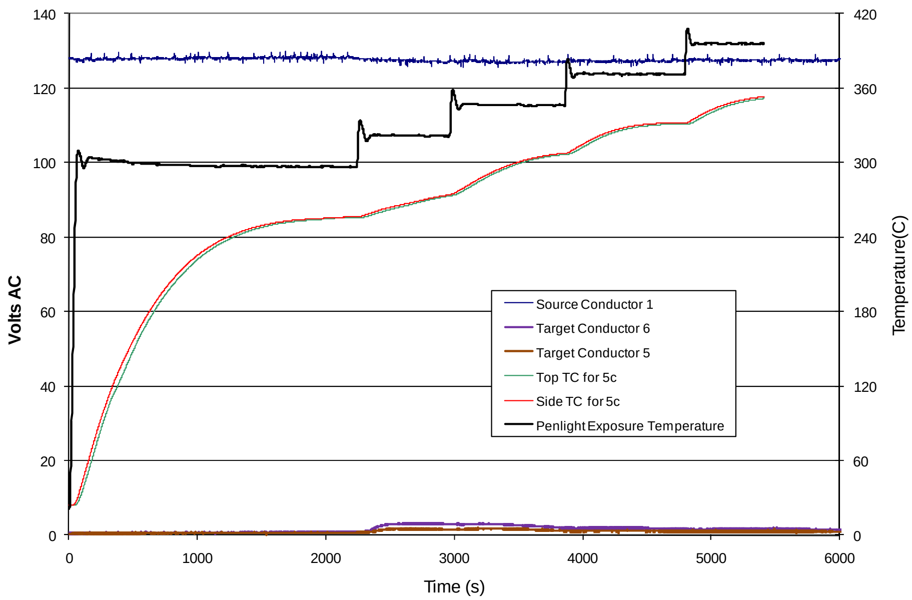

Figure 21: Test results for SCDU 1 and the 5/C cable in Test 15.

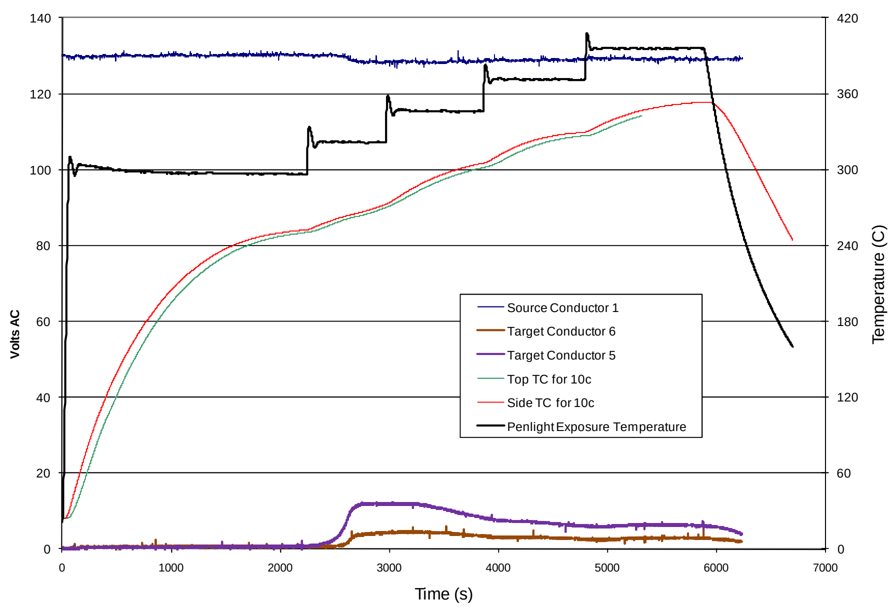

Figure 22: Test results for SCDU 2 and the 10/C cable in Test 15.

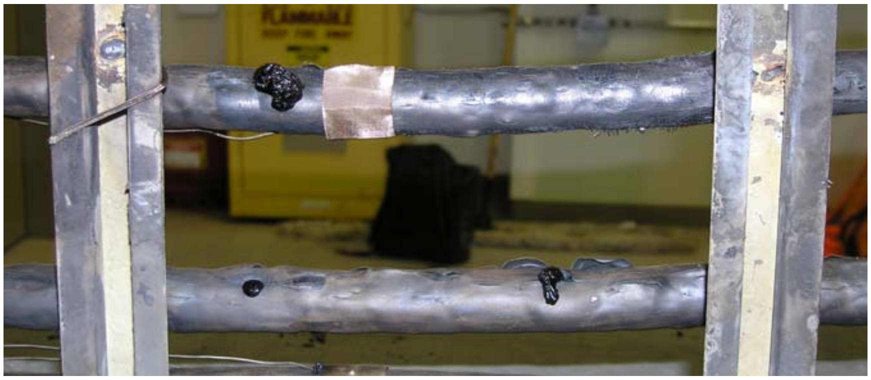

Figure 23: Hardened residue on the jacketing material.

Figure 24: Post-test examination of the 10/C Kerite cable from Test 15.

Figure 25: Insulation cracking observed in Test 15.

5.5 Penlight Tests using the Kerite HT Insulated cables

Three tests were performed (Test 17-qual, Test 17 and Test 18) using a total of five samples of the 3/C Kerite® HT insulated cables (cable item 3). Each test was similar in nature with the primary variable being the exact heating protocol. While the focus of this report is on the FR-insulated cables, this section provides a brief summary of these three tests for comparison.

The conductor numbering scheme for the 3/C cables is provided in Figure 26 and the specific connections are given in Table 7. Conductor 1 was connected to an energized source and the other two conductors were each connected to active target pathways (T5 and T6).

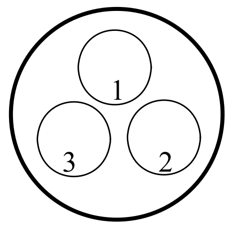

Figure 26: Conductor numbering scheme for the 3/C-6AWG cables.

Table 7: SCDU connections for the 3/C cable in Test 17-qual.

SCDU Circuit Path	Cable Conductor Numbers (per Figure 26)
Energized Source S1	1
Active Target T5	2
Active Target T6	3

Figure 27 illustrates the typical results for this cable type. The case shown is that from test 17-qual, but Tests 17 and 18 show virtually identical behavior, in particular, during the earlier stages of the test (at cable temperatures below 350ºC).

For the HT insulated cables, there are no indications of early cable degradation as were noted when testing the FR-insulated cables. Note that the target voltages (T5 and T6) as shown in Figure 27 remain at essentially zero until the cable temperature nears 400ºC or higher. This is further illustrated by Figure 28 which shows the source conductor (S1) current flow through the course of the test. Note that no discernable trend is evident until approximately 2600s which is after the time of cable ignition. In this case, the cable ignited spontaneously at about 2370s when the internal cable temperature 378-389°C. Shortly thereafter, a more typical and abrupt failure occurs (in this case, a fuse-blow failure indicating the source conductor shorted to ground. Note that beyond the time of ignition, the measured cable temperatures are not considered reliable indicators of the actual cable condition due to exposure of the thermocouple to the flames.

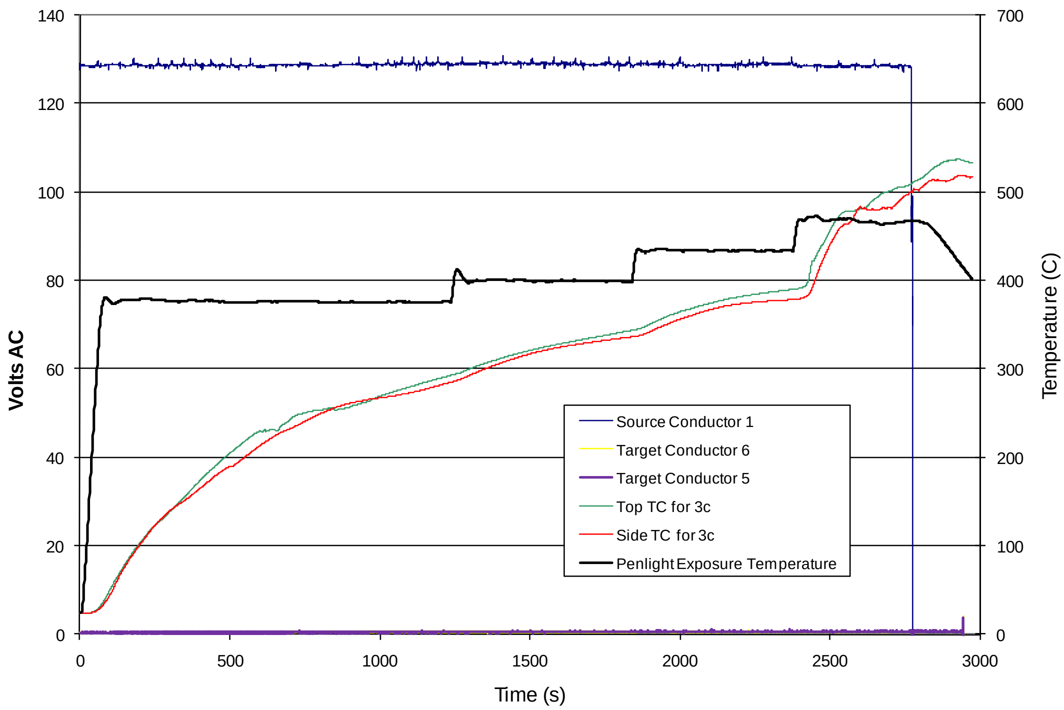

Figure 27: Test results for the HT-insulated cable in Test 17-qual.

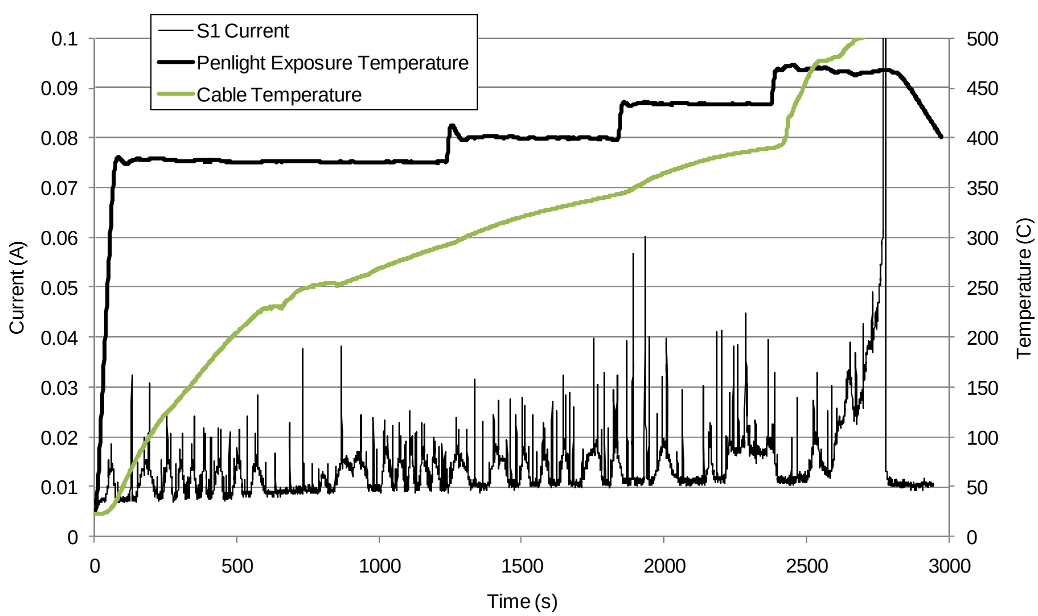

Figure 28: Plot for Test 17-qual showing source conductor current leakage.

5.6 Penlight Tests Using the dc-Powered Circuits

Three tests (Tests 44, 49 and 50) were conducted using the dc-powered test circuits and the Kerite cables provide by Progress Energy. All three tests were conducted using the same physical and electrical test configurations and differ only in the applied heating protocol. For testing, two electrical performance cable were used with one connected to each of the two dc-powered MOV circuits (MOV1 and MOV2).

Each of the two MOV circuits was wired in a specific configuration intended to represent a nominal MOV circuit. This is in contrast to the ac-based SCDU units which, when used in the earlier Kerite tests, were wired so as to maximize the likelihood that the first conductor failures would be detected rather than to represent an actual MOV circuit. As a result, for the dc tests, only certain specific conductor interactions will be detected. Also note that two of the nine conductors in each test cable had no connections to the data recording systems. The conductor numbering scheme for this cable is illustrated in Figure 29 and the electrical connections are specified in Table 8.

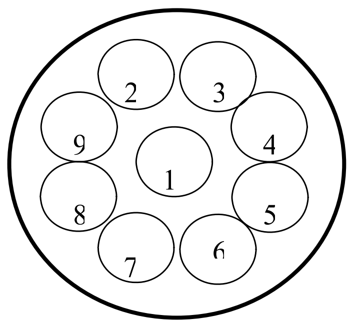

Figure 29: Conductor numbering scheme for the 9/C cables.

Table 8: 9/C Wiring scheme for the 9/C cables and the DC MOV circuits.

MOV Circuit Path	Cable Conductor Numbers (per Figure 30)
Battery Positive (P)	1
NC Auxiliary Contact (G)**	2
Close coil power in (YC1)*	3
NO Auxiliary Contact (R)**	4
Battery Negative (N)	5
Spare (SP)	6
Open coil power in (YO1)*	7
Not used - no connection	8
Not used - no connection	9
* coil power in for each coil runs through auxiliary interlock relays on the opposite coil ** the R and G circuit paths simulate indicator lights and are connected through relays to battery negative.	

One observation made during testing was that the Progress Energy cables also displayed a liquid material leaking from the cut ends of the cables during testing. Figure 30 shows the end of the thermal response cable in Test 44 pre-test (left), at the initial onset of the leaking material (center) and later in the test (right). Note that the material darkens as the test progresses and the cable temperature increases.

Figure 30: Progression of the liquid residue leaking from the cut end of the thermocouple cable: pre-test on the left, and then progressively later in the test for the center and right photos.

Test 44 was the first test of the 9/C-12AWG Progress Energy cable. This was also the first experiment involving the dc-powered surrogate control circuits and Kerite cable. The test configuration was similar to other prior tests but used one temperature response cable and two electrical performance cables in order to maximize the electrical failure data while minimizing the length of cable needed to conduct the test (very limited cable sample lengths were available). For testing, the temperature response cable was centered between two energized cables and all were located near the center of the tray.

Note that for all three of these tests, the ground-fault detection circuit provides a relatively direct indication of the overall circuit condition. Recall that the battery bank is ungrounded but also had a ground fault detection circuit present. In all three tests, the first signs of cable degradation were seen on the ground fault circuit with a drift towards formation of a ground fault between the battery negative and ground. The data graphs for these three tests will focus on this behavior. One difficulty here is that both circuits are powered from the same battery bank so ground faulting behavior impacts both circuits equally.

The test results for Test 44 are illustrated in Figure 31. Note that in this test there are some signs of early cable degradation as had been noted in previous tests, although they are less pronounced than in prior tests. The degradation begins at approximately 1400 s into the test and at a time when the cable temperature was near equilibrium. The cable temperature measured between 1400 and 2000 s ranged from 256-267ºC. A voltage increase of approximately 4V was detected on the coil power circuit path for MOV1 motor contactors a few minutes after leaking of liquid materials from the cable ends was first noticed. This occurred about 31 minutes (1860 s) into the test and, at that time, the cable sub-jacket temperature was about 265°C. MOV2 also experienced similar but somewhat lower voltage increases (about 3V) around the same time.

At about 133 minutes (8000 s) more significant signs of degradation are evident. The drift in battery voltages relative to ground actually began roughly 1000s into the test, but the early drift was minor and was not accompanied by substantive electrical currents. However, beginning at about 8000s, both the battery positive (+) and battery negative (-) begin a more pronounced drift upwards in voltage indicating that a ground fault was forming initially on the negative side of the battery. At this point, the cable internal temperature had just risen above 415°C. The ground developed over a prolonged period and could be associated with either of the two MOV circuits present. The final stages of cable failure (just past 10,000s) occurred after the cable ignited.

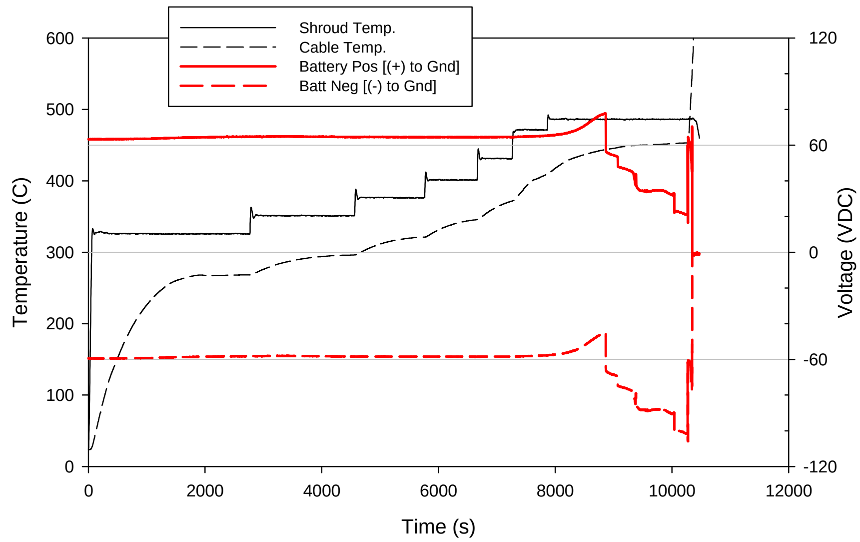

Figure 31: Test results for Test 44.

The test results for Test 49 are shown in Figure 32. As with the previous tests, liquid residue was observed coming from the cut end of the thermocouple cable in both tests. Again, a discernable drift in the ground fault detection is seen relatively early in the test, beginning at about 600s and peaking at about 1000s. The cable temperature at the beginning of this time period was about 234ºC and had climbed to 293ºC by the end of that time period. The voltage increases on the motor contactor target conductors during the early stages of test 49 were minimal, reaching approximately 1V prior to cable ignition and ultimate circuit failure. Again, more substantive signs of degradation were noted after the cable passed 400°C when signs of a drift were noted in the ground fault detection circuit. Cable ignition and failure of MOV 1 were both noted at about 4360 s (just under 73 minutes) when the cable temperature was about 415°C.

The test results for Test 50 are shown in Figure 33. Test 50 used a more aggressive heating profile with the initial shroud temperature set to 450°C. Auto-ignition of the cables occurred just over 780 s (13 min) into the test. At that time, the internal temperature of the cable was about 320°C although with the aggressive heating profile the outside of the jacket would have been substantially hotter. The first discernable drift in the ground fault voltages occurs roughly 500-600 s into the test. The cable temperatures recorded during this time period were 247-283ºC. At about 840s more pronounced voltage drifts on the ground fault circuit are noted. At this point the cable temperature had reached about 328ºC but is considered unreliable given that the cable had already ignited. MOV2 failed approximately 1260 s (21 min) into the test with a fuse blow. MOV1 failed about 1320 s (22 min) into the test also with a fuse blow. The temperatures at this time are indeterminate given that the cable had already ignited.

Overall, the data from the three dc-powered circuit tests are quite consistent. There are some limited signs of early degradation, but they are less pronounced in these tests than in the SCDU tests. The wiring configuration would almost certainly impact this behavior, although the data in that regard are not conclusive. The first signs of substantive degradation noted in each test were voltage drift on the ground fault detection circuit indicating the development of a ground fault on the negative side of the battery.

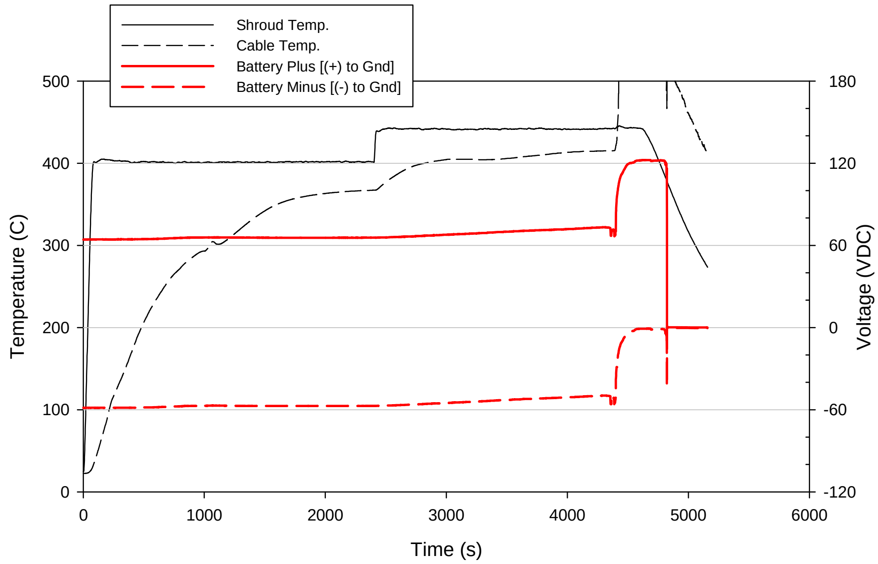

Figure 32: Voltage and temperature profile from Test 49.

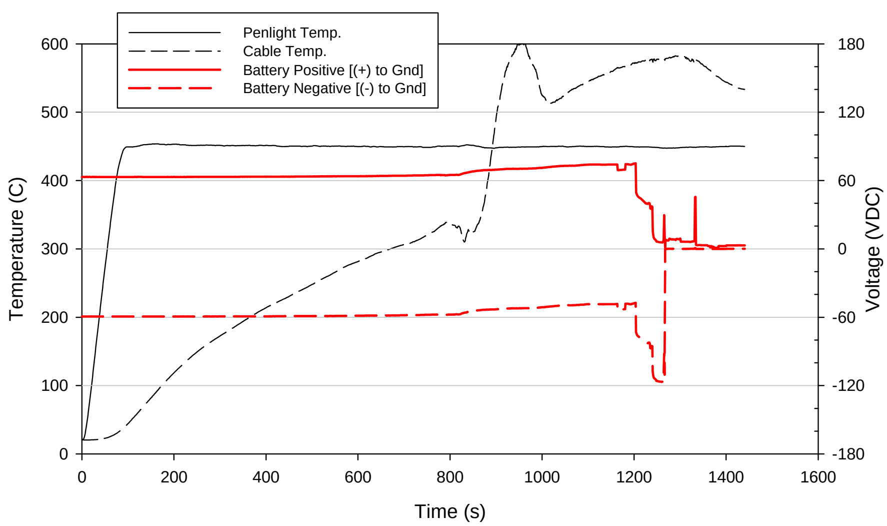

Figure 33: Voltage and temperature profile from Test 50.

6 Kerite® FR Failure Modes Summary and a Working Hypothesis

6.1 Data Summary

Table 9 provides a summary of the small scale test data. The table has been organized to focus attention on the behavior of each of the four cable types tested. Included in the table are the time at which the first signs of degradation were noted and the corresponding cable temperatures at that time. The time value is reported mainly to provide a reference index to the source data files (i.e., fire time). The last column indicates the cable temperature at the time of ultimate cable failure. Recall that the cable temperature data after ignition are considered unreliable. For cases where initial degradation or ultimate failure occurred after ignition, the table reports either that the corresponding temperature of greater than a specified value (i.e., the last reliable pre-ignition temperature measurement) or that it is "indeterminate."

6.2 Working Hypothesis

Based on the test results it appears that two distinct failure modes may be active for the Kerite® FR cables tested. One mode is potentially active when the cable is in the 275-300°C range, and the second is active at temperatures in the 390-410°C range. One key observation is that during the cable heating process in every test performed, a liquid material was observed oozing from the ends of the exposed cables. This oozing material was typically first observed about the time the cable reached a temperature of 265-275°C and typically continued through the course of any given test.

In each test the ends of the cables were outside the Penlight shroud and the liquid was clearly flowing from inside the cable, out the end, and dripping to the floor. After one early test, the material that had dripped to the floor was examined found to still be in a liquid state, to be somewhat oily in its feel, and to have a strong chemical odor. No chemical analysis has been performed to determine the composition of the material, but it was clearly not simple water and it was not melted thermoplastic material (or it would have solidified on cooling). The oozing of some materials from the exposed ends of a test cable is not an especially unusual observation during cable testing. Various cable types will show similar behaviors.

The only test where a gross circuit failure (i.e., a fuse blow or spurious actuation failure) was observed early in the test while the cable was still below 300°C was the very first test run (Test 13-qual). It was initially suggested that this case might have been an anomaly, perhaps caused by the use of a cable end-segment (i.e., a section of cable at the outer end of a cable reel that might have been damaged or contaminated). This supposition can be neither verified nor dismissed in part because there is no way to determine whether or not the sample use was, in fact, and end sample.

However, pre-test cable damage or contamination to this one cable sample would not explain the observed behaviors. The SCDU tests indicates consistent signs of substantive cable degradation when the cable reaches about 250°C for both of the SCG&E Kerite FR samples tested (i.e., substantive voltage increases on the target conductors and indications of leakage of electrical power from the source conductors). The DC tests on the Progress Energy Kerite FR cables also show some signs of cable degradation in the same temperature range, although for those tests the signs are somewhat less pronounced. There is also the question of the through-cracks observed in the insulation of those un-burned cable samples examined after exposure testing (i.e., Tests 13-qual and 15). These facts tend to support the conclusion that the results of Test 13-qual are valid and that the results for all tests are relatively consistent but with varying degrees of degradation occurring in different tests.

Table 9: Summary of test results for each cable type tested.

Test ID	Tested Cable				Circuits Used (note 1)	Time first signs of degradation are observed (s) (note 2)	Temperature at first signs of degradation (°C) (note 2)	Temperature at ultimate failure (°C) (note 3)
	Item 1 – 10/C 12AWG (FR)	Item 2 – 5/C 12AWG (FR)	Item 3 – 3C 8AWG (**HT**)	Item 4 – 9/C 14AWG (FR)				
13-qual					SCDU	2200	246-247	285-287
13						1320	264-265	>370
14	X				SCDU2	720	258-261	Indeterminate
15						2300	251-254	DNF (350)
16						Indeterminate	Indeterminate	Indeterminate
13						1020	276	>385
14						680	341-363	Indeterminate
15		X			SCDU1	2200	255-256	DNF (350)
16						Indeterminate	Indeterminate	Indeterminate
17-qual					SCDU	N/A	N/A	>378
17					SCDU	N/A	N/A	Indeterminate
			X		SCDU	N/A	N/A	
18					SCDU	N/A	N/A	>390
					SCDU	N/A	N/A	
44					MOV1	~1400-2000	256-267	>415
					MOV2			
49				X	MOV1	600	234-293	415
					MOV2			
50					MOV1	500-600	247-283	Indeterminate
					MOV2			

Note 1: Recall that the SCDU1 and SCDU2 are both ac-powered and MOV1 and MOV2 are both dc-powered.
Note 2: Time is reported only in order to provide a reference index to the "fire time" as reported in the data files. An entry of "indeterminate" indicates that degradation occurred only after a relatively early cable ignition (temperatures unreliable).
Note 3: If the table reports a temperature as greater than a given values (>###) this indicates that cable ignition occurred prior to failure. Cable temperatures recorded after cable ignition are considered unreliable. The value reported is the last recorded pre-ignition cable temperature. DNF indicates "did not fail" and the temperature reported is the maximum temperature recorded during the test (applies to Test 15 only). An entry of "Indeterminate" indicates a very early cable ignition relative to ultimate failure time (temperatures unreliable).

The test results point to at least one possible explanation for this behavior that would account for both the early failure in Test 1 and the early signs of degradation noted in other tests. Three factors seem key to this hypothesis. The first factor is the liquid material seen oozing from the cable ends during testing. The second factor is the signs of electrical degradation observed coincident with the liquid material. The third factor is the observation of insulation cracks during the post-test cable inspection for the cables (after Tests 13-qual and 15). These factors taken together suggest at least one potential explanation for the observed behaviors.

On heating, most polymeric materials will shrinks somewhat. The visual inspection of test cables from Tests 13-qual and 15 also revealed that the insulation had become less flexible and more brittle. The combination of minor shrinkage and slight embrittlement could induce cracking in the insulation as observed during post-test visual inspection. The observed cracks in the insulation material would likely fill with the liquid material seen oozing from the cable interior during heating. If that liquid material is electrically conductive, then this could create conductive paths between conductors within the cable. The effective resistance over that conductive path would likely vary depending on how close together the cracks in separate conductors were and on the conductivity of the liquid material. For example:

- Based on the post-test cable examination, the cable in Test 13-qual experienced coincident circumferential through cracking in the insulation for two adjacent conductors. Bridging the gap between the two conductors would have been relatively easy and this may explain the early gross circuit failure in that test.
- If through-cracks in the conductor insulation occur, but the cracks are not co-located along the length of the cable, or the cracks are co-located but do not occur on adjacent conductors, then the liquid material might create a higher resistance short circuit path. A higher-resistance short circuit path might not allow enough current flow to cause gross circuit failure (i.e., a fuse blow or spurious actuation), but could cause varying degrees of electrical degradation signals (increased leakage currents and voltage signals) such as those that were in fact observed in each of the SCDU-based tests.
- If the liquid material is eventually forced away from the heated cable section (the heated section "dries out") then the circuit path would increase in resistance and the signs of electrical degradation would fade, again consistent with the test observations.

One confirming element the remains missing is that no attempt was made to measure the electrical conductivity of the liquid material; hence, this is considered a preliminary working hypothesis subject to verification via further testing. During follow-up tests under JCN N6959, samples of the liquid material will be collected and tested for electrical conductivity.

7 References

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2. Nowlen, S.P. and M.J. Jacobus, "The Estimation of Electrical Cable Fire-Induced Damage Limits," SAND92-1404C, presented at Fire and Materials 1st International Conference and Exhibition, Sept. 24-25, 1992, Washington DC.
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