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Response of Nuclear Power Plant Instrumentation Cables Exposed to Fire Conditions

Office of Nuclear Regulatory Research

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Response of Nuclear Power Plant Instrumentation Cables Exposed to Fire Conditions

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ABSTRACT

This report presents the results of instrumentation cable tests sponsored by the US Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research and performed at Sandia National Laboratories (SNL). The goal of the tests was to assess thermal and electrical response behavior under fire-exposure conditions for instrumentation cables and circuits. The test objective was to assess how severe radiant heating conditions surrounding an instrumentation cable affect current or voltage signals in an instrumentation circuit.

A total of thirty-nine small-scale tests were conducted. Ten different instrumentation cables were tested, ranging from one conductor to eight-twisted pairs. Based on a previous study, the focus of the tests was thermoset (TS) cables. As such, only two of the ten cables had thermoplastic (TP) insulation and jacket material and the remaining eight cables were one of three different TS insulation and jacket material. Two instrumentation cables from previous cable fire testing were included, one TS and one TP. Three test circuits were used to simulate instrumentation circuits present in nuclear power plants: a 4–20 mA current loop, a [1]0–50 mA current loop and a 1–5 VDC voltage loop. A regression analysis was conducted to determine key variables affecting signal leakage time.

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EXECUTIVE SUMMARY

PRIMARY AUDIENCE: Fire Probabilistic Risk Assessment (PRA) and Human Reliability Analysis (HRA) methodology developers, NRC staff, and other stakeholders concerned with determining impact of delayed signal degradation for instrumentation circuits exposed to fire conditions.

SECONDARY AUDIENCE: Engineers, reviewers, utility managers, and other stakeholders who conduct, review, or manage PRAs and HRAs and engineers that route and plan instrument circuits.

KEY RESEARCH QUESTION

What are the fire-induced failure modes of instrumentation cables and circuits?

RESEARCH OVERVIEW

In 2001, a series of cable fire tests was performed by the Nuclear Energy Institute (NEI) and the Electric Power Research Institute (EPRI) which were designed to address specific aspects of the cable failure and circuit fault issues of concern (Ref. 1). These early tests concluded that thermoplastic (TP) cables generally displayed no characteristics of signal degradation prior to complete loss of signal and thermoset (TS) cables displayed up to ten minutes of signal degradation prior to complete loss of signal. The conclusions made in the 2001 study were based on a limited series of testing. To obtain better insights into this type of failure behavior on and a wider variety of cables and circuit configurations, a series of small-scale instrumentation cable tests sponsored by NRC/RES and performed at Sandia National Laboratories (SNL).

The objectives of this report are to document the bench-scale testing efforts and identify focus areas for further testing necessary to address the research question comprehensively.

KEY FINDINGS

This research provides insights into the performance and signal response of low voltage instrumentation circuits in fire conditions. A total of 39 small-scale tests were conducted, primarily on TS cables. The signal leakage time during the fire test were monitored and reported as a measure of circuit response. *Signal leakage time* represents the time from when a signal has dropped 0.25 percent from its starting value to when the single has fallen to zero percent of the measurement (i.e., less than 4 mA for 4–20 mA circuits, less than 10 mA for 10–50 mA circuits, and less than 1 V for 1–5 VDC circuits).

The tests provided evidence that under the appropriate circumstances, instrumentation cables can have a slow signal leakage time under fire-exposure conditions. The signal leakage time varied from 0 seconds to slightly over 2 ½ minutes for TP cables. The signal leakage time for TS cables ranged from 0 seconds to over 21 minutes.

There are three note-worthy general observations on the performance of instrumentation cables:

- The results from the testing of TP cables showed some differences when compared to the findings from prior, limited 2001 testing which stated that TP cables had no signal leakage characteristics prior to signal loss. TP cables were found to have a smaller leakage time on average when compared with TS cables and most TP cables failed instantly; however,

one TP test had a leakage time of 2.6 minutes. Therefore, TP cables may have some signal degradation prior to failure.

- Conclusions from the 2001 testing stated that TS cables displayed some amount of signal leakage before the signal failed. During this series of testing, twelve out of the thirty-two tests had less than one minute of signal leakage before failure and four of these tests experience no signal leakage. Four other tests had signal leakage for longer than ten minutes. Therefore, this testing does not support the previous conclusion that TS cables will always experience signal leakage before failure.

- A regression analysis was performed on the test data to determine key variables that contributed to longer leakage times. The fitted model coefficient methodology concluded that there is a significant relationship between the number of conductors and the signal leakage time.

WHY THIS MATTERS

Fire scenarios in a plant could include a fire affecting a thermoset instrument cable causing the indicator to display an intermediate, but not obviously erroneous, value due to signal degradation. This misleading information in a single indicator circuit could potentially cause operators to take an action based on faulty information depending on the nature of the signal and the direction of the signal leakage. The current tests were designed as a first step in better understanding the failure behavior for fire PRA and HRA applications.

HOW TO APPLY RESULTS

The results can be used to inform full-scale testing to better address the research problem and its implications for HRA. Several areas were identified that would further the understanding of parameters affecting signal time delay in instrumentation circuits. These areas are summarized as follows:

- Assess the performance of instrumentation in various—likely cable-tray—configurations. This includes bundling of cables, vertical and horizontal positions, and more realistic configurations.
- Determine the implications of prolonged signal leakage on HRA.
- Assess the potential heating effects on digital transmitters and receivers.
- Assess the performance of different TP insulation/jacket cables materials. The focus of this testing was on TS cables; however, TP cables were shown to have some signal leakage before failure. Different TP insulation/jacket materials should be tested for a more comprehensive understanding of the signal leakage.

LEARNING AND ENGAGEMENT OPPORTUNITIES

Users of this report may be interested in the annual fire PRA training, Module III – Fire PRA, sponsored jointly between EPRI and the US NRC-RES.

ACKNOWLEDGMENTS

ABBREVIATIONS AND ACRONYMS

A or Amp	Ampere
AC	Alternating Current
AWG	American Wire Gauge
CAROLFIRE	Cable Response to Live Fire
CFR	Code of Federal Regulations
cp	Complexity Parameter
CPE	Chlorinated Polyethylene
CSPE	Chloro-Sulphonated Polyethylene
DAQ	Data Acquisition
DC	Direct Current
DESIREE-Fire	Direct Current Electrical Shorting in Response to Exposure Fire
EPDM	Ethylene Propylene Diene Monomer
EPR	Ethylene-Propylene Rubber
EPRI	Electric Power Research Institute
EQ	Equipment Qualification
ESFAS	Engineering Safeguard Feature Actuation System
FR	Flame-Retardant
HRA	Human Reliability Analysis
IR	Insulation Resistance
JACQUE-FIRE	Joint Assessment of Cable Damage and Quantification of Effects from Fire
LSZH	Low Smoke Zero Halogen
mA	Milliamps
MOU	Memorandum of Understanding
MS	Mean Square
NEI	Nuclear Energy Institute
NIST	National Institute of Standards and Technology
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
PE	Polyethylene
PIRT	Phenomena Identification and Ranking Table
PRA	Probabilistic Risk Assessment
PVC	Polyvinyl Chloride
RES	Office of Nuclear Regulatory Research (at NRC)
SNL	Sandia National Laboratories
SS	Stainless Steel
TC	Thermocouple

THIEF	Thermally-Induced Electrical Failure
TP	Thermoplastic
TS	Thermoset
V	Volt
XLPE	Cross-Linked Polyethylene

1   INTRODUCTION

This report describes a series of cable fire tests performed by Sandia National Laboratories (SNL) under the sponsorship of the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES). This effort was conducted in collaboration with the Electric Power Research Institute (EPRI) as a working group under the memorandum of understanding (MOU) for collaborative research. This effort provides data to better understand the failure behavior of instrumentation cables subjected to damaging fire conditions.

1.1   Background

In 1990, the NRC sponsored a series of tests at SNL to investigate the effects of thermal aging on fire damageability, documented in NUREG/CR-5546, "An Investigation of the Effects of Thermal Aging on the Fire Damageability of Electric Cables" (Ref. 2). An instrumentation cable was tested to determine the failure time and temperature for both aged and unaged cables. During the testing, levels of leakage current on the order of 15 mA were observed prior to the onset of catastrophic failure. This phenomenon was not explored further as the damage thresholds and times were based only on the failure of a 2 Ampere (A) fuse in the circuit.

In 2001, the Nuclear Energy Institute (NEI) and EPRI, together hereafter referred to as "industry," conducted a series of cable fire tests designed to address specific aspects of cable failure and circuit fault issues of concern (Ref. 1). "Issues of concern" refers to the problems associated with post-fire safe-shutdown circuit analysis, as presented in NRC Information Notice 99-17: "Problems Associated with Post-Fire Safe-Shutdown Circuit Analyses" (Ref. 3). The NRC observed and participated in the 2001 tests by providing supplemental cable performance monitoring equipment for the tests. The NRC contracted SNL who provided instrumentation designed to monitor cable degradation through the measurement of insulation resistance (IR) for several of the NEI/EPRI tests. In addition to the IR tests, a separate surrogate instrument circuit was used in six of the tests. This circuit simulated a 4–20 mA instrument circuit loop with a constant current source set to 15 mA. The instrument wire transmitting the signal was exposed to fire conditions and the output signal was monitored for degradation of the transmitted signal. These tests are documented in NUREG/CR-6776, "Cable Insulation Resistance Measurements Made During Cable Fire Tests" (Ref. 4).

These tests concluded that there are pronounced behavior differences observed between the failure of the thermoplastic (TP) and thermoset (TS) cables. TP cables generally displayed no characteristics of signal degradation prior to complete loss of signal. TS cables displayed a substantial amount of signal degradation, the worst case had signal degradation for approximately ten minutes prior to the total loss of the signal, as shown in Figure 1-1. Fire scenarios in a plant could postulate a fire affecting a TS instrumentation cable to cause the indicator to read an intermediate, but not obviously erroneous, value. This misleading indication could potentially cause operators to take an action based on faulty information (depending on the nature of the signal and the direction of the signal leakage). In contrast, a fire affecting a TP cable would likely cause an abrupt and obviously faulty off-scale indication. This would be far less likely to mislead operators who would likely diagnose the instrumentation failure.
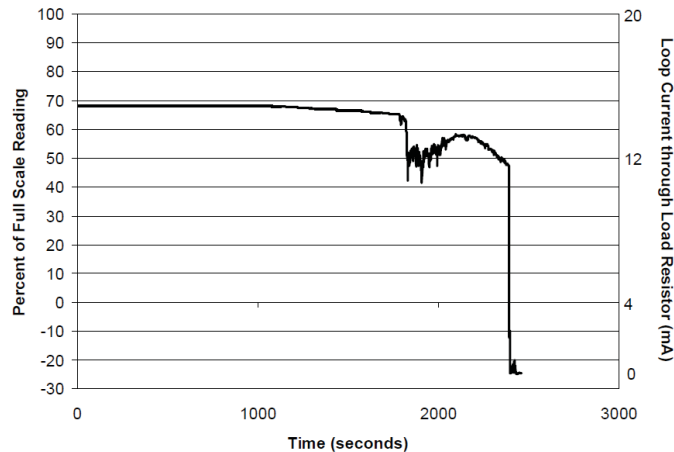
Figure 1-1   Degradation of Signal Data from Thermoset Test (Ref. 4)

1.2   Purpose and Objectives

The objective of this research is to better understand the fire-induced failure modes of instrumentation cables. This research is intended to better quantify the cable failure characteristics (i.e., leaks in current) that may occur before catastrophic failure in instrumentation circuits.

The Joint Assessment of Cable Damage and Quantification of Effects from Fire (JACQUE-FIRE), Volume 1 report documented the results of a Phenomena Identification and Ranking Table (PIRT) exercise that was performed on fire-induced electrical circuit failures that may occur in nuclear power plants as a result of fire damage to cables (Ref. 5). The PIRT panel ranked instrumentation circuits as the top research priority and recommended additional testing due to the low level of knowledge and potential high consequences of fire-induced failure. The Probabilistic Expert Elicitation (PEE) panel indicated that the spurious operation and duration conditional probabilities developed for control and power circuits should not be used for instrumentation circuits (Ref. 6). The panel restated the need to advance the knowledge of fire-induced circuit failure for instrumentation circuits.

1.3   Project Planning and General Approach

The draft project plan was developed over the course of several months and included several rounds of review and revision. The first draft of the test plan was issued to NRC on August 25, 2016, and included a subsequent 30-day public comment period (see Federal Register notice 81 FR 80688) starting November 16, 2016 and ending December 16, 2016. The project plan was revised based on public comments. Industry input led to refinements of various aspects of the project plan including defining industry practices for grounding the circuit. The draft test plan can be found on the NRC website, titled "Response of Nuclear Power Plant Instrumentation Cables When Exposed to Fire Conditions – Test Plan" (Ref. 7); the final test plan is included in APPENDIX C .

Tests were performed between February 16, 2017 and March 9, 2017 using SNL fire test facilities in Albuquerque, New Mexico.

The project employed basic quality assurance provisions, but was not subject to a strict quality assurance program. The instruments (voltage and current transducers) were covered by manufacturer supplied certificates of calibration and were included in the SNL instrument calibration system for verification or re-certification at the completion of testing. All other instruments used in testing, particularly the various thermocouples (TC) and temperature measurement instrumentation, were subject to the SNL calibration process which provides calibration services traceable to National Institute of Standards and Technology (NIST) standards.

Field notes were maintained by the lead test engineer documenting all variable aspects of the individual tests and recording other observations during each test. All data processing and plotting was performed using commercial software (Microsoft Excel®). The regression analysis presented in Section 5 was performed using the R Project software. The original data files in their native format have been preserved for archival purposes. All data from the testing program is publicly available without restriction on a CD.

1.4 Scope

While the project involved collaboration between the RES and EPRI, SNL acted as the primary test laboratory and produced the contents of this report. This project complements previous research conducted in the Cable Response to Live Fire (CAROLFIRE) project in 2006 (Ref. 8), the Kerite Analysis in Thermal Environment of FIRE project in 2011 (Ref. 9), and the Direct Current Electrical Shorting in Response to Exposure Fire (DESIREE-Fire) project in 2012 (Ref. 10). Although this report provides a general overview of the testing approach, the reader unfamiliar with these two tests should consult Vol. 1 of NUREG/CR-6931 (Ref. 8) and NUREG/CR-7100 (Ref. 10) for full understanding of the approach and reasoning.

This report includes a summary description of all tests performed including experimental setups, test matrices, and a description of instrumentation fielded during each experiment. APPENDIX A contains the processed test data. A detailed timeline of the onset of signal degradation and failure is included. A regression analysis was performed on the data to focus the analysis on key variables which lead to longer signal leakage times. Additional interpretation of the test results applied to risk analysis is outside the scope of this project. In addition, the potential overheating of digital transmitters and receivers themselves is not in the scope of this test.

This balance of this report is organized as follows:

- **Section 2**   provides general background discussions describing previous test programs investigating related phenomena. Section 2 also provides an overview of the testing needs addressed by this project.
- **Section 3**   describes the general approach taken in this project. Included in this section are summary descriptions of the test facilities, protocols, circuits, and cables used.
- **Section 4**   presents the test matrix.
- **Section 5**   provides a description of the regression analysis performed on test results. In addition, there is a discussion on key variables in the results.
- **Section 6**   presents summary discussions highlighting general insights gained from the testing and future recommendations.
- **Section 7**   identifies referenced documents.

2   OVERVIEW OF TESTING NEEDS

2.1   Instrumentation Circuit Background

Instrument circuits (also known as instrumentation and control circuits) provide critical information to operators regarding the status of plant conditions. Circuit fault effects on instrument systems are unique and more complex than power and control circuits. Instrument sensors typically convert process variable values (temperature, pressure, level, flow, etc.) to an electric signal (e.g., voltage and current) for transmission to a remote readout or display. Instrumentation readings can also be used to actuate an automatic plant response, as instrumentation circuits can be tied to process equipment, such as the reactor protection system and engineered safety features actuation system (ESFAS). The current loop typically exists in two forms: 10–50 mA (old standard) and 4–20 mA (new standard). The 4–20 mA became the industry standard because it has lower circuit voltages and current levels so there is less chance for personal shock injury or the generation of sparks.

In either case, the principle of operation is the same; current produced by the loop power supply is sent around the loop, flowing through every device and load—or burden device—in the circuit. The current is modulated into a process variable by a transmitter, which converts a sensor's measurement into a current signal and amplifies and conditions the output. A sensor typically measures temperature, humidity, flow, level, or pressure. The current loop also has a receiver, a device that interprets the current signal into units that can be easily understood by the operators. The receiver converts the 4-20 mA current back into a voltage which can be displayed, or actuate another component based on its start/stop logic. In this setup, 4 mA represents 0 percent of the measurement, 20 mA represents 100 percent; when the current is between 4 mA and 20 mA the voltage across the resistor is in direct proportion to that current. See Figure 2-1 for an example current loop showing the components discussed above.
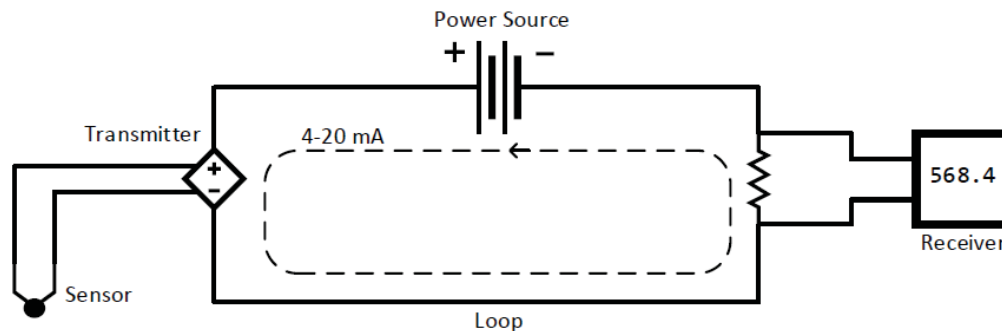
Figure 2-1   4–20 mA Current Loop Example[1]

Current loops are extremely robust systems; they are impervious to electrical noise, and routing the signal through shielded, twisted-pair cables further reduces noise. Grounding the negative of the power supply to the shield provides additional noise protection. It is ideal for long distances as current does not degrade over long connections, unlike voltage which can degrade. It is also easier to detect and troubleshoot a fault in the system. One disadvantage to the current loop

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[1]   Figure derived from: https://www.predig.com/indicatorpage/back-basics-fundamentals-4-20-ma-current-loops

design is that it can only transmit one process signal. However, programmable logic controllers or other digital control systems are designed to take inputs from multiple current loops.

2.2   Instrumentation Cable Background

Instrumentation cables transmit low-level signals from the instrument sensor to an indicator, controller, or recorder. Instrumentation cables are low voltage and low ampacity (Ref. 11). They are used for digital or analog transmission from various types of transducers. Resistance temperature detectors, pressure transducers, and TCs are usually of a shielded twisted-pair configuration whereas radiation detection and neutron monitoring circuits often use coaxial or triaxial shielded configurations (Ref. 11). Instrumentation cables typically use single, shielded twisted-pair conductor cables or much larger multi-conductor cables consisting of fifty or more conductors. Each instrument conductor is typically size 16 American Wire Gauge (AWG) or smaller. These cables frequently enclose several shielded twisted pairs of conductors contained within a protective outer jacket. The twisting of conductors reduces magnetic noise, while the shield and drain wire reduce electrostatic and radio-frequency interference. The shield consists of a conductive material that is wrapped around the twisted pair of conductors. The uninsulated drain wire, which is in physical and electrical contact with the shield, provides for easier termination of the foil shield to a common ground point.

2.3   Cable Failures and Circuit Faults

2.3.1   Cable Failures

Cable failure implies that the cable is no longer able to perform its intended function, which is to maintain the electrical integrity and continuity of the associated circuit sufficiently to ensure proper operation of the circuit (Ref. 12). Hence, cable failure implies that one or more of the cable conductors have lost electrical integrity or continuity. Cables can fail in the following ways.

Open Circuit: An open circuit is failure condition that results when a circuit (either a cable or individual conductor within a cable) has a loss of continuity (Ref. 13). Such failures would likely be diagnosed as a circuit fault by operators. However, a complete loss of several signals may mean that operators would not know the actual reactor status, depending on available independent and redundant sensors.

Short Circuit: A short circuit is an abnormal connection (including an arc) of relatively low impedance, whether made accidentally or intentionally, between two points of different potential (Ref. 13).

A short circuit does not involve an external ground. Twisted pairs, especially shielded twisted pairs, would be more likely to short-to-ground rather than form a short circuit given the proximity of the ground (i.e., properly grounded shield). If the power for the current loop is provided by a power supply that is physically independent of the loop's transmitter, a conductor-to-conductor short across the transmitter could possibly drive the loop current high and give a false reading. Both intra-cable and inter-cable faults are possible, but again the possibility decreases with the addition of shielding (properly grounded) protecting the twisted pairs and/or the cables.

Hot Short: Hot shorts occur when individual conductors of the same or different cables come in contact with each other and may result in a voltage or current on the circuit being analyzed (Ref. 13).

Short-to-Ground: A short-to-ground is a short circuit between a conductor and a grounded reference point (e.g., grounded conductor, conduit or other raceway, metal enclosure, shield wrap, or drain wire within a cable) (Ref. 13). Twisted pairs, shields for the pairs, and overall shields can be grounded in instrumentation circuits, so shorts-to-ground may occur more than hot shorts.

2.3.2   Circuit Faults

A circuit fault is undesired or unplanned behavior in an electrical circuit induced by the failure of one or more elements of the circuit, including the failure of an associated electrical cable (Ref. 13). For the purposes of this test plan, this term refers to effects that postulated cable failures have on the associated electrical circuits and components. Circuit faults that could be applicable to instrumentation circuits are as follows.

Loss of circuit operability: Some cable failures may lead to a total loss of circuit operability. This may result from failures involving instrumentation and control interlocks and permissive signals. For example, the failure of an oil pressure signal cable in such a manner that a false low oil pressure was indicated may lead to the loss of function of an associated pump or motor due to an oil pressure interlock (Ref. 13).

Loss of indication: In some cases, cable failures may leave a system or component nominally operational, but will compromise the indication functions of the circuit. This may lead, for example, to status indicator lights going dark (Ref. 13).

Inaccurate indications: Some cable failures may result in misleading or even conflicting instrument signals. A relatively low level of degradation in the insulation of an instrumentation cable may be sufficient to substantially bias an instrument's readout (Ref. 13). For example, a false low water level signal could lead operators to activate additional water sources leading to the reactor vessel being overfilled. A false high reading could lead operators to shut down or throttle coolant injection systems, potentially leading to low water levels in the reactor.

Spurious operation: Spurious operation is the undesired or unplanned operation or activation of a system or component. Spurious operations are most commonly associated with cable hot short failures, although various cable failure modes may lead to spurious operations (depending on circuit design), and not all hot shorts will lead to spurious operations (Ref. 13).

The functional impact of cable failures and circuit faults on plant systems, components, and functions can vary. This unpredictability in the process variable as a result of cable failures may elicit undesired automatic or human responses that may complicate or compromise the overall response to the effects of fire.

The other unknown is the change of voltage that would indicate a change of state to the operator if the signal has a binary output. For example, a valve position indicator could be designed to alert the operator only if the valve is open or closed. If a voltage change is minimal for a long period of time, the operator may not know something is wrong until several minutes have passed. If controlled by a digital device, the setting determines the voltage or amperage at which a system problem is indicated. Because the digital transmitter set points vary by plant, set points were not analyzed during testing.

2.4 Instrumentation Needed for Safe Shutdown

For the purposes of this test, there are two concerns for instrumentation readings. First, an instrumentation reading for a component that is time-sensitive and operator-dependent could cause unanalyzed problems if the signal is delayed or failed. Second, instrumentation readings that automatically actuate a plant response are also of interest. For example, a pump (dependent on the operation of a lubrication system) commonly has a permissive tie to an oil pressure reading. If the instrument cable failure led to an inaccurate indication of a loss of oil pressure, the pump may trip or fail to start on demand (Ref. 13).

Information Notice 84-09, titled "Lessons Learned from NRC Inspections of Fire Protection Safe Shutdown Systems" provides guidance for licensees implementing requirements of 10 CFR 50, Appendix R (Ref. 14). Section III.L.1 of Appendix R requires that alternative shutdown capability achieve and maintain subcritical reactivity conditions in the reactor for III.G.3 fire areas. Section III.L.2 requires provision for direct readings of the process variables necessary to perform and control the reactor shutdown function. The minimum process monitoring capability described in IN 84-09 includes the following instruments:

2.4.1 Instrumentation Needed for Pressurized Water Reactors

- Pressurizer pressure and level
- Reactor coolant hot leg temperature or exit core TCs, and cold leg temperature
- Steam generator pressure and level (wide range)
- Source range flux monitor
- Diagnostic instrumentation for shutdown systems
- Level indication for all tanks used (e.g., condensate storage tank)

2.4.2 Instrumentation Needed for Boiling Water Reactors

- Reactor water level and pressure
- Suppression pool level and temperature
- Emergency or isolation condenser level
- Diagnostic instrumentation for shutdown systems
- Level Indication for all tanks used

Diagnostic instrumentation is instrumentation needed to ensure the proper actuation and functioning of safe-shutdown equipment and associated support equipment (e.g., instrumentation for flow rate, pump discharge pressure, etc.). The diagnostic instrumentation needed is plant-specific and should be based on the design of the alternative shutdown capability. All of the instrumentation listed have multiple channels and within any given fire area, fire detection may alert the operators to a fire. However, this analysis is applicable if fire detectors are not present or have not yet sensed the fire or for single instrument circuits, such as battery/bus voltages or pump oil pressure.

3   APPROACH

3.1   Project Planning and General Approach

An extended process of project planning was undertaken to ensure that the testing program and protocols would address the identified data needs. Based on early discussions, a definition of the overall project goals and technical approach was developed. Several key parameters that would need to be decided upon as a part of test planning were identified as follows:

- Selection of instrumentation test circuits
- Circuit monitoring objectives and instruments
- Power source characteristics (e.g., current source and voltage source)
- Power source, circuit and instrument grounding
- Cable types to be used in testing

A RES/EPRI working group was established to discuss test parameters and the test plan. From these working group discussions, SNL developed a preliminary test plan that was issued by the NRC for public comment in November 2016. The public comment process resulted in several comments which were addressed in subsequent revisions. In addition, the RES/EPRI working group also reviewed the test plan and provided feedback. The test plan was nominally finalized in January 2017. However, it should be noted that while the final test plan was "frozen" as a document, additional changes and adjustments were made throughout testing to address minor issues identified as the test plan was implemented. The final test matrix is found in Section 4.

To meet the project goals, a fairly large number of tests involving varied arrays of cable types, heating conditions, and circuit types were performed. Preliminary testing was conducted on a small-scale radiant heat testing apparatus. Small-scale heating apparatus is described more completely in Section 3.4. The ceramic heater used in the small-scale tests allows for well-controlled heat exposures that are beneficial for comparison purposes. The small-scale radiant heat tests can be conducted very efficiently so that many tests can be conducted in a short time and at relatively low cost.

The test design was optimized to allow for considerable flexibility as the testing proceeded. As noted above, the test plan document was nominally frozen in January 2017. However, the actual implementation of the test matrix allowed for considerable flexibility. Changes were made to cable, circuit, and instrumentation configurations and to test procedures to reflect insights gained as the tests progressed. That is, as experience was gained through the performance of the tests, opportunities for improvement were identified and implemented. Hence, the test matrix in the final test plan was modified. The final test matrix is presented in Section 4.

The small-scale tests for this project were conducted at the Thermal Test Complex at Sandia National Laboratories in Albuquerque, NM using a ceramic heater for the radiant heating apparatus. Volume 2 of the CAROLFIRE report provides a detailed description of the small-scale test facilities and the general test protocols that were followed during this series of tests.

3.2   Cable Selection

Surveys conducted under the equipment qualification (EQ) research programs in the 1980s and 1990s were an important factor in determining cable insulation materials for the CAROLFIRE and DESIREE-Fire tests. Instrumentation circuits were also analyzed in the EQ program and

comprised almost 20 percent of the various types of circuits found at one nuclear power plant during this study.[2] The NRC EQ inspections identified that a common instrumentation cable is a 2-conductor, twisted shielded pair, 16 AWG (Ref. 15).

During the 2001 cable tests, manufacturers and specific cable properties were not included in the documentation (Ref. 4). The types of cable insulations and jackets recorded are listed below.

- Ethylene-propylene rubber (EPR)/Chloro-Sulphonated Polyethylene (CSPE) 8/Conductor armored cable
- Polyethylene (PE)/ Polyvinyl Chloride (PVC) 2/Conductor shielded cable
- PVC/PVC
- Ethylene Propylene Diene Monomer (EPDM)/CSPE

None of the common suppliers of EPR cables still advertise them according to the CAROLFIRE project plan. The CAROLFIRE project explored a wide range of cable types and the results indicated that TS and TP insulated cables behaved differently; however, the various TS cable types behaved similarly, as did the various TP cable types. The four instrumentation cables tested during the CAROLFIRE project included:

- Cross-linked Polyethylene (XLPE)/CSPE, 16 AWG, 2/Conductor, Shielded Rockbestos-Surprenant Cable
- XLPE/CSPE, 18 AWG, 12/Conductor, Rockbestos-Surprenant Cable
- PVC/PVC, 16 AWG, 2/Conductor, Shielded General Cable
- PVC/PVC, 18 AWG, 12/Conductor General Cable

The CAROLFIRE report stated that the single most popular insulation material used in the US nuclear power industry is the TS material XLPE. The most popular jacket with the XLPE insulation type is CSPE, also known by the trade name Hypalon. The most common TP insulation material in use at US Nuclear Power Plants (NPPs) is PE, while another very popular material is PVC. The types of cables from the 2001 tests were unavailable so other cables and cable manufacturers were used.

The tested cables are described below with summary information provided in Table 3-1. For this testing project, TP cable tests were limited because the scope of this project is to define the failure characteristics of TS cables based on the 2001 testing. All cables are rated for 600 V.

For convenience, this report identifies the cable materials in the format 'insulation/jacket' (e.g., PE/PVC corresponds to a cable with PE insulation surrounding the individual conductors and a PVC jacket encapsulating the collection of insulated conductors).

General descriptions of the TS-insulated and jacketed cables are as follows:

- XLPE/CSPE: As stated above, XLPE/CSPE is the most popular cable insulation/jacket combination found in U.S. NPPs. The cables tested were Rockbestos Firewall® III products in various configurations, shown in Table 3-1. The cables have an overall shield

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[2] There were a number of US NRC-sponsored cable aging research efforts at Sandia National Laboratories in the 1980s associated with the Nuclear Plant Aging Research (NPAR) programs, and at EPRI and the U.S. Department of Energy relative to Plant Life Extension (PLEX) programs. The work cited here can be found in the reference SAND 96-0344, "Aging Management Guideline for Commercial Nuclear Power Plants – Electrical Cable and Terminations," September 1996.

that is helically applied aluminum/polyester laminated tape shield in continuous contact with a flexible strand, tin-coated copper drain wire. The cables with shielded pairs have a helically applied aluminum/polyester laminated tape shield with a flexible strand, tin-coated copper drain wire.

- FR-EPR/CPE: EPR is the second most popular insulation material and is another TS used during this testing. This Flame-Retardant (FR) EPR insulated, Chlorinated Polyethylene (CPE) jacketed cable was procured from Houston Wire & Cable Company and manufactured by Belden.

- XLPE/LSZH: The cable insulation consists of XLPE and the jacket is low smoke zero halogen (LSZH). This cable was procured from Houston Wire & Cable Company and manufactured by Belden.

General descriptions of the TP-insulated and jacketed cables are as follows:

- PVC/PVC-Nylon: PVC is a very popular TP material in the U.S. and abroad as a general commercial and industrial grade cable. The cable jacket consists of PVC with a thin layer of nylon material between the jacket and the insulation. This cable was procured from Houston Wire & Cable Company and manufactured by Belden.

In addition to the purchased cables, two instrumentation cables from the CAROLFIRE project were included in the test matrix. All cables are new and have not been in service. These are shown, along with the recently purchased cables, in Table 3-1.

Table 3-1   Project Cable List

Cable type				Cable Characteristics				
Manufacturer	Insulation & Jacket Materials	TS	TP	Num. of Twisted Pairs or Conductors	Part Number	Overall Shield	Shielded Pairs	Notes
Rockbestos Firewall III	XLPE/CSPE	x		2/c	I46-5700	x		From the Firewall III product line, a nuclear qualified cable brand. Equipment qualification certificates were not requested.
Rockbestos Firewall III	XLPE/CSPE	x		4/c	I46-5844	x		
Rockbestos Firewall III	XLPE/CSPE	x		2	I46-0021	x	x	
Rockbestos Firewall III	XLPE/CSPE	x		4	I46-3433	x	x	
Belden	PVC/PVC-Nylon		x	2	HW10501602	x		Industrial-grade cable
Belden	PVC/PVC Nylon		x	8	HW10501608	x		

Table 3-1   **Project Cable List (Cont'd.)**

Cable type				Cable Characteristics				
Manufacturer	Insulation & Jacket Materials	TS	TP	Num. of Twisted Pairs or Conductors	Part Number	Overall Shield	Shielded Pairs	Notes
Belden	FR-EPR/CPE	x		2	HW110 01602	x	x	
Belden	FR-EPR/CPE	x		8	HW110 01608	x	x	
Belden	XLPE/LSZH	x		1	HW120 01601	x	x	
Belden	XLPE/LSZH	x		8	HW120 01608	x	x	
General Cable	PVC/PVC		x	2/c	230830	x		CAROLFIRE Test Cable 4
Rockbestos-Surprenant	XLPE/CSPE	x		2/c	I57-0120	x		CAROLFIRE Test Cable 7

Project Cable List

Additional Notes:

Insulation and jacket materials shown as: (insulation type) / (jacket type).
XLPE = Cross-linked polyethylene; CSPE = Chlorosulfunated polyethylene (also known as Hypalon); PVC = Polyvinyl chloride; FR-EPR = Flame-retardant ethylene-propylene rubber; CPE = Chlorinated Polyethylene; LSZH = Low smoke zero halogen
TS = Thermoset; TP = Thermoplastic.
All cables are 16 AWG.
"2/c" represents a 2-conductor cable, "2" represents a cable containing 2 twisted pairs of conductors

3.3   Test Circuits

Three test circuits were used to simulate instrumentation circuits similar to what may be seen in industry. The most popular instrumentation circuit is the 4–20 mA current loop, given its insensitivity to electrical noise, was one of the instrumentation circuits that was tested. The 4–20 mA current loop is also the standard output signal, according to ANSI/ISA-50.00.01-1975 (R2012), "Compatibility of Analog Signals for Electronic Industrial Process Instruments" (Ref. 5). The 10–50 mA control signal circuit design began back in the days of vacuum tubes where high line voltages were required to power up the circuitry. Since transistor circuits have become more widely used (and are more stable and accurate), the 10–50 mA current loop is not as prevalent in industry, however, these types of circuits may be present in older NPPs and were therefore included in testing. Finally, a 1–5 VDC instrumentation circuit was also included in the testing to understand how a voltage loop reacts in response to a fire. Each cable type was tested three times for the three different test circuit configurations.

3.3.1　4–20 mA Test Circuit

A schematic representation that simulates a typical 4–20 mA current loop is shown in Figure 3-1. Figure 3-2 illustrates the same 4–20 mA current loop, but not connected to a ground. The instrument loop design for the test consisted of a low-power current source, two 10 Ω resistors to simulate a long run of instrument cable (in this case 610 m (2,000 ft.), as opposed to the short length exposed during the fire test), a 250 Ω load resistor, and a National Instruments LabVIEW module to provide the simulated readout circuit. Note that the 250 Ω load resistor is analogous to a shunt resistor in an output meter that would convert the 4–20 mA signal into a 1–5 V signal. Use of such a shunt resistor at the output device is typical of many instrumentation circuit designs; 250 Ω is the maximum for a 4–20 mA standard current input (Ref. 5). If twisted pairs had grounded shielding, they were grounded at one and not both ends based on discussions with the project industry working group, who determined this as a common industry practice.
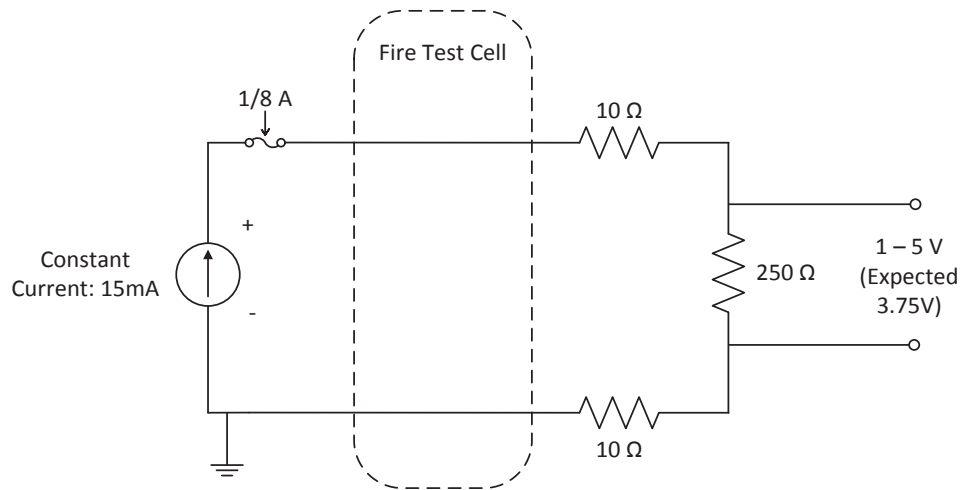

Figure 3-1　　4–20 mA Instrumentation Circuit for Fire Test, Grounded
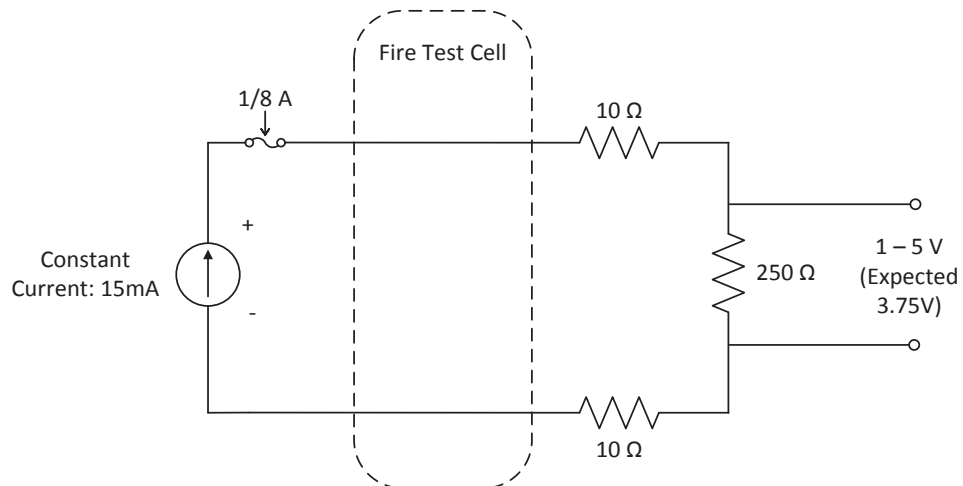

Figure 3-2　　4–20 mA Instrumentation Circuit for Fire Test, Ungrounded

The circuit was driven by a constant current output from a current source of approximately 15 mA. In typical instrumentation circuits, DC voltages are converted to current at the transmitter based

on sensor signals. To simulate this, a current source was used to maintain consistency instead of adding another variable to the fire test. A fire is assumed to only affect the instrumentation cable; the transmitter or receiver are assumed to be located in other rooms. Consequently, a constant current is expected from the transmitter, which is emulated through the current source.

As the fire degrades the instrument cable, some current can leak between the cable conductors, resulting in an apparent change in the instrument signal at the display device. That is, portions of the fixed 15 mA current signal may leak directly from conductor to conductor, bypassing the load/shunt resistor. This behavior was reflected as an inaccurate reading at the load resistor/voltmeter assembly.

Note that in presenting the data from this device, the actual measured output voltage was converted to an equivalent 0 to 100 percent process variable scale to ease the interpretation of the results. That is, an output reading of 1 V corresponds to 0 percent on the process variable scale, and an output reading of 5 V corresponds to 100 percent on the process variable scale. Given the constant input current of 15 mA, a reading of about 68 percent on the process variable scale is expected. If the two conductors form a "hard" (or very low impedance) short, the reading would go off-scale low on the process variable scale (i.e., a zero voltage would be off-scale low because the minimum anticipated current load under normal circuit conditions is 4 mA). Since the circuit is of such a simplistic nature, robust circuit simulators that Sandia has used in the past, specifically Surrogate Circuit Diagnostic Unit (SCDU), were not necessary.

3.3.2   10–50 mA Test Circuit

The 10–50 mA current loop design is similar to the 4–20 mA because a constant current source is used instead of a transmitter. Two 10 Ω resistors were again used to simulate a long length of instrument cable, and a 100 Ω load resistor acted as a shunt resistor. A LabVIEW module was again used to capture the voltage across the shunt resistor in the range of a 1–5 V signal.

The constant current output from the current source was approximately 37.5 mA. The output was chosen to have the same expected output as the 4–20 mA circuit: 3.75 V. The rest of the setup was the same as the ungrounded 4–20 mA instrumentation circuit. The fire behavior was reflected as an inaccurate reading at the shunt resistor and LabVIEW module assembly. See Figure 3-3 for the 10–50 mA current loop test setup.
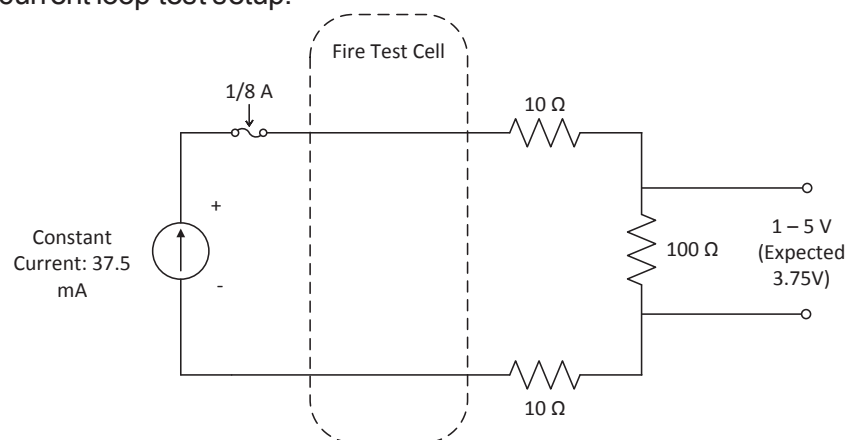

Figure 3-3   10–50 mA Instrumentation Circuit for Fire Test

3.3.3   1–5 VDC Test Circuit

A 24 VDC power supply was used instead of a current source. A resistor with a 620 Ω load, along with a line drop of 100 Ω and an intrinsic safety resistor of 250 Ω were included in the instrumentation circuit in place of a transmitter. The voltage drops across these loads equaled the constant voltage of 24 V. The load resistor was 250 Ω, which provided a standard output of 5 V, instead of the 3.75 V in the previous two instrumentation circuits. This is the maximum load for the voltage source, and in the field the transmitter load drop would be less than 620 Ω, but for the purposes of this test we decided to test the loop at 100 percent of its normal operating characteristics. A LabVIEW module was again used to measure the expected voltage from the shunt resistor. This ungrounded test circuit is illustrated in Figure 3-4.
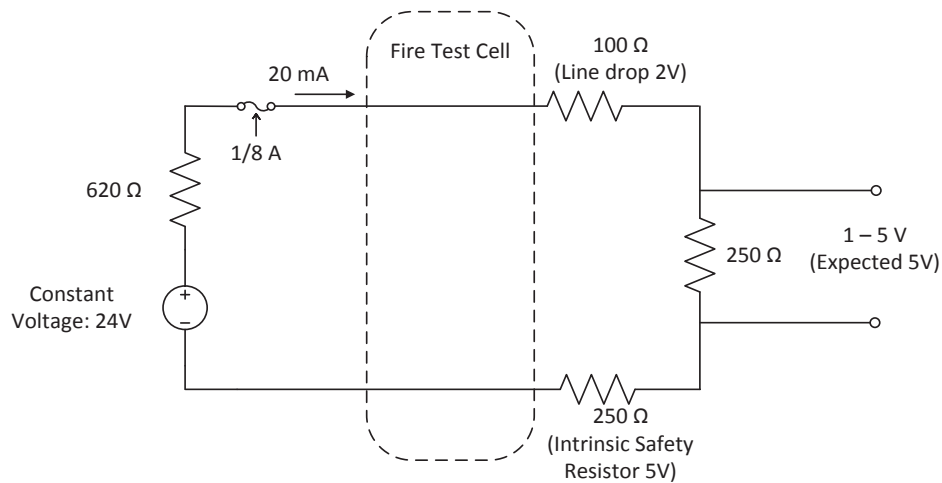

Figure 3-4   1–5 VDC Instrumentation Circuit for Fire Test

3.4   Small-Scale Radiant Heater

The ceramic fiber heater is constructed of ceramic fiber insulation, which isolates the heating chamber from the outside. The heater is light-weight, and its low-density properties make it ideally suited for high temperature applications requiring low thermal mass. The heater size was customized with the same cylindrical ring configuration that the Penlight heating apparatus utilized in previous testing. Penlight consisted of a cylindrical ring of 0.61 m (24 in) long water-cooled quartz lamps with a stainless cylindrical shroud 0.46 m (18 in) in diameter and 0.6 m (24 in) long. The ceramic fiber heater has an inner diameter of 0.41 m (16 in) and is 0.6 m (24 in) long. Similar to Penlight, the ceramic heater transferred heat radially onto the surface of the cables.

The exposure temperature was controlled and monitored by TCs mounted on the inner surface of the shroud. This created 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. The ceramic fiber heater simulates these conditions with shroud temperature and heat flux, assuming a constant emissivity of 0.85, listed in Table 3-2. The heater has a high emissivity coating which enables constant emissivity, shown in Figure 3-6.

Figure 3-5   Picture of Cable Test Setup (Left) and Ceramic Heater (Right)

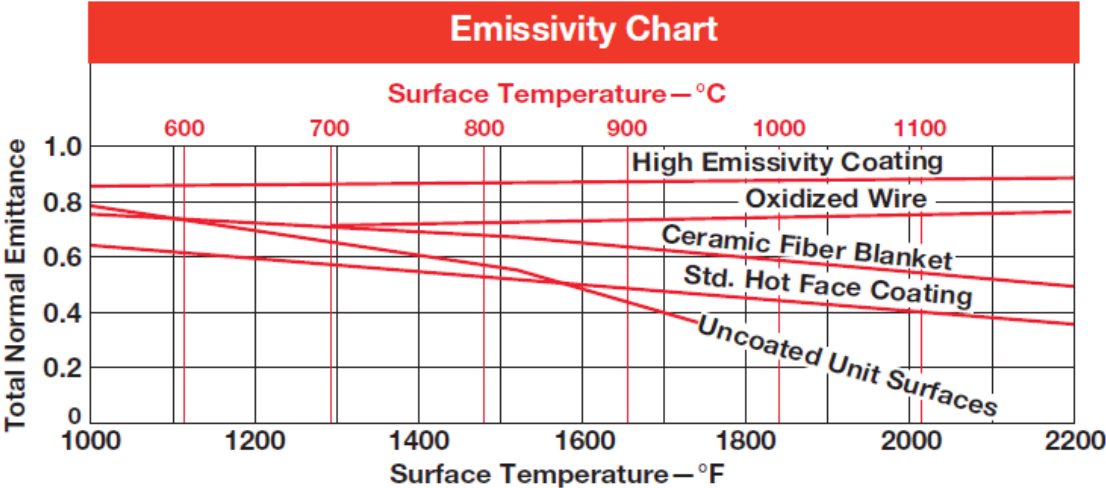

Figure 3-6   Emissivity of Heat Surface for Watlow Ceramic Fiber Heater[3]

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[3]   Source: Performance Data for Ceramic Fiber Heaters, Watlow Heaters
       http://catalog.watlow.com/Asset/Performance-Data-for-Ceramic-Fiber-Heaters.pdf

Table 3-2   Relationship between the Ceramic Fiber Heater Shroud Temperature and Radiant Heat Flux Based on Measured Emissivity of 0.85.

Temperature (°C)	Heat Flux (kW/m²)
200	2.42
225	2.97
250	3.61
275	4.35
300	5.20
325	6.17
350	7.27
375	8.51
400	9.90
425	11.45
450	13.18
475	15.10
500	17.22
525	19.56

Tests were conducted using paired cable lengths supported on a 30 cm (12 in) wide ladder-back style cable tray suspended through the center of the ceramic heater. There were no tests conducted using a conduit or air drop configuration. The cable tray and other physical test conditions are effectively identical to those used in CAROLFIRE and DESIREE-Fire. The plan for this series of testing was to lay the cables on a B-line ladder-back style cable tray suspended through the center of the ceramic fiber heating shroud. In every test, two cables were placed on the cable tray, shown in Figure 3-7. The tray was placed inside the heating apparatus. One of the cables was used for thermal monitoring and one for electrical monitoring, described further in Section 3.6. One additional test, not in the initial test plan, was conducted to determine whether the two parallel cables were receiving the same radiant heat flux from the ceramic heater. The Sandia team determined that, to properly test the TCs, an object with enough mass to represent the size of the cable had to be included. Two stainless steel rods were placed on the cable tray with one TC placed on the outside of each rod. This is shown in Figure 3-8.

Figure 3-7 Representative Cable Setup (Test 28)

Figure 3-8 Stainless Steel Rod Test Setup

The heating apparatus was set to 470°C with a ramp of 45°C/min. The difference in temperatures between the stainless steel (SS) rods was at maximum 4°C, which is a tolerable difference between cable temperatures. The final results of the test are shown in Figure 3-9.
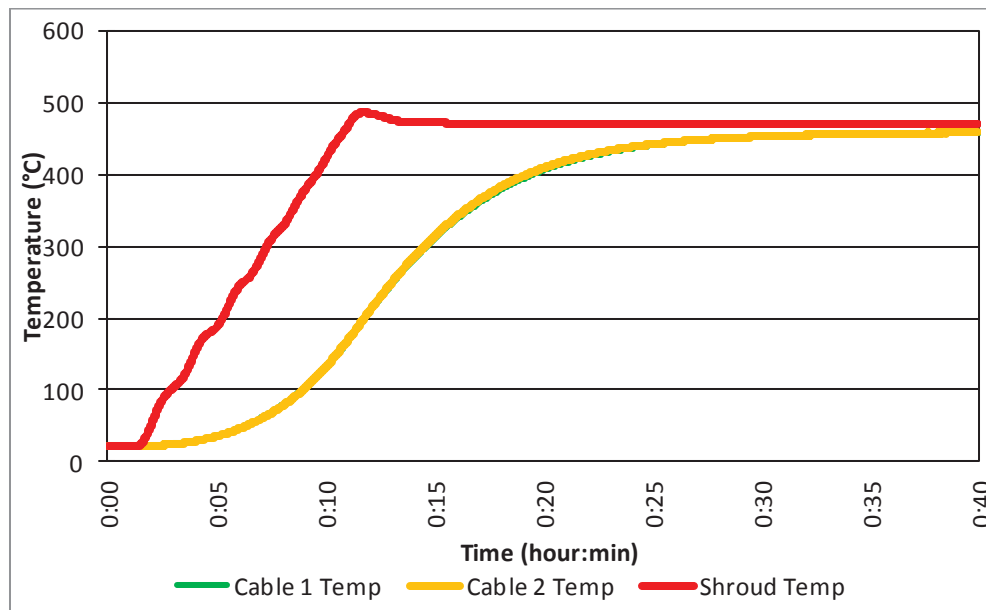

Figure 3-9 Shroud Thermocouple Test with Two SS Rods

The results of the testing determined that the difference in temperature between the two cables is negligible. For the testing results analysis, the TC temperature was used to determine the temperature at failure for the electrically monitored cables.

3.5 Temperature Heating Profiles

For comparison, heat profile information for the 2001 tests is included here, as the objective of this test plan was to confirm circuit behavior demonstrated in the 2001 tests. The 2001 testing took place in a 10 ft. by 10 ft. steel enclosure serving as a test chamber. A diffusion flame burner was used for all tests, with the radiant heat flux, shown in Table 3-3, calculated using the Oxygen Consumption Calorimetry principle described in ASTM E 1537. Cables were tested on a horizontal raceway in either a plume exposure, where the burner is placed directly under the cables, or a hot gas layer exposure, where the burner is offset approximately two feet toward the center of the room. Tests 14 and 16 were in plume exposure; Tests 13, 15, and 18 were in hot gas layer exposure. Test 17 was tested vertically with a radiant exposure. More details on test exposures can be found EPRI TR-1003326 (Ref. 16).

The CAROLFIRE and DESIREE-Fire series of tests used Penlight which has a maximum shroud temperature of about 900°C. Although one test was conducted at this temperature during the CAROLFIRE project, the rest of the tests used shroud temperatures ranging from 260–675°C to gauge when failure occurs. The instrumentation cables that were tested during the CAROLFIRE project were tested with a shroud temperature of 325°C for TP cables, and 470 or 475°C for the two TS cables. The thermal response cable for the TS cables ignited prior to electrical failure.

Table 3-3   Heat Fluxes and Temperatures from Previous Instrumentation Cable Testing

Test	Cable Description	Radiant Heat Flux Tested (kW/m^2)	Heat Release Rate (kW)	Shroud Temp. (°C)	Cable Temp. at Failure
IRMS_13	EPR/CSPE 8/c Armored (TS/TS)	n/a	350	n/a	unknown
IRMS_14	PE/PVC 2/c Shielded 16 AWG (TP/TP)	n/a	145	n/a	unknown
IRMS_15	Thermoset[1], 1/pair shielded 16 AWG (TS/TS)	n/a	Variable (350/200/450)	n/a	unknown
IRMS_16	PVC/PVC 3/pair shielded (TP/TP)	n/a	145	n/a	unknown
IRMS_17	EPDM/CSPE 2/c (TS/TS)	n/a	200	n/a	unknown
IRMS_18	EPR/CSPE (TS/TS)	n/a	250	n/a	unknown
CAROLFIRE_62	XLPE/CSPE 12/c 18 AWG (TS/TS)	14.5	n/a	475	n/a
CAROLFIRE_63	PVC/PVC 12/c 18 AWG (TP/TP)	5.9	n/a	325	205
CAROLFIRE_64	XLPE/CSPE 2/c 16 AWG (TS/TS)	14.1	n/a	470	n/a
CAROLFIRE_65	PVC/PVC 2/c 16 AWG (TP/TP)	5.9	n/a	325	225
[1]Although the exact cable material couldn't be found, based on the information from the cable notebook the material is most likely FR-XLPE/CSPE.					

As in previous tests, the goal was to characterize the degradation of cable integrity and behavior, nominally on the order of 10–30 minutes. This amount of time to failure was selected given the nature of typical NPP fires and the types of fire scenarios found to be important in risk analysis.

TP cables fail electrically when their inner (under the jacket) temperatures reach somewhere between 200°C and 250°C (Ref. 17). The failure temperature of 200°C is used in the NRC Thermally-Induced Electrical Failure (THIEF) Model (Ref. 18) for TP instrumentation cables. A ramp-and-hold profile was used to achieve this failure within the target time frame of 10–30 minutes. The intent of the ramp-and-hold profile is not to explicitly represent any particular fire profile but to generically represent typical fire behavior. The temperature of the heating shroud was 325°C for TP cables in the DESIREE-Fire series of tests. This temperature provides a heat flux of 6.17 kW/m^2 and is expected to cause longer TP failure times. When this testing was conducted, the heating apparatus was set to the desired temperature, which it achieved quickly and maintained. Times to failure were expected to be longer than the CAROLFIRE and DESIREE-Fire results due to the gradual increase in temperature, which is more representative of fire behavior.

The ceramic fiber heater was started at ambient temperature, around 20°C (68°F). The first test for both TP and TS cables was intended to determine the appropriate temperature to achieve failure within the target time frame of 10–30 minutes and were performed at lower temperature levels. The damage criteria for generic electrical cables in a fire probabilistic risk assessment is 205°C for TP cables and 330°C for TS cables, according to the EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities (Ref. 19).

Preliminary Test 1 was conducted with a temperature rate of rise of 10°C/min to a maximum temperature of 205°C for a TP cable. After an hour of heating, the cable had not failed, so the temperature was raised incrementally until failure occurred. The test director determined that the higher heater temperature would align better to the desired failure time of 10–30 minutes, and reflect realistically expected heating profiles in a fire. Preliminary Test 3 ramped to a higher temperature of 325°C, and failure of the TP cable occurred around 30 min. Therefore, the ramp slope was increased from 10°C/min to 45°C/min. This heating ramp reaches the maximum temperature at 410 seconds (6.8 min). The heating apparatus held this constant temperature until failures were observed. Note that time t=0 was defined as the time when the primary ramp was initiated. Figure 3-10 illustrates the final heating profile that was used during all non-preliminary TP cable tests.
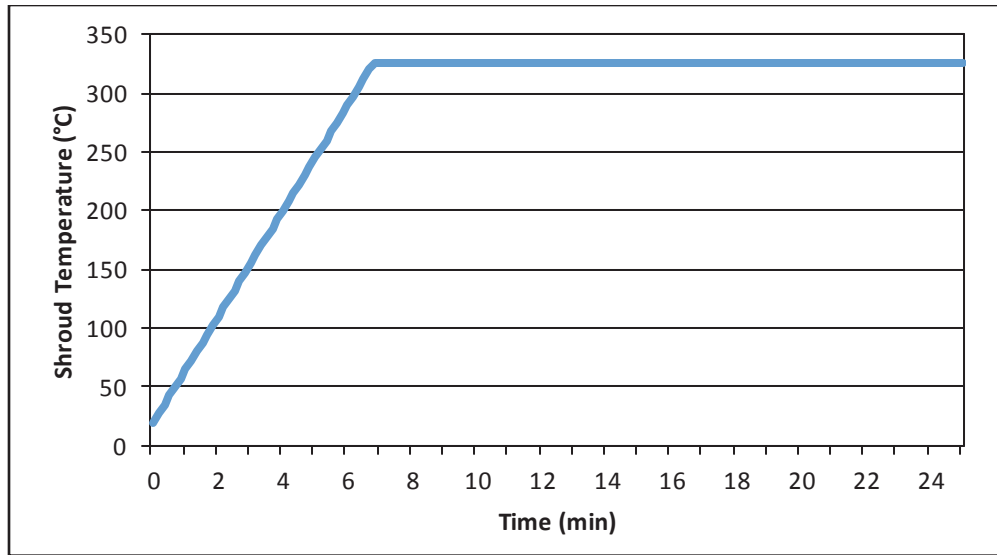
Figure 3-10   Thermoplastic Cable Heating Profile - 325°C

To test the TS cables, a similar heating profile was created. TS cables failed electrically when their inner (under the jacket) temperatures reached somewhere between 400°C and 450°C (Ref. 17). The failure temperature of 400°C is used in the THIEF model (Ref. 18) for TS instrumentation cables. The temperature of the heating shroud was 470°C for TS cables in the DESIREE-Fire tests. This temperature provides a heat flux of 14.1 kW/m^2 and is expected to cause longer TS failure times. TS cables fail earlier than the desired time at a heat flux of 26.9 kW/m^2 (600°C) (Ref. 10).

Preliminary Test 2 was conducted with a rise of 10°C/minute to a maximum temperature of 330°C for a TS cable. After an hour of heating, the cable had not failed, so the test was concluded. Again, the test director determined that the higher heater temperature would align better to the desired failure time of between 10–30 minutes reflecting a realistic expected heating profile in a fire. Preliminary Test 3 ramped to a higher temperature (470°C) using the same 10°C/min ramp and failure occurred around 48 minutes for the TS cable. Therefore, the ramp slope was increased from 10°C/min to 45°C/min. The ramp began from 20°C to 470°C at the rate of 45°C (113°F) per minute. The shroud should reach 470°C at 600 seconds (10 min). The higher temperatures for TS cables correspond to the higher temperature failure rates observed in the CAROLFIRE series of tests. Again, time t=0 is defined as the time when the primary ramp was initiated and the maximum temperature (470°C) was held until failures are observed. Figure 3-11 illustrates the final heating profile that was used during all subsequent TP cable tests.
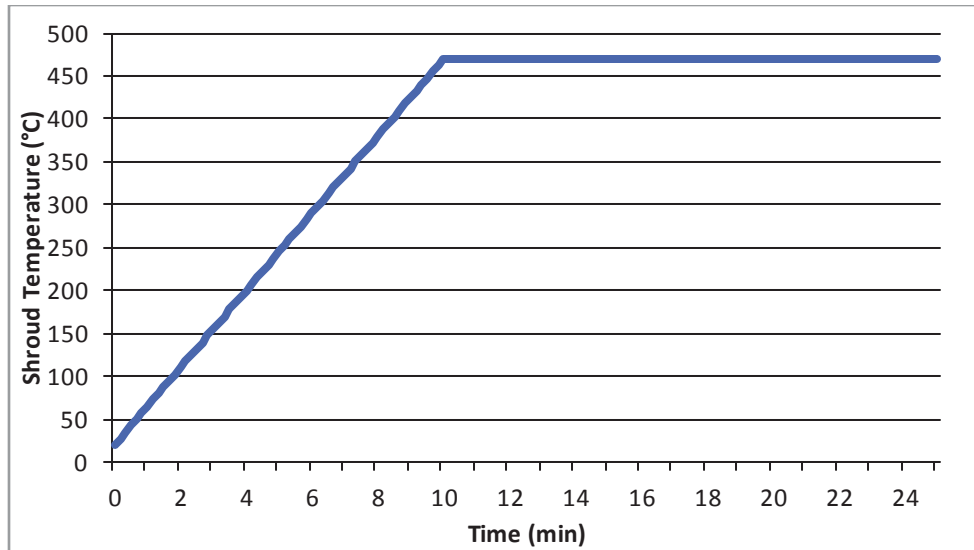
Figure 3-11   Thermoset Cable Heating Profile - 470°C

The exact heating protocol for each test is specified in the detailed test matrix provided in Section 4.

3.6   Diagnostic Instrumentation Summary

As a general practice, cables were tested in symmetric pairs; one cable was instrumented with Type-K TCs and inserted just below the outer cable jacket to measure the cable temperature response, while a second length of cable was routed in a symmetric position on the tray (relative to the shroud) and connected to energized electrical integrity test circuits to monitor electrical performance. This cable pairing approach allowed for a direct correlation of temperature response to electrical performance without compromising the electrical integrity of the energized cable. It is not appropriate to instrument any single cable for both thermal and electrical response, because the instillation of a TC on or within a cable could impact the electrical failure behavior. Given the results of testing performed, the temperature and electrical signal can be correlated because the temperature difference between the two cables is negligible, as discussed in Section 3.4. The conductor number used for electrical monitoring was documented in lab notebooks during testing. Raceways used were B-Line Brand Series 268, ladder back, 12 in-wide galvanized steel trays.

3.6.1   Cable Electrical Performance Monitoring

National Instruments LabVIEW modules were used to read current and voltage from the circuits as described in Section 3.3. The power supply is a Keithley 2400 Source Meter. LabVIEW outputted the following information:

- Upper Shell Temperature from a TC on the upper part of the heating shroud
- Lower Shell Temperature from a TC on the lower part of the heating shroud
- Internal Shell Temperature from a TC placed on the side of the heating shroud
- Tray Temperature from a TC placed on the cable tray
- Cable Temperature from a TC placed in the thermally monitored cable
- Cable Voltage captured at the load resistor
- Heater Setpoint captured the temperature at which the heater was set

- Heater Setpoint captured the temperature at which the heater was set
- Heater Power percent captured the power the heater was consuming to reach the heater setpoint.

For the analysis of the results, upper shell temperature was used to compare the shroud temperature. Lower shell temperature, internal shell temperature and the cable tray temperature were not included in the analysis or the graphs but was preserved in the original documentation. Heater setpoint and heater power were also not included in the analysis, but again are preserved in the original documentation. Cable temperature and cable voltage were the primary variables analyzed.

The corresponding data for the tests contain two sets of time records. The first set of time records is a "raw" data acquisition time and is labeled "DAQ time" for Data Acquisition time. The "DAQ Time" starts at time=0 and is the time when the data acquisition time was started. This is the time that is original to the data files. The second set of time records is labeled "Heater Time" and this set is indexed such that time time=0 corresponds to when the heater ramp was initiated. The difference between the "DAQ Time" and the "Heater Time" is a simple constant offset that reflects the length of time over which baseline data was collected prior to initiation of initial conditions and proper operation of data acquisition systems. For the purposes of data reporting, all time references use the "DAQ Time" records, unless otherwise noted. APPENDIX A lists the difference in "DAQ Time" and "Heater Time."

3.6.2   Thermal Response Monitoring

The cable's temperature response was measured using a TC inserted below a 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 (Ref. 8)). That is, prior testing has shown that the cable insulation temperature is well correlated to electrical failure, and subjacket TCs provide a reasonable measure of cable insulation temperature. Insertion of a TC potentially compromises a cable's electrical integrity, so temperature response cables were not monitored for electrical performance. The cable used for monitoring temperature response was the same instrumentation cable type as the cable used for determining electrical failure.

The TCs were Omega, Type-K (part number KMQIN-040U-18) and were placed just below the cable jacket. A small slit in the cable jacket allowed for TC bead insertion. The bead itself was inserted at a distance of approximately 2.5–10 cm (1–4 in) along the length of the cable, placing it well away from the cut in the outer jacket, shown in Figure 3-13. The slit was then closed and secured with a single layer of fiberglass tape. In Figure 3-13, the tape indicates where the slit was made and the silver mark on the cable shows where the TC ended. Figure 3-12 demonstrates the placement of the TC under the jacket and shows the relation of the temperature monitored cable to the electrically monitored cable. TCs were electrically isolated from conductors.
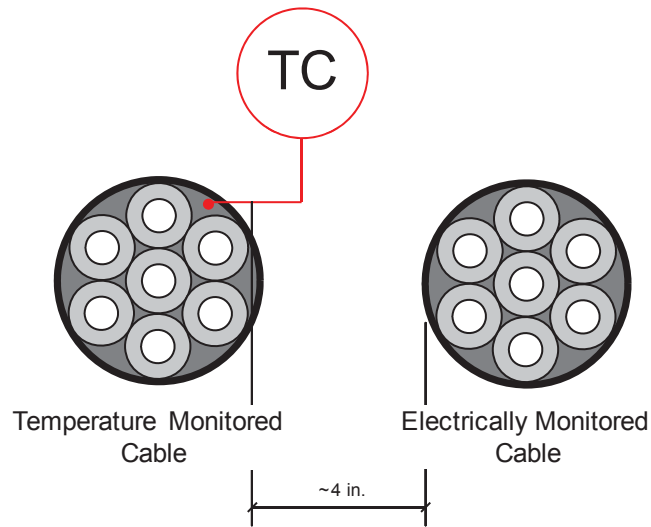
Figure 3-12   Example Thermocouple Arrangement for Monitoring of 7-Conductor Cable near the Electrically Monitored Cable in Tray

Figure 3-13   Representative Cable Setup Illustrating TC Placement (Test 21)

4   TEST MATRIX

Table 4-1 provides test matrices details for small-scale tests performed at Sandia National Laboratories. The goal of the program was to maintain the option to adjust test matrices based on insights gained as the program progressed. Test matrices described here document tests performed. The test numbers were designated in the initial test plan matrix. Tests were not performed sequentially in the same order as would indicate the test number; therefore Table 4-2 provides an alternate listing of the tests arranged by order performed, with comments relating to test anomalies, changes in test configurations, or changes in test protocols implemented during testing. The order varied according to logistics and productivity optimization. A total of thirty-eight tests were conducted with cables, in addition to four preliminary tests, and one test designed to examine heat applied to the cable tray.

Four preliminary tests were conducted prior to entering the primary test matrix and are numbered separately from the primary tests. Data from these tests was used to determine the optimal setpoint and ramp rate to simulate cable failure between 10–30 minutes, the target time frame as documented in the test plan. A 45°C ramp was deemed sufficient to achieve the 325°C setpoint for TP and 470°C setpoint for TS cables.

For the other cited test parameters, an "X" in any given column indicates the active choice for each experimental variable. The primary test variables are as follows:

- <u>Cable manufacturer</u> specifies the cable manufacturer
- <u>Cable insulation and jacket material</u> specifies the cable insulation and jacket material for the cables tested
- <u>Number of twisted pairs or conductors</u> specifies the number of twisted pairs in each cable or the number of individual conductors in each cable
- <u>Shielded pairs</u> specifies whether the twisted pairs have a shield
- <u>Thermal exposure</u> defines the initial setpoint temperature of the heating apparatus; the final set point is either 325°C or 470°C (617°F or 878°F), for TP and TS samples, respectively. Two tests were done on a lower heating setting of 205°C or 330°C or (401°F or 626°F) for TP and TS samples to analyze the failure in a less severe but still damaging condition.
- <u>Instrumentation circuit</u> specifies which instrumentation circuit was utilized

For all tests, conductor size was 16 AWG. All cables had overall shields between insulated conductors and the cable jacket. When twisted pairs were grounded, overall shields were also grounded. Three additional variables warrant further discussion. First, as shown in Table 4-1 there was variability in whether the circuit was grounded. As discussed in the CAROLFIRE report, grounding the power supply had a pronounced effect on the testing of armored cables in 2001 tests. As a result, CAROLFIRE test data revealed no significant differences between ungrounded and grounded circuits for non-armored cables. In this series of testing, tests were conducted with the circuit grounded and ungrounded, as many instrumentation circuits are ungrounded for increased reliability. Second, industry practice defines that in most instances cable shields are grounded at one end to the station ground. This was also included as a variable for a few tests to determine if grounding the shield made a difference in the failure of the cable. Finally, the inclusion of a fuse between the power supply and circuit was considered a variable. The fuse was initially included to match the 2001 tests; however, the impact of the fuse addition was considered minimal, and therefore was included as a variable.

Table 4-1   Matrix of Small-Scale Instrumentation Cable Tests

Burn Test Number	Cable Number	Manufacturer	TP PVC/PVC	TP XLPE/CSPE	TS FR-EPR/CPE	TS XLPE/LSZH	Pairs 1	2	4	8	2/c	4/c	Pairs Shielded	Thermal Exposure (°C)	Circuit 4-20 mA	10-50 mA	1-5 VDC	Circuit Grounded to Power Supply	Cable Shielding Grounded	Circuit Included Fuse	Date Completed	Notes
Prelim 1	1004	B	x					x						205	x			x			2/16/2017	
Prelim 2	1008	B				x	x						x	330	x			x			2/17/2017	
Prelim 3	1004	B	x					x						325	x			x			2/17/2017	
Prelim 4	1008	B				x	x						x	470	x			x			2/20/2017	
1	1004	B	x					x						325	x			x			2/20/2017	
2	1005	B	x							x				325	x			x			2/21/2017	
3A	1006	B			x			x					x	470	x			x			2/21/2017	
3B	1006	B			x			x					x	470	x			x			2/21/2017	1
3C	1006	B			x			x					x	470	x			x			2/21/2017	1
4A	1007	B			x					x			x	470	x			x			2/23/2017	
4B	1007	B			x					x			x	470	x			x			2/23/2017	1
5	1008	B				x	x							470	x			x			2/27/2017	
6A	1009	B				x				x			x	470	x			x	x		2/27/2017	2
6B	1009	B				x				x			x	470	x			x			2/27/2017	2
7	1000	RB		x							x			470	x			x			2/22/2017	3
8A	1001	RB		x								x		470	x			x			2/22/2017	4
8B	1002	RB		x								x		470	x						2/22/2017	4
9	1003	RB		x				x					x	470	x			x			2/23/2017	
10	1004	B		x					x				x	470	x			x			2/23/2017	
11	1000	RB		x							x			470	x			x			2/22/2017	3
12	1004	B	x					x						325		x		x	x		3/2/2017	

Table 4-1   Matrix of Small-Scale Instrumentation Cable Tests (Cont'd.)

Burn Test Number	Cable Number	Manufacturer	TP PVC/PVC	TP XLPE/CSPE	TS FR-EPR/CPE	TS XLPE/LSZH	1	2	4	8	2/c	4/c	Pairs Shielded	Thermal Exposure (°C)	4–20 mA	10–50 mA	1–5 VDC	Circuit Grounded to Power Supply	Cable Shielding Grounded	Circuit Included Fuse	Date Completed	Notes
13	1005	B	x							x				325		x		x	x		3/2/2017	
14	1006	B			x			x					x	470		x		x	x		2/28/2017	
15	1007	B			x					x			x	470		x		x	x		3/2/2017	
16	1008	B				x	x							470		x		x	x		2/28/2017	
17	1009	B				x				x			x	470		x		x	x		3/1/2017	
18A	1000	RB		x							x			470		x		x	x		2/28/2017	5
18B	1000	RB		x							x		x	470		x		x	x	x	3/3/2017	5
19	1001	RB		x								x		470		x		x	x		3/1/2017	
20	1002	RB		x				x					x	470		x		x	x		3/1/2017	
21	1003	RB		x					x				x	470		x		x	x		3/1/2017	
22	1004	B	x					x						325			x	x	x	x	3/6/2017	
23	1005	B	x							x				325			x	x	x	x	3/6/2017	
24	1006	B			x			x					x	470			x	x	x	x	3/6/2017	
25	1007	B			x					x			x	470			x	x	x	x	3/7/2017	
26	1008	B				x	x							470			x	x	x	x	3/6/2017	
27	1009	B				x				x			x	470			x	x	x	x	3/8/2017	
28	1000	RB		x							x			470			x	x	x	x	3/6/2017	
29	1001	RB		x								x		470			x	x	x	x	3/7/2017	
30	1002	RB		x				x					x	470			x	x	x	x	3/7/2017	
31	1003	RB		x					x				x	470			x	x	x	x	3/7/2017	
32	CC4	GC	x								x		x	325		x		x	x	x	3/8/2017	
33	CC7	RB-S		x							x		x	470		x		x	x	x	3/8/2017	
34	SS Rod	n/a												470							3/9/2017	6

Notes

Conductors for all experiments were 16 AWG.
A cable tray was used for all experiments.
Manufacturers: Rockbestos (RB), Belden (B), General Cable (GC) and Rockbestos-Surprenant (RB-S)
1: These tests are repeats to determine the reproducibility of the test.
2: The difference between these tests is the cable shield was ungrounded for 6B.
3: The difference between these tests is the circuit is grounded for Test 7 and ungrounded for 11.
4: The difference between these tests is the circuit is grounded for Test 8A and ungrounded for 8B.
5: The difference between these tests is Test 18B had a fuse addition.
6: This test analyzed the TC response for two stainless steel tubes.

Table 4-2:   Chronology of Instrumentation Tests

Date	Burn Test #	Cable Number	Comments including changes to test protocols
Begin Small Scale Testing 2/16/2017			
2/16/2017	Prelim 1	1004	
2/17/2017	Prelim 2	1008	
2/17/2017	Prelim 3	1004	
2/20/2017	Prelim 4	1008	
2/20/2017	1	1004	
2/21/2017	2	1005	
2/21/2017	3A	1006	
2/21/2017	3B	1006	
2/21/2017	3C	1006	
2/22/2017	7A	1000	Moved to nuclear grade Rockbestos cables to try to see the delayed failure behavior.
2/22/2017	11	1000	This test is listed as test 7-U (ungrounded) in the lab notebook. In this test, 7A was repeated except the circuit was ungrounded.
2/22/2017	8A	1001	
2/22/2017	8B-U	1001	This test repeated 8A except the circuit was ungrounded. After seeing no apparent difference between grounding and not circuit, the remaining tests grounded all the circuits.
2/23/2017	9	1002	
2/23/2017	10	1003	
2/23/2017	4A	1007	
2/23/2017	4B	1007	Repeated Test 4A to determine if 20+ minute leakage time is an anomaly. The same long leakage was seen during this test.

Table 4-2:   Chronology of Instrumentation Tests (Cont'd)

Date	Burn Test #	Cable Number	Comments including changes to test protocols
2/27/2017	5	1008	
2/27/2017	6A	1009	This is the first test where the shield was grounded. Likely, the shield touches the cable tray so it becomes ground, however industry practice is to ground one end of the shield.
2/27/2017	6B	1009	This test repeats 6A but the shield is ungrounded to determine if there is a difference. There was not a substantial difference between test 6A and 6B so from here the cable shield and, if available the twisted pair shield, will be grounded to the facility ground.
2/28/2017	14	1006	
2/28/2017	16	1008	
2/28/2017	18A	1000	
3/1/2017	19	1001	
3/1/2017	20	1002	
3/1/2017	21	1003	
3/1/2017	17	HW6	
3/2/2017	15	1007	
3/2/2017	12	1004	
3/2/2017	13	1005	
3/3/2017	18B	1000	This test added a fuse to the circuit. The intent was to determine if there was a difference with the addition of the fuse. Due to no significant difference, remaining tests included a fuse in the circuit.
3/6/2017	22	1004	
3/6/2017	23	1005	
3/6/2017	24	1006	

Table 4-2:   Chronology of Instrumentation Tests (Cont'd)

Date	Burn Test #	Cable Number	Comments including changes to test protocols
3/6/2017	26	1008	
3/6/2017	28	1000	
3/7/2017	29	1001	
3/7/2017	30	1002	
3/7/2017	31	1003	
3/7/2017	25	1007	
3/8/2017	27	1009	
3/8/2017	32	CC4	The CAROLFIRE cables were added at the end of the test plan. Although CAROLFIRE had a faster ramp rate, we decided to test these cables according to our test plan.
3/8/2017	33	CC7	
3/9/2017	34	SS Rod	This test looked at the difference in heating profile between the cable with the thermocouple verses the cable that carries the electrical signal. Two stainless steel rods with thermocouples were tested to determine if there was a difference in the heater's profile. The difference was minimal so no additional testing is needed.

5 SMALL-SCALE TEST RESULTS

5.1 Organization and Content

Test results are presented in this section with specific plots to illustrate key aspects of testing. Section organization is as follows:

- Section 5.2 includes the calculation of signal degradation, failure and leakage times
- Section 5.3 introduces the regression analysis
- Section 5.4 reviews the experimental test results in the order of the regression analysis

Test results have been presented in a summarized form and only those plots that illustrate an important point or test result have been reproduced here. A detailed summary and graphs for every test are included in APPENDIX A .

5.2 Calculating Signal Degradation, Failure and Leakage Times

An important part of analysis is the definition of the time the signal begins to degrade and the time the signal fails. After a discussion with a Sandia research reactor operator who has previous experience with a commercial plant, the significance criteria for signal degradation varies widely from 0.25 percent to 2 percent, depending on what is being measured and the required accuracy (Ref. 20). For the purposes of this analysis, the conservative 0.25 percent degradation was used to designate signal degradation times for all tests.

The next step is to determine signal failure times. Typical 4–20 mA circuits are designed to show circuit failure when the current is less than 4 mA. For example, a loss of power would indicate 0 mA, instead of the expected 0 percent output of 4 mA for a typical 4–20 mA design. For this analysis, anything less than 4 mA was designated a signal failure time for the 4–20 mA circuit. For the 10–50 mA circuit, the signal failure time was less than 10 mA. Finally, for the 1–5 VDC circuit the failure point was when the voltage was less than 1 V.

For both cable insulation/jacket material types, as the temperature was nearing the failure temperature, at times a sudden drop and restoration of the current was seen, as shown in detail in Appendix A. This noise is shown in Test 8A and Figure 5-1, and illustrates how the current could drop to 0 mA and restore itself quickly. Signal failure was designated as the first time the current or voltage fell below 4 mA, 10 mA, or 1 V, depending on the circuit design, since this would be the first indication of an issue.
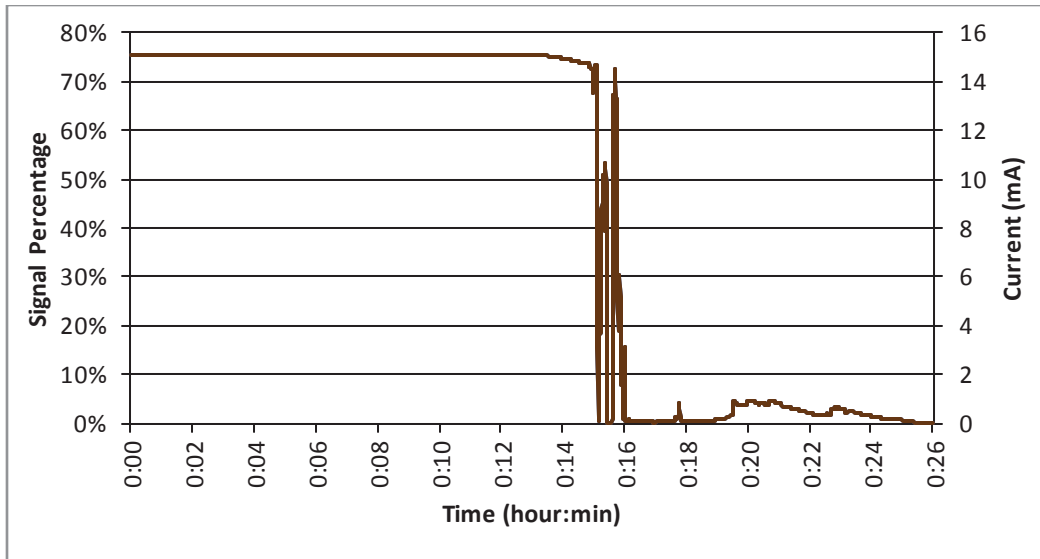
Figure 5-1   Test 8A Noise Example

To summarize, *signal degradation time* is when the signal has dropped 0.25 percent from its starting value. *Signal failure time* is when the current or voltage has fallen to less than 4 mA for 4-20 mA circuits, less than 10 mA for 10–50 mA circuits, and less than 1 V for 1–5 VDC circuits. The difference between the signal failure time and the signal degradation time is called *signal leakage time*.

The signal degradation, failure, and leakage times and the temperature of the cable at signal degradation and failure for all tests are shown in Table 5-1. Figure 5-2 illustrates the temperatures for the cables at signal failure by TP or TS cable type and number of conductors.

Table 5-1   Signal Degradation, Failure, and Leakage Times for All Tests

Burn Test Number	Cable Number	Insulation/ Jacket Material	TS or TP	Number of Conductors	Signal Degradation Time (s)[1]	Temp. at Signal Degradation Time (°C)	Signal Failure Time (s)	Temp. at Signal Failure Time (°C)	Signal Leakage Time (min:sec)[2]
1	1004	PVC/PVC	TP	4	674	226	675	226	00:01
2	1005	PVC/PVC	TP	16	835	229	835	229	00:00
3A	1006	FR-EPR/CPE	TS	4	912	445	963	461	00:51
3B	1006	FR-EPR/CPE	TS	4	958	420	989	444	00:31
3C	1006	FR-EPR/CPE	TS	4	911	483	951	489	00:40
4A	1007	FR-EPR/CPE	TS	16	1134	404	1739	516	10:05
4B	1007	FR-EPR/CPE	TS	16	1142	428	1975	494	13:53
5	1008	XLPE-LSZH	TS	2	1023	499	1023	499	00:00
6A	1009	XLPE-LSZH	TS	16	1804	444	1804	444	00:00
6B	1009	XLPE-LSZH	TS	16	1665	449	1665	449	00:00
7	1000	XLPE/CSPE	TS	2	745	418	839	476	01:34
8A	1001	XLPE/CSPE	TS	4	750	406	847	476	01:37
8B	1001	XLPE/CSPE	TS	4	746	416	860	477	01:54
9	1002	XLPE/CSPE	TS	4	858	384	1013	452	02:35
10	1003	XLPE/CSPE	TS	8	926	376	1130	443	03:24
11	1000	XLPE/CSPE	TS	2	745	415	833	502	01:28
12	1004	PVC/PVC	TP	4	621	242	621	242	00:00
13	1005	PVC/PVC	TP	16	922	226	923	226	00:01
14	1006	FR-EPR/CPE	TS	4	909	443	946	451	00:37
15	1007	FR-EPR/CPE	TS	16	1113	380	2382	475	21:09
16	1008	XLPE/LSZH	TS	2	897	501	898	501	00:01
17	1009	XLPE/LSZH	TS	16	1820	421	1821	421	00:01
18A	1000	XLPE/CSPE	TS	2	738	406	845	463	01:47
18B	1000	XLPE/CSPE	TS	2	767	398	896	454	02:09
19	1001	XLPE/CSPE	TS	4	763	404	898	456	02:15
20	1002	XLPE/CSPE	TS	4	865	402	1013	453	02:28

Table 5-1   Signal Degradation, Failure, and Leakage Times for All Tests (Cont'd.)

Burn Test Number	Cable Number	Insulation/ Jacket Material	TS or TP	Number of Conductors	Signal Degradation Time (s)[1]	Temp. at Signal Degradation Time (°C)	Signal Failure Time (s)	Temp. at Signal Failure Time (°C)	Signal Leakage Time (min:sec)[2]
21	1003	XLPE/CSPE	TS	8	971	376	1235	443	04:24
22	1004	PVC/PVC	TP	4	657	242	660	244	00:03
23	1005	PVC/PVC	TP	16	875	236	1031	250	02:36
24	1006	FR-EPR/CPE	TS	4	900	422	959	451	00:59
25	1007	FR-EPR/CPE	TS	16	1116	383	2379	460	21:03
26	1008	XLPE/LSZH	TS	2	939	465	940	465	00:01
27	1009	XLPE/LSZH	TS	16	1820	423	1820	423	00:00
28	1000	XLPE/CSPE	TS	2	741	380	872	461	02:11
29	1001	XLPE/CSPE	TS	4	744	386	895	453	02:31
30	1002	XLPE/CSPE	TS	4	843	377	1023	446	03:00
31	1003	XLPE/CSPE	TS	8	949	369	1222	434	04:33
32	CC4	PVC/PVC	TP	2	549	229	549	229	00:00
33	CC7	XLPE/CSPE	TS	2	725	401	818	452	01:33

[1]Signal Degradation Time is based on a 0.25 percent degradation
[2]Signal Leakage Time is equal to Signal Failure Time minus Signal Degradation Time.
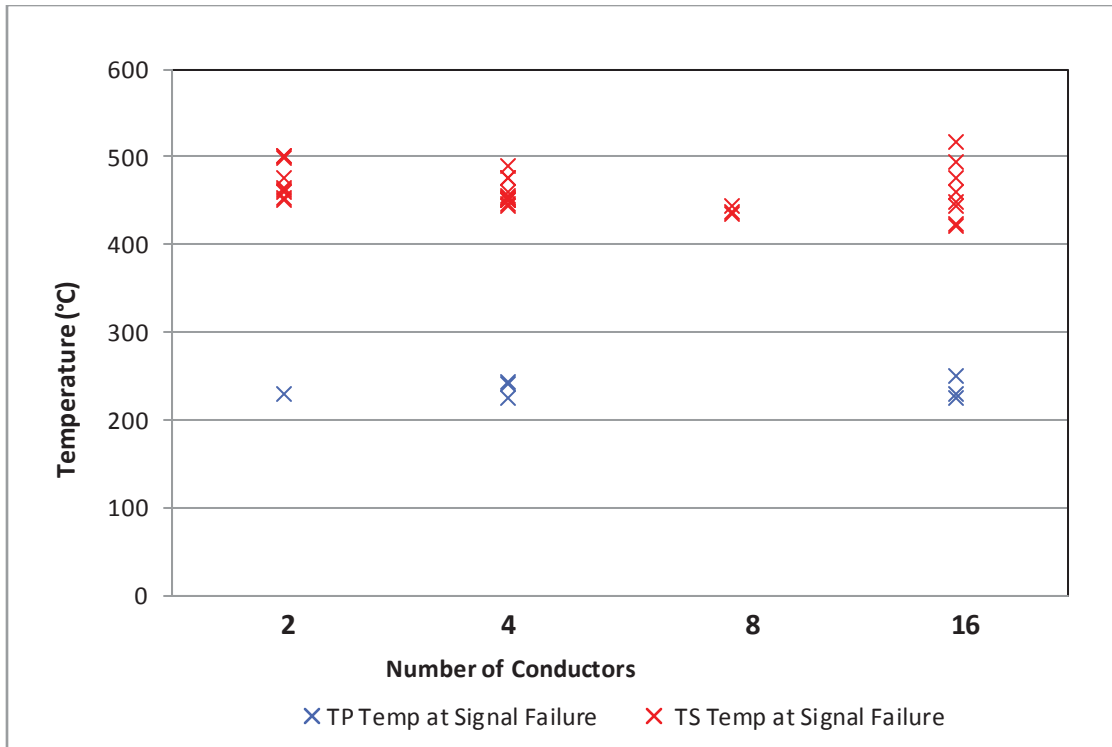
Figure 5-2   Temperature at Signal Failure

At first glance, the FR-EPR/CPE eight-twisted pair cable had a significant signal leakage time compared to the other cables. However, a regression analysis was performed to better understand the key variables that drive signal leakage time.

5.3   Regression Analysis

A linear regression analysis was performed on the test data to determine the key variables that contribute to longer leakage times. Regression analysis is used to predict the value of one variable on the basis of other variables (Ref. 21). The dependent variable is the variable to forecast (i.e., the variable of interest to understand dependencies); for this analysis, it is the time it takes for the cable to lose signal below a certain threshold, or signal leakage time. The other variables are called independent variables. In our analysis, the independent variables are:

- Manufacturer
- Insulation/jacket material combination
- Thermoset or thermoplastic
- Number of conductors
- Pairs shielded or not shielded
- Circuit type
- Circuit grounded or not grounded
- Shield grounded or not grounded
- Circuit with a fuse or circuit without a fuse

The independent and dependent variables were put into the RPART package[4] in R[5], a program for statistical and computing graphics, which performs recursive partitioning for the analysis. Recursive partitioning was optimal for this analysis because it detects how the leakage time might be affected by two parameters interacting, versus a linear regression which can only detect linear trends and not the effects of two interacting parameters.

R constructed a decision tree by splitting or not splitting nodes to best classify or estimate a response variable. The advantage of using a decision tree is that is easier to understand because of its binary nature and visual representation (Ref. 22). The top node of a decision tree is called the parent node and shows the independent variable with the most influence over leakage time. This top node is split at a determined value along a range of values for a variable, thus producing two child nodes with greater homogeneity than the parent node. R iterates all possible values of independent variables to identify the first split, as well as the cut point for the split, to result in one group having a strong link to signal leakage time. The terminal or bottom nodes of the tree are where the data is not split further and shows the different regions of data categorization.

The decision tree is shown in Figure 5-3. The node color gradient represents the magnitude of the leakage time (i.e., the darker the color the longer the leakage time). Percentages at each node indicate the percentage of data in that node. For example, the top node is set to 100 percent because it encompasses the entire data set. The 'n' value is the number of data points (i.e., tests) in that node; the number on top of each node is the mean leakage time for that node. The complexity parameter (cp) value determines the cutoff valve for improvements to the model R-squared value, or whether to split a node. The main role of the cp value is to prune splits from the tree that are not worthwhile (Ref. 9). The cp value for this tree was set to 0.01, which means only the most significant parameters were identified. A smaller cp leads to a larger decision tree.

As shown, the first split is material type, separating out FR-EPR/CPE cables with other insulation/jacket material types (PVC/PVC, XLPE/LSZH, XLPE/CSPE). These next layer of nodes are then recursively treated as parent nodes, thereby continuously splitting the data to further sift out key variables with the most impact on leakage time. For this analysis, the FR-EPR/CPE node is split between number of conductors and the remaining insulation/jacket material types.

The decision tree shows the regression analysis in an understandable manner. The results for a linear regression are shown in

Table 5-2. These results include the number of degrees of freedom (related to the number of data points and variables used), the sum of the squares which is a measure of the variability in the data, and the mean square (MS) which is the sum of squares divided by the degrees of freedom for normalization. The f-test compares the variance in the data explained by the model (row titled "Regression") to the variation in the data that is seemingly due to random error (row titled "Residual"). If the regression model is explaining some of the variance in the data, then the MS Regression value increases compared to the MS Residual. Therefore, because the f-test value is greater than 1, there is evidence that more of the variation in the data is explained by the model than random chance, highlighted in the table. The significance level for this test is at a typical cutoff point, so the model is explaining some variance but more investigative work can be done.

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[4] Recursive partitioning for classification, regression and survival trees. An implementation of most of the functionality of the 1984 book by Breiman, Friedman, Olshen and Stone.

[5] R is a free software environment for statistical computing and graphics. https://www.r-project.org/
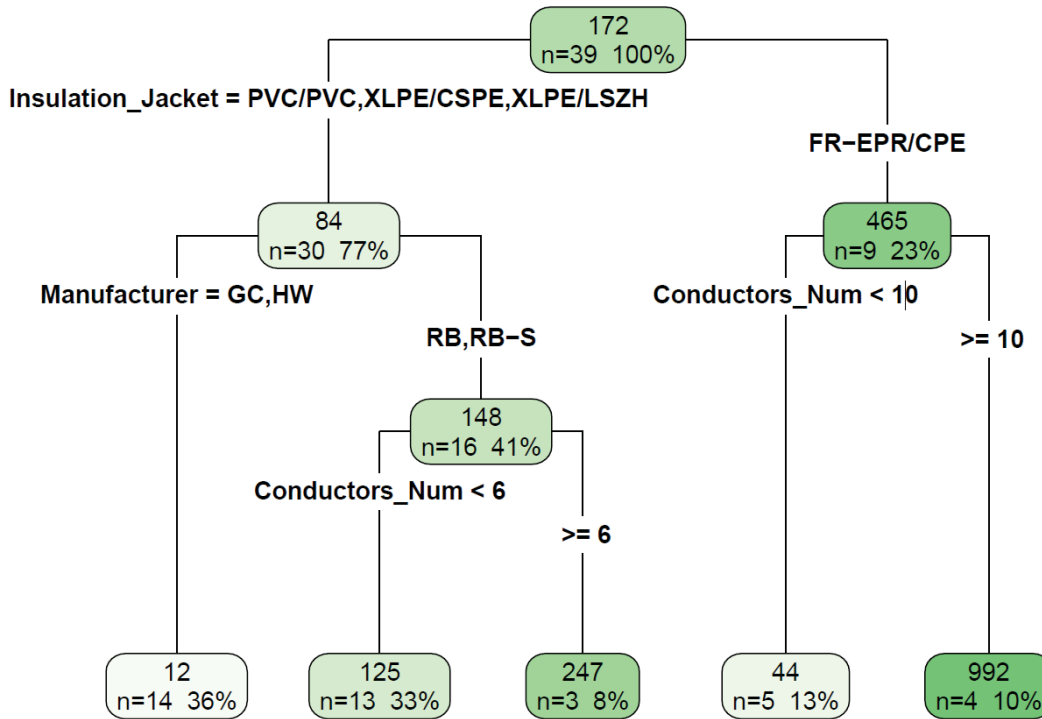
Figure 5-3   Regression Analysis Decision Tree with cp=0.01

Table 5-2   Regression Analysis for Leakage Time

	Degrees of Freedom (df)	Sum of the Squared Deviations	Mean Square (MS)	F-test	Significance F
Regression	4	804539	201135	2.5	0.06
Residual	34	2737162	80505		
Total	38	3541701			

Table 5-3 shows fitted model coefficients (with confidence intervals around those coefficients) as well as standard error values, t-test statistics, and p-values for each independent variable. The intercept row in the table does not have a physical interpretation, but it is required for the linear regression model to prevent bias in the other coefficients. Mathematically, the intercept is the estimated value of the output when all other parameters are zero; however, it is not possible for all parameters in our data set to be zero. It is included here because it adjusts the position of the model so it is not required to contain the origin. If a confidence interval for a variable coefficient contains the value of zero, there is not enough evidence to conclude that parameter has a significant impact on the leakage time.

Table 5-3   Model Coefficients for Leakage Time

	Coefficients	Standard Error	T Stat	P-value	Lower 95 percent	Upper 95 percent
Intercept	-11.28	143.91	-0.078	0.938	-303.7	281.2
Material	-15.03	16.56	-0.907	0.370	-48.7	18.6
Number of Conductors	26.79	8.79	3.048	0.004	8.9	44.7
Circuit Type	74.31	121.8	0.61	0.546	-173.2	321.8
Grounding Types	-26.19	82.75	-0.317	0.754	-194.4	142.0

Based on the table, the only conclusion that we can make with a 95 percent confidence is that there is a significant relationship between the number of conductors and leakage time. This is highlighted in the table.

5.4   Experimental Results

Based on the regression analysis, the experimental results are presented according to variables that influence leakage time the most: the number of conductors and whether the insulation/jacket material is FR-EPR/CPE. In addition, the conclusions drawn from the 2001 testing [4] on the difference between TS and TP cables are reinvestigated.

5.4.1   Number of Conductors Results

The number of conductors was a key variable in the regression analysis performed and discussed in Section 5.3. The decision tree first split branches based on material type, separating out FR-EPR/CPE cable materials from other cable insulation/jacket materials. In the FR-EPR/CPE section the cables are further split by the number of conductors. For the other insulation/jacket materials, only the Rockbestos cables (XLPE/CSPE) are split up by number of conductors. The number of conductors tested varied from two to sixteen. As shown in Table 5-4, the 8/c and 16/c cables had longer leakage times than the 2/c and 4/c cables.

Table 5-4   Summary of Number of Conductors Testing

Number of Conductors	Number of Tests	Average Leakage Time (s)
2	10	64
4	15	80
8	3	247
16	11	375

The number of conductors is a key variable because the heat transfer rate into the cable is dependent upon the heat transfer area and material thickness. Cables with the most conductors had the largest mass per linear foot, and were found to have a longer signal leakage time than cables with a small number of conductors. A graphical representation of the number of conductors and their corresponding leakage time is shown in Figure 5-4.

Overall, the number of conductors appears to impact the signal leakage time, with more conductors generally leading to a longer signal leakage time. However, there are exceptions to this analysis. For example, the 16/c XLPE/LSZH cables had a short leakage time. This will be discussed more in the next section.
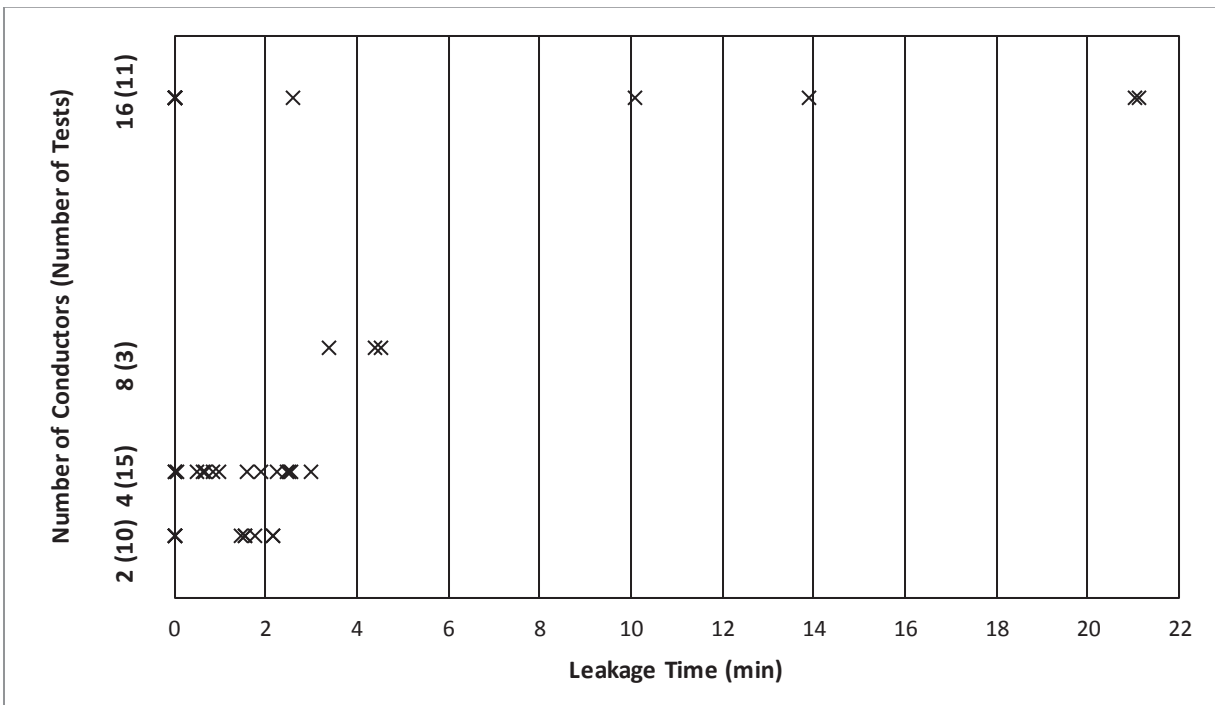
Figure 5-4   Number of Conductors and Corresponding Signal Leakage Time

5.4.2 FR-EPR/CPE Cable Material Results

The regression analysis decision trees indicated the driving key variable as insulation/jacket cable material, as discussed in Section 5.3. The highest four leakage times in the testing all had the same insulation/jacket material: FR-EPR/CPE. Table 5-5 summarizes the number of tests and average leakage times for different insulation/jacket material combinations, and Figure 5-5 shows the difference in leakage times between the four-cable insulation/jacket materials tested. As shown, FR-EPR/CPE cables have the longest signal leakage times, with the maximum leakage time equaling 1,269 seconds (21.15 min). XLPE/LSZH cables had the shortest leakage time.

Table 5-5   Summary of Cable Material Testing

Cable Material Type	TP or TS	Number of Tests	Average Leakage Time (s)
XLPE/LSZH	TS	7	0.4
PVC/PVC	TP	7	23
XLPE/CSPE	TS	16	148
FR-EPR/CPE	TS	9	465
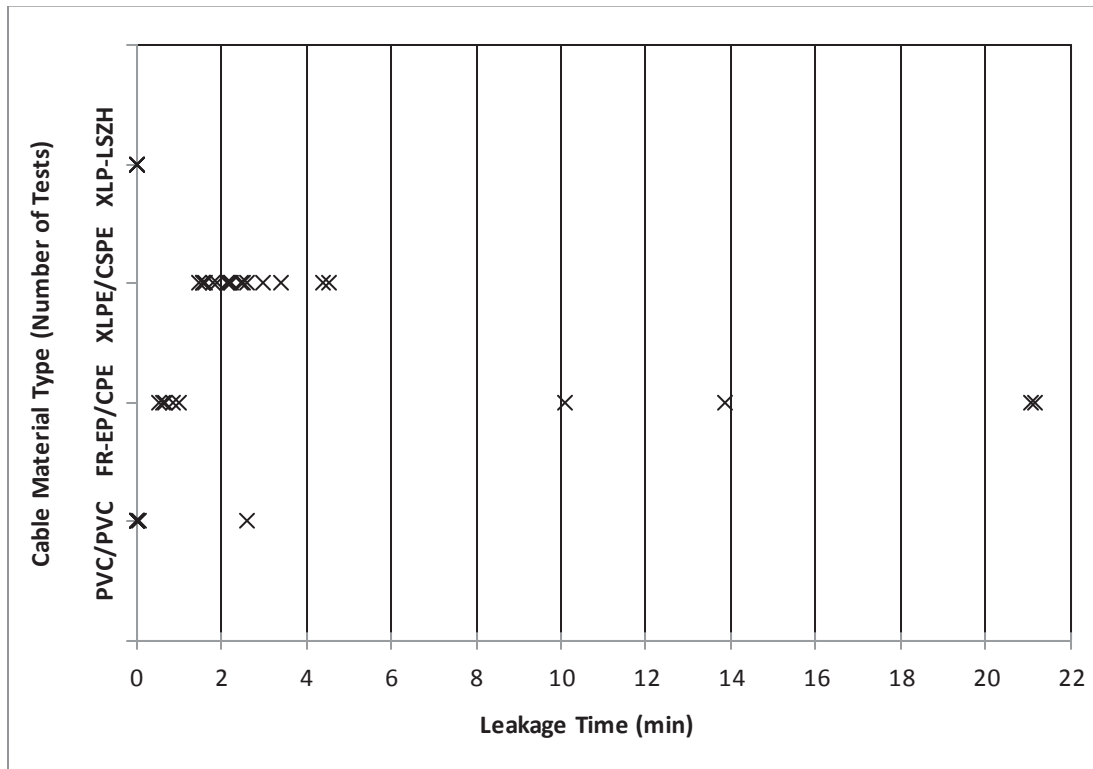
Figure 5-5   Signal Leakage by Cable Material Type

However, not all FR-EPR/CPE cables demonstrated the same long leakage time. The two-twisted pair (four conductors) cables had a significantly shorter leakage time than the eight-twisted pair cables (sixteen conductors). The split in the decision tree for the number of conductors is simply the average of ten between four and sixteen conductors in the FR-EPR/CPE cables. The difference in leakage time between the two-twisted pair and eight-twisted pair FR-EPR/CPE cables is shown in Figure 5-6. Figure 5-7 illustrates typical cable temperatures and voltage drop for all FR-EPR/CPE cables. This figure shows Tests 14 and 15.
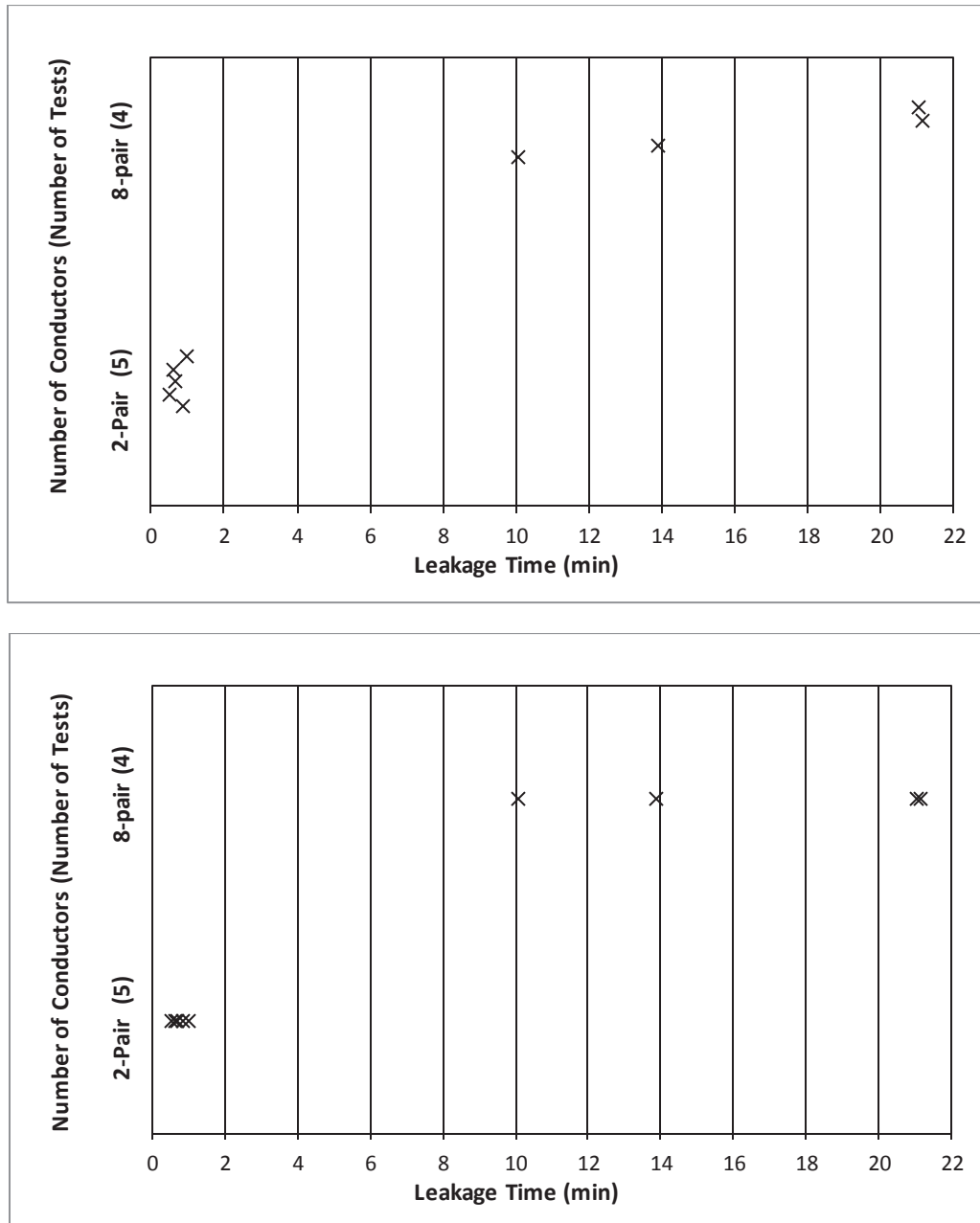
Figure 5-6   Signal Leakage Time for FR-EPR/CPE Cables
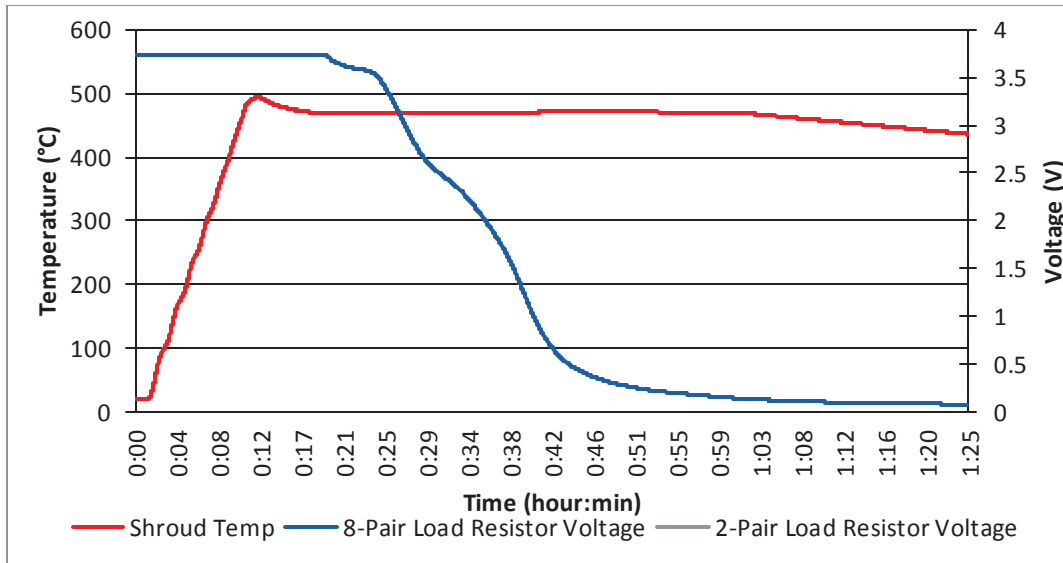
Figure 5-7   Test 14 (2-pair FR-EPR/CPE Cable) and Test 15 (8-pair FR-EPR/CPE Cable)

5.4.3 TS and TP Cable Results

The TS versus TP variable was not found to be a key variable in the regression analysis; however a discussion is included to reassess the conclusions found during 2001 testing (Ref. 4). The 2001 tests concluded the following (Ref. 4):

"The most notable result of these tests is the pronounced behavioral differences observed between the failure of the thermoplastic cables and that of the thermoset cables. Thermoplastic cables generally displayed no characteristics of signal degradation prior to the complete loss of signal. On the other hand, the thermoset cables usually displayed some substantial amount of signal degradation for a relatively prolonged time period prior to the total loss of signal."

The analysis is based on the industry current loop test, results shown in Table 5-6.

Table 5-6   Current Loop Test Data from 2001 Tests

Test Number	Cable Material	Raceway Type	Time of Signal Degradation[1] (s)	Time of Signal Loss[1] (s)	Signal Leakage Time[2] (s)
13	TS	Horiz. Tray	1100	2390	1290
14	TP	Conduit	—	2225	—
15	TS	Horiz. Tray	1100	1500	400
16	TP	Horiz. Tray	—	100	—
17	TS	Vert. Tray	930	1600	670
18	TP	Conduit	1140	1325	185
[1]Although these are the similar names to the calculations performed in Table, the methodology used to designate the signal degradation and signal loss time was not documented. Therefore, these values cannot be used for a direct comparison. [2]Not included in the report, however it is simply calculated as the time of signal loss minus the time of signal degradation.					

Although the TP and TS designator was listed as a key variable in the regression analysis, it was not found to be significant in the decision tree or confidence interval analysis. Part of this reason could be that the TS material was further deconstructed into material type as another variable so that was more dominant. The difference in leakage times is shown in Figure 5-8.
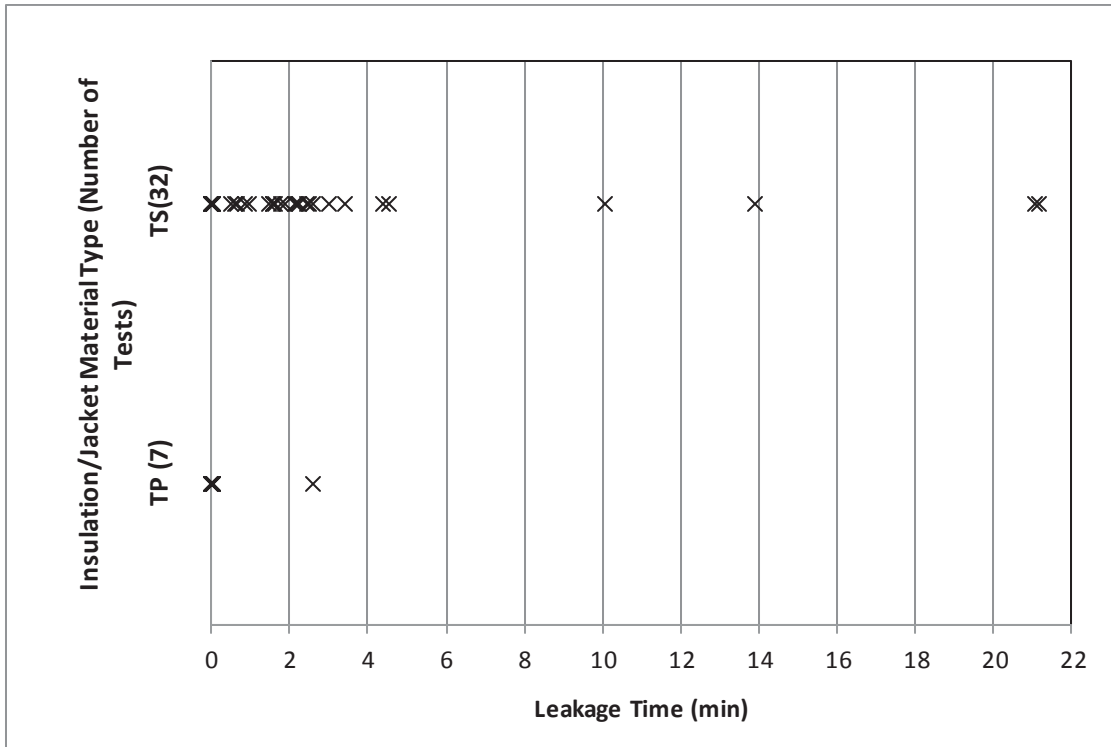
Figure 5-8   Signal Leakage Time for TP and TS Cables

As shown, the TP cables overall have a shorter leakage time than the TS cables on average. However, there were a number of TS tests that had a shorter leakage time than the maximum TP leakage time. An example is shown in Figure 5-9. Tests 23 and 26 were both using the same 1–5 VDC circuit; however, Test 23 was conducted on a TP cable and Test 26 was conducted on a TS cable. As shown, the TS cable has a 1 sec leakage time, smaller than the TP cable which had a 156 seconds leakage time.
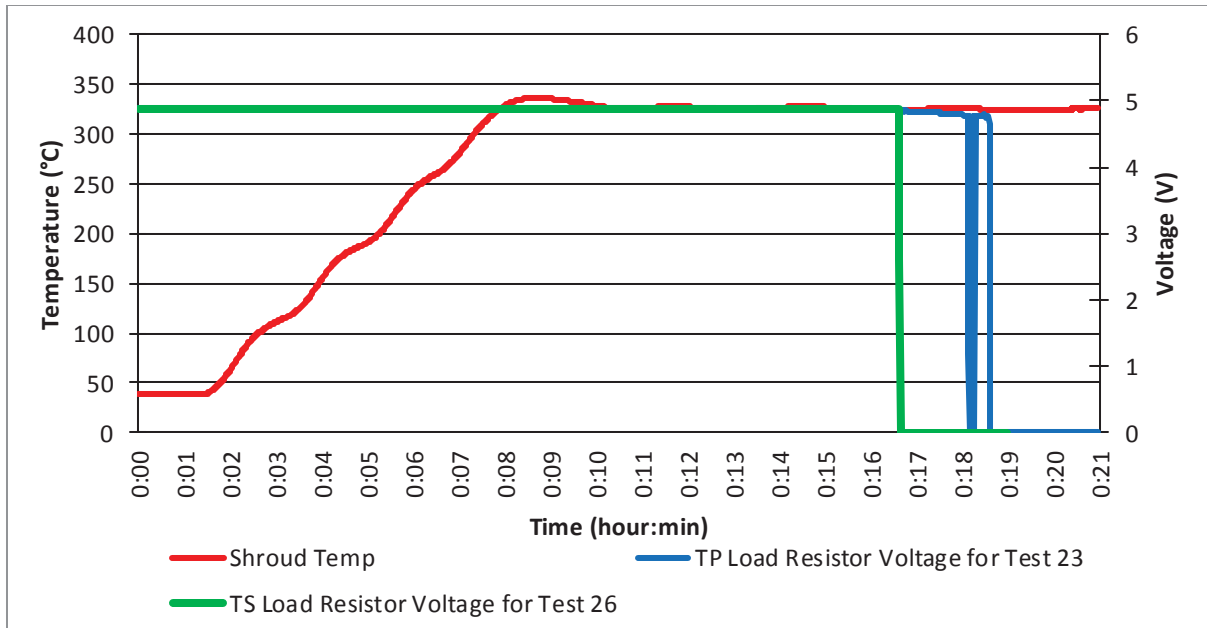
Figure 5-9   Test 23 (TP Cable) and Test 26 (TS Cable)

This example illustrates that the TP or TS designation does not necessarily correlate to a long signal leakage time. The results of the regression analysis show that other key variables contribute more to the signal leakage time than the TP or TS cable designation.

6   CONCLUSIONS AND RECOMMENDATIONS

6.1   General Conclusions Regarding Instrumentation Cable Failures

A total of thirty-nine small-scale tests were conducted. Tests provide evidence that instrumentation cables can, under certain circumstances, have a slow signal leakage time under fire-exposure conditions. General observations are included in this section.

Conclusions from the 2001 testing stated that TP cables had "no characteristics of signal degradation prior to the complete loss of a signal," documented in NUREG/CR-6776 (Ref. 4). In the industry series of tests, the term *signal degradation* is equivalent to this report's usage of the term *signal leakage*. The results of this testing series determined that, in one out of seven tests, TP cables may not fail instantaneously. Although, most TP cables failed instantaneously, one TP test had a leakage time of 2.6 min. There were a limited number of TP tests (seven out of the total thirty-nine) because the focus of the test series was on TS cables. Additional TP testing, which varies the number of conductors and TP insulation/jacket material, has been included in the recommendation section.

The focus of this series of testing was on TS cables. Regarding TS cables, the conclusions of prior 2001 testing stated that they "usually displayed some substantial amount of signal leakage for a relatively prolonged time period prior to the total loss of signal" (Ref. 4). During this series of testing, twelve out of the thirty-two tests had less than 1 min of signal leakage before failure and four of these tests experienced no signal leakage. Four other TS tests had a signal leakage longer than 10 min. Therefore, it is difficult to conclude that TS cables will always experience signal leakage before failure.

A regression analysis was performed on the test data to determine key variables that contributed to longer leakage times. The dependent variable is the variable to forecast (i.e., the variable of interest to understand dependencies); for this analysis, it is the time it takes for the cable to lose signal below a certain threshold (signal leakage time). The other variables are called independent variables. In our analysis, the independent variables are:

- Manufacturer
- Insulation/jacket material combination
- Thermoset or thermoplastic
- Number of conductors
- Presence or absence of shielding
- Circuit type
- Presence or absence of circuit grounding
- Presence or absence of shield grounding
- Presence or absence of a circuit fuse

Two analyses were conducted for the regression analysis: fitted model coefficients and a decision tree. Based on the fitted model coefficients method, the number of conductors is the only key variable where the confidence interval does not include the value of zero. Therefore, it is the only parameter that has a significant impact on leakage time. The only conclusion that can be made with this regression methodology with a 95 percent level of statistical confidence is that there is a significant relationship between the number of conductors and the signal leakage time.

The second regression methodology performed consisted of utilized the R program to construct a decision tree by splitting or not splitting each node on the tree to best classify or estimate a response variable. The top node of a decision tree is called the parent node and shows the independent variable with the most influence over leakage time. This top node is split at a determined value along a range of values for a variable, thus producing two child nodes with greater homogeneity than the parent node. The first split in the decision tree was material type where FR-EPR/CPE cables were split away from the other insulation/jacket material types (PVC/PVC, XLPE/LSZH, XLPE/CSPE). However, material was not a key variable, according to the linear regression analysis and model coefficient table. This could also be because only eight-twisted pair FR-EPR/CPE cables had significant signal leakage times, versus the two-pair FR-EPR/CPE cable with leakage times of less than 2 min. The decision tree corroborated visual results that FR-EPR/CPE eight-twisted pair cables had the highest leakage times for all thirty-nine tests.

6.2   Recommendations for Follow-On Work

This series of instrumentation cable tests were limited to small-scale radiant heater tests. Full scale testing that is more representative of in-plant conditions is recommended to gain better understanding of the key parameters during signal leakage time. It is especially recommended to assess the performance of instrumentation in various, likely cable-tray configurations including varying the bundling of cables and positions, both vertical and horizontal. Configuration changes may have an impact on signal leakage; exposing cables to more varied and representative conditions would provide a more complete understanding of instrumentation cable failure.

Signal leakage times, defined as the time difference between where the signal has dropped 0.25 percent from its starting value to the time of failure based on the circuit's current or voltage (4 mA for 4–20 mA circuits, 10 mA for 10–50 mA circuits, and less than 1 V for 1–5 VDC circuits), ranged from 0 to over 21 min. If a signal does not fail immediately, then the delay may have an impact on nuclear power plant operators and the timely decisions they must make. Therefore, it is recommended that Fire PRA and HRA evaluation be performed to analyze the potential impacts of a long signal delay to operators. Testing realistic circuit configurations that have the potential of being single point items, for example battery/bus voltage or pump oil pressure, will be important to HRA of realistic NPP scenarios.

The impact of heating on digital transmitters and receivers was not explored in this test series. Sandia has conducted testing on the impact of smoke on digital instrumentation and controls, documented in "Results and Insights on the Impact of Smoke on Digital Instrumentation and Control" (Ref. 23), which concluded that smoke can cause interruptions and upsets in active electronics. The impact of heating on the digital instrumentation and controls was not analyzed in the report, but reviewing it is recommended to understand the comprehensive effects of fire on digital transmitters and receivers.

This series of instrumentation cable testing was predominantly focused on TS cable tests; however, seven out of twenty-nine tests were performed on TP cables. The results of the testing determined that TP cables may not fail instantaneously, with one test having a leakage time of 2.6 min. Additional testing on TP cables is recommended, particularly to vary the number of conductors and insulation/jacket material. Testing a variety of TP cables would provide a more comprehensive understanding of the signal leakage behavior.

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APPENDIX A TEST RESULTS

A.1 Test 1 Results

Test conditions: 2/21/17, 7:35 am
Cable: HW2, 1005, TP, 16-AWG, PVC/PVC, 8-twisted pairs, pairs not shielded.
Exposure conditions: Shroud set to temperature of 325C, with a 45°/min ramp, nominal 6.17 kW/m2 flux from shroud.
Shroud power: Initiated after 30 seconds of baseline data monitoring.
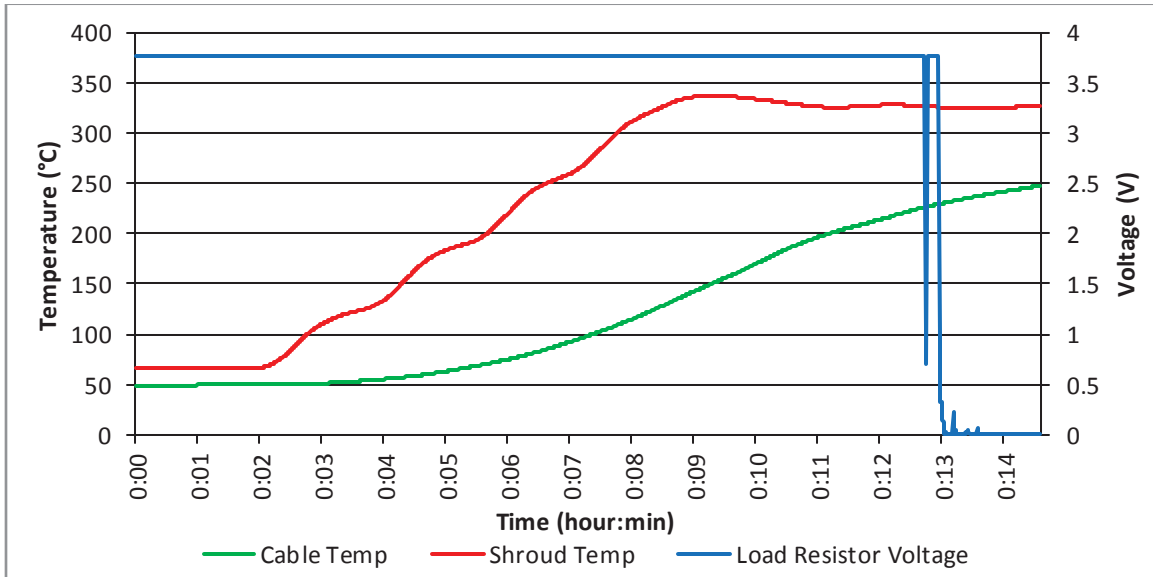
Figure A-1   Test 1 Temperature and Voltage
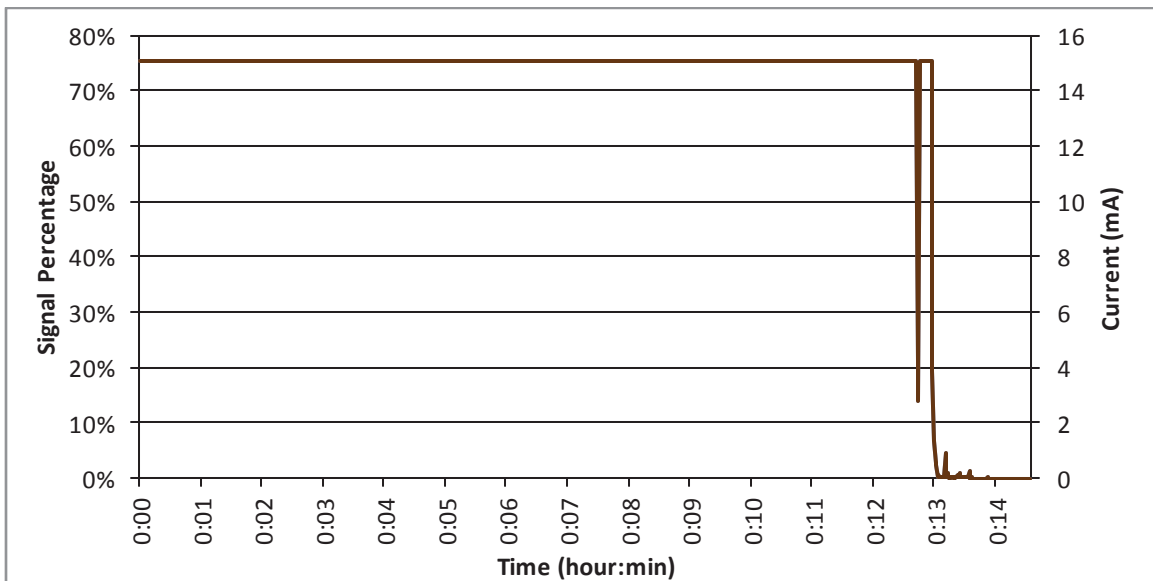
Figure A-2   Test 1 Signal Percentage and Current

A.2 Test 2 Results

Test conditions: 2/21/17, 7:35 am
Cable: HW2, 1005, TP, 16-AWG, PVC/PVC, 8-twisted pairs, pairs not shielded.
Exposure conditions: Shroud set to temperature of 325C, with a 45°/min ramp, nominal 6.17 kW/m2 flux from shroud.
Shroud power: Initiated after 30 seconds of baseline data monitoring.
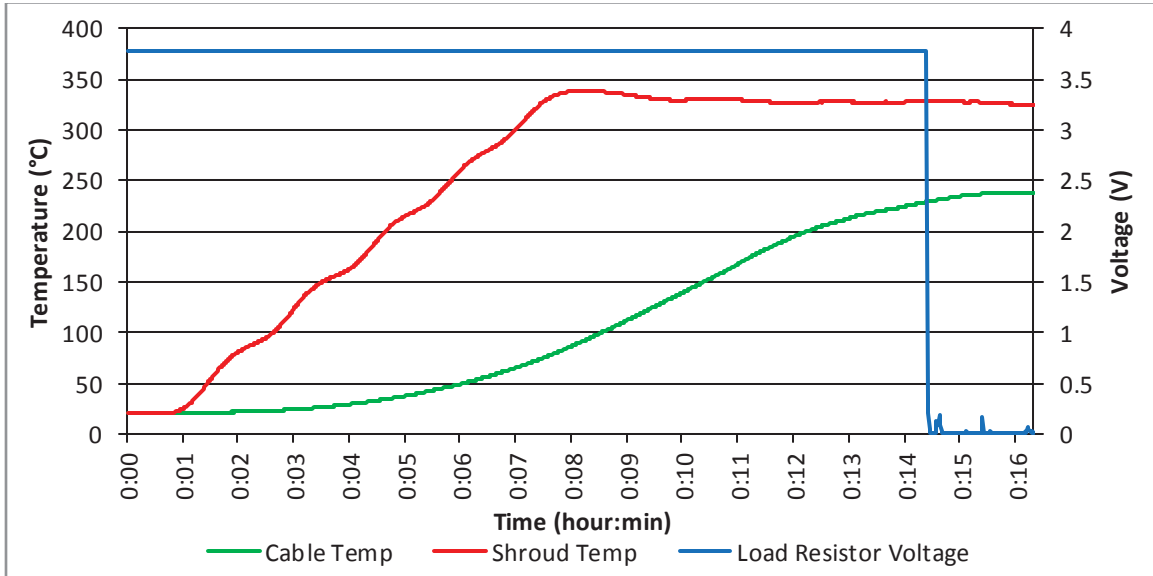
Figure A-3   Test 2 Temperature and Voltage
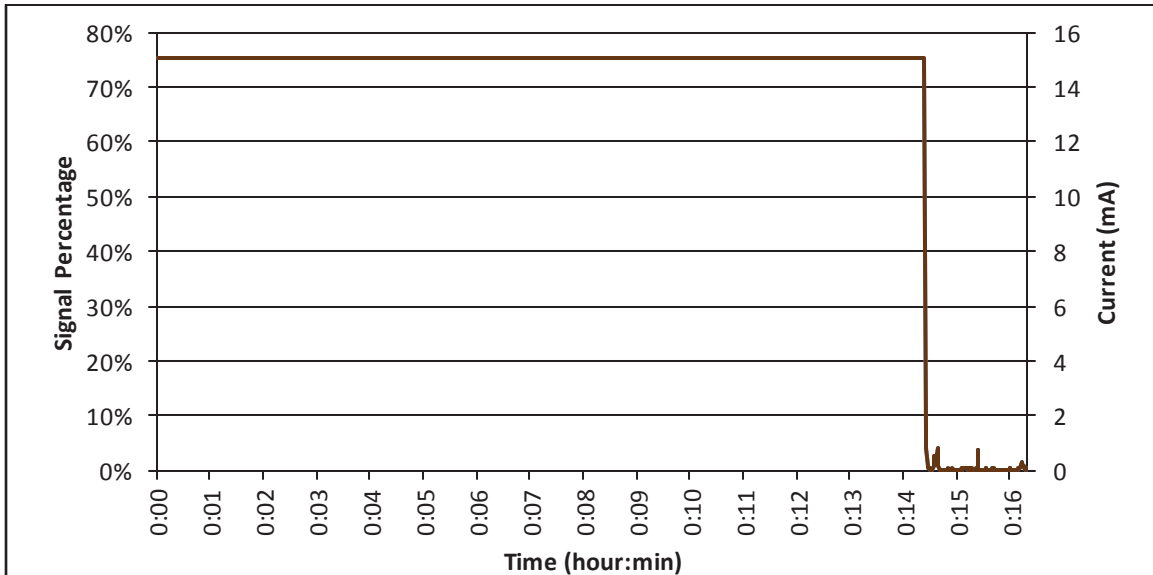
Figure A-4   Test 2 Signal Percentage and Current

A.3 Test 3 A Results

Test conditions: 2/21/17, 9:17 am
Cable: HW3, 1006, TS, 16-AWG, FR-EP/CPE, 2-twisted pairs, pairs shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
Shroud power: Initiated after 45 seconds of baseline data monitoring.
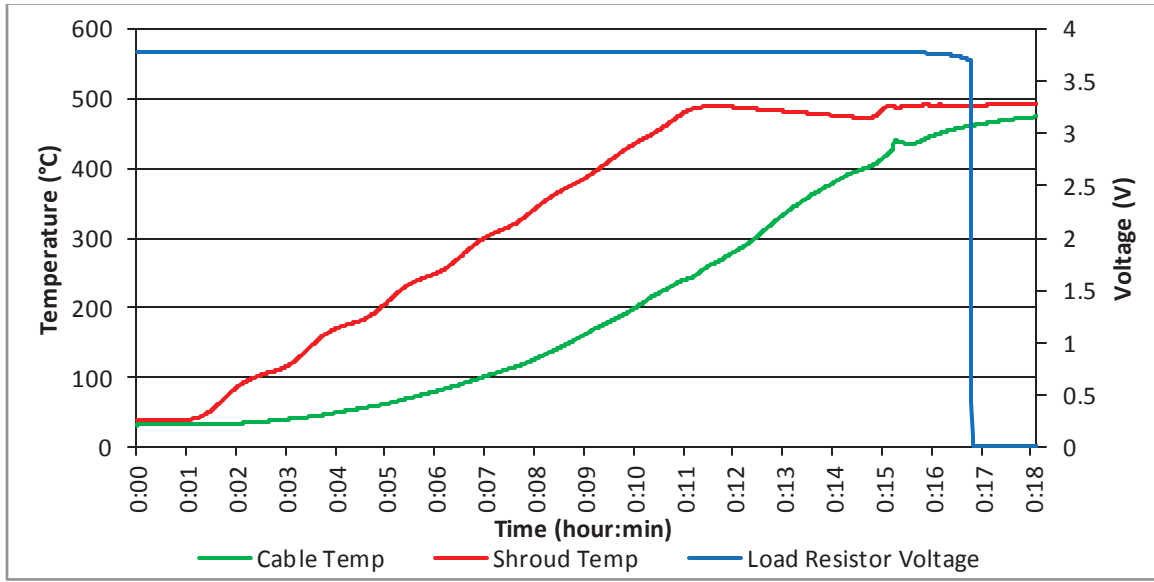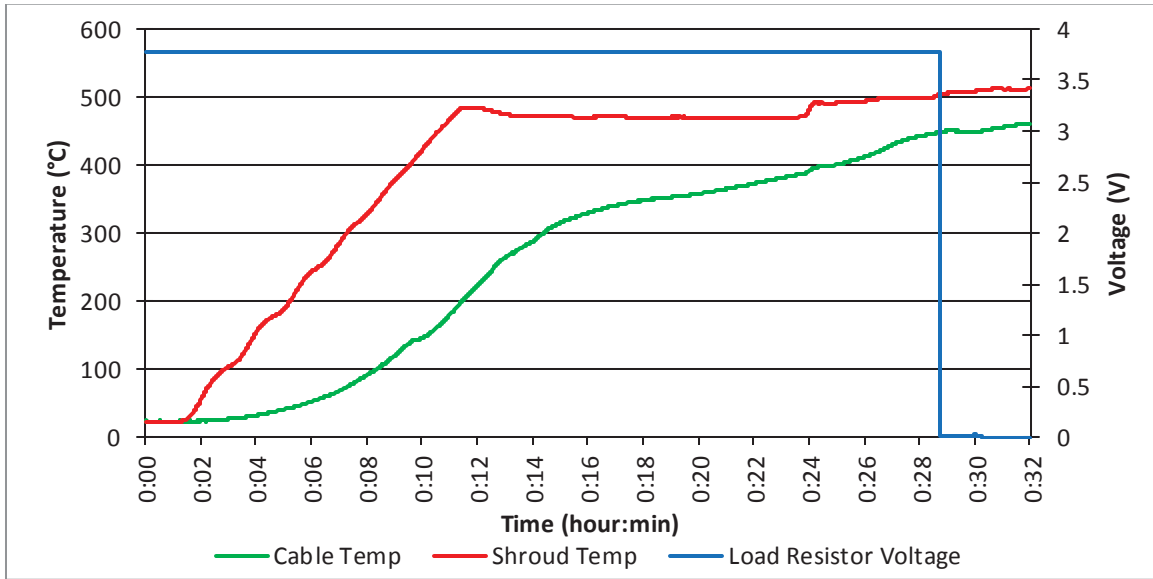

Figure A-5   Test 3 A Temperature and Voltage
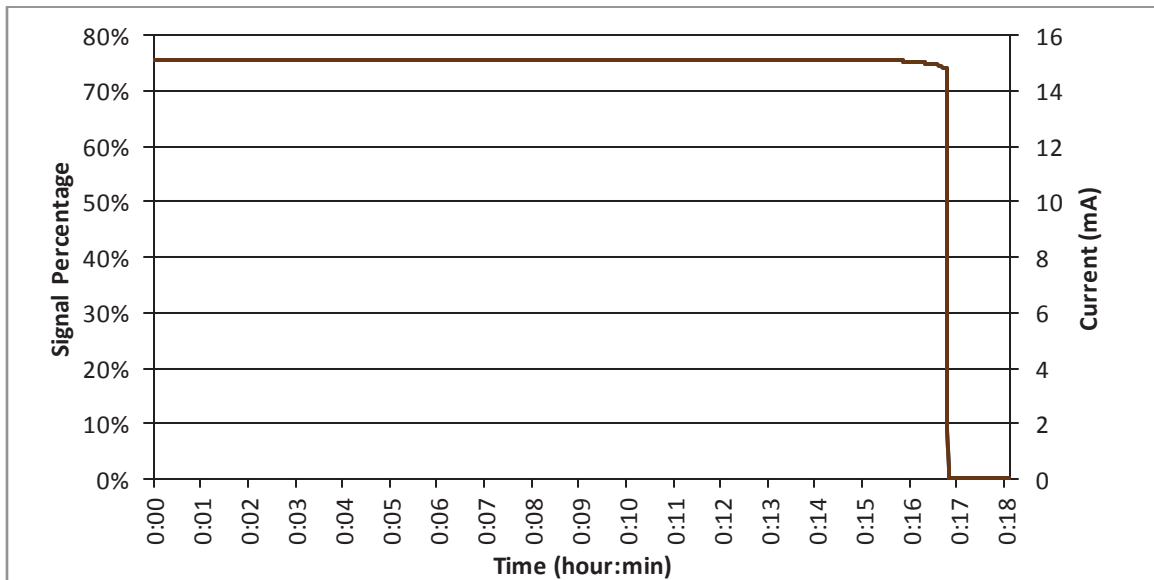
Figure A-6   Test 3 A Signal Percentage and Current

A.4 Test 3 B Results

Test conditions: 2/21/17, 1:00 pm
Cable: HW3, 1006, TS, 16-AWG, FR-EP/CPE, 2-twisted pairs, pairs shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
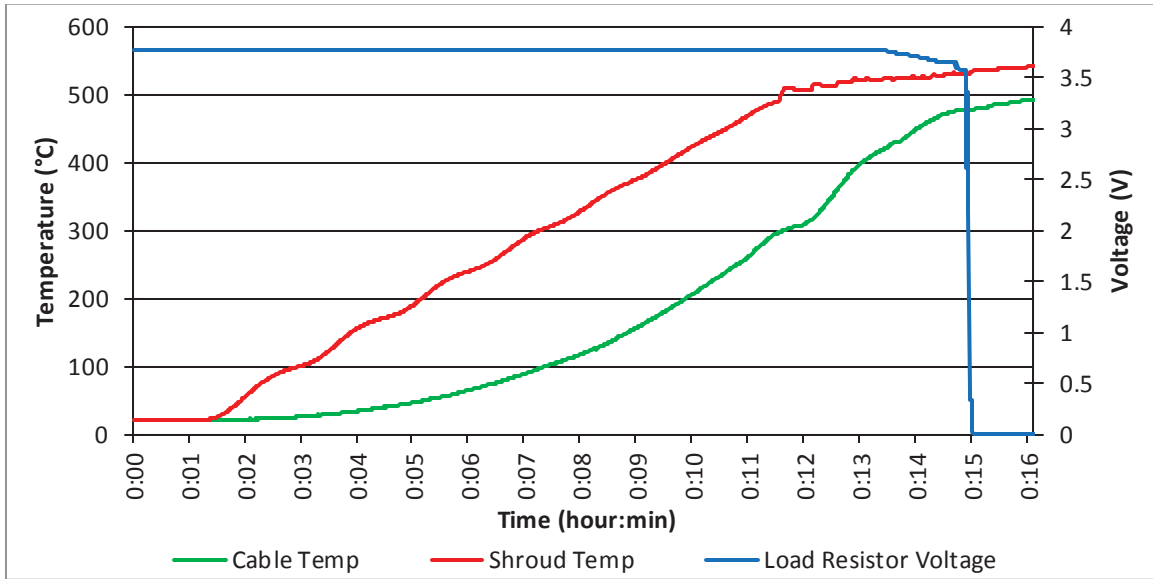Shroud power: Initiated after 60 seconds of baseline data monitoring.
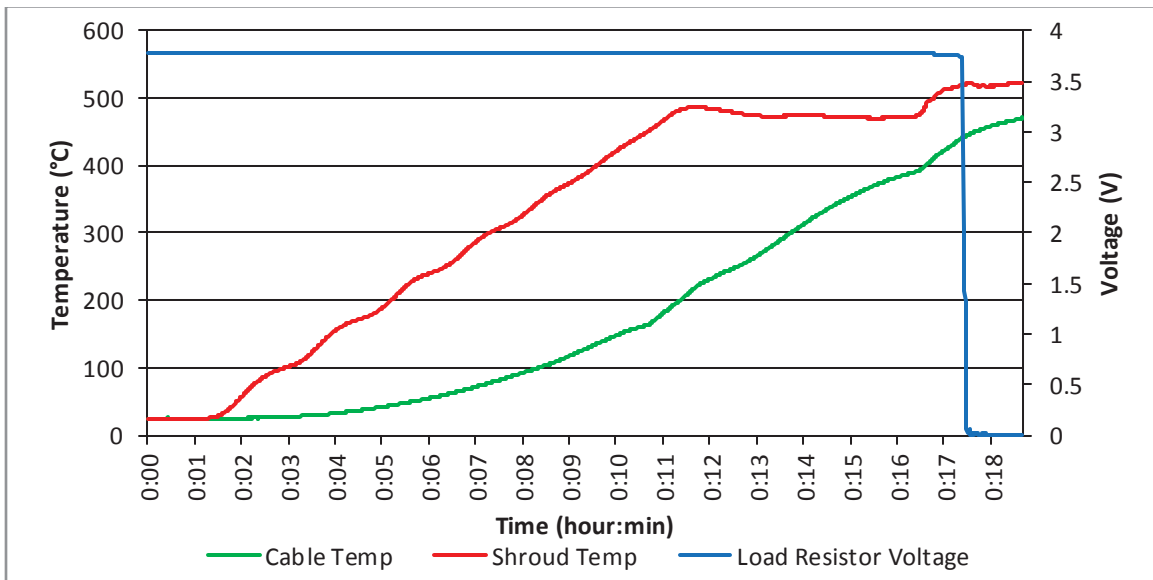
**Figure A-7   Test 3 B Temperature and Voltage**
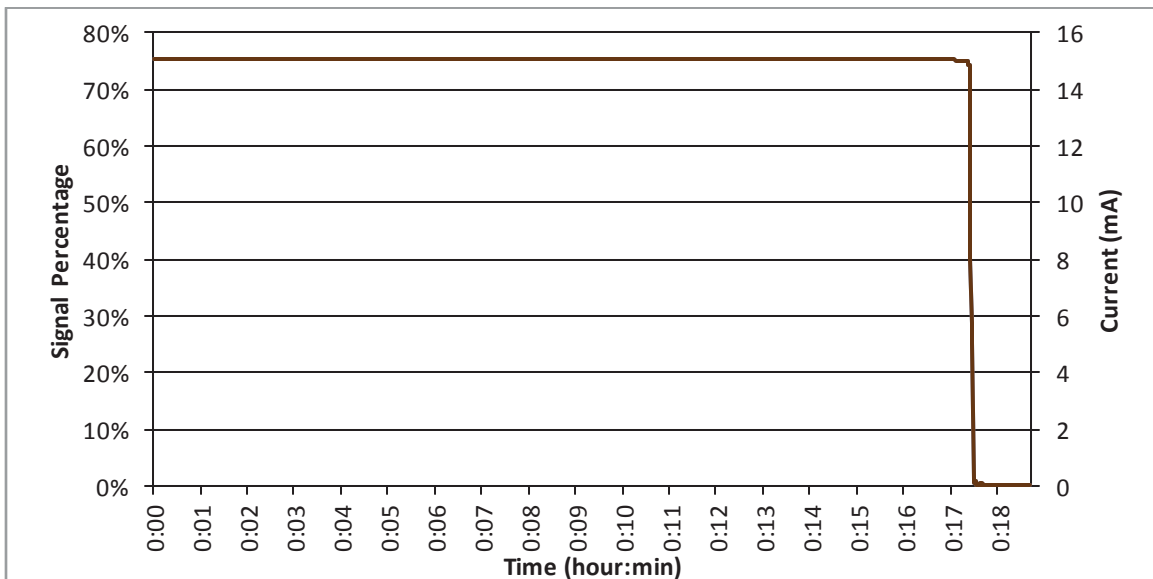
Figure A-8   Test 3 B Signal Percentage and Current

A.5 Test 3 C Results

Test conditions: 2/21/17, 3:00 pm
Cable: HW3, 1006, TS, 16-AWG, FR-EP/CPE, 2-twisted pairs, pairs shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
Shroud power: Initiated after 30 seconds of baseline data monitoring.
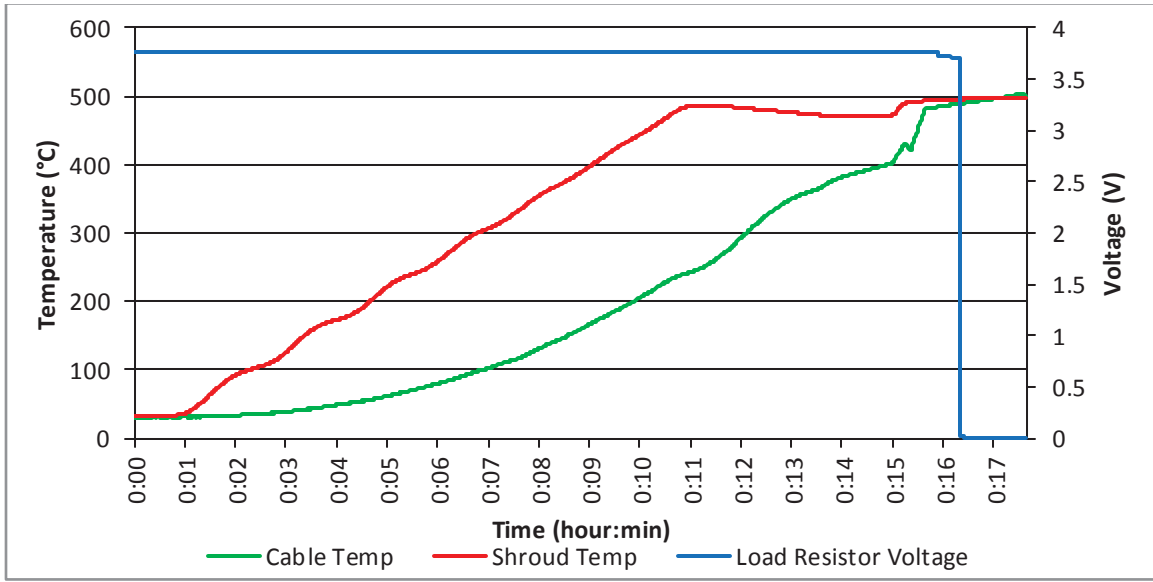
Figure A-9   Test 3 C Temperature and Voltage
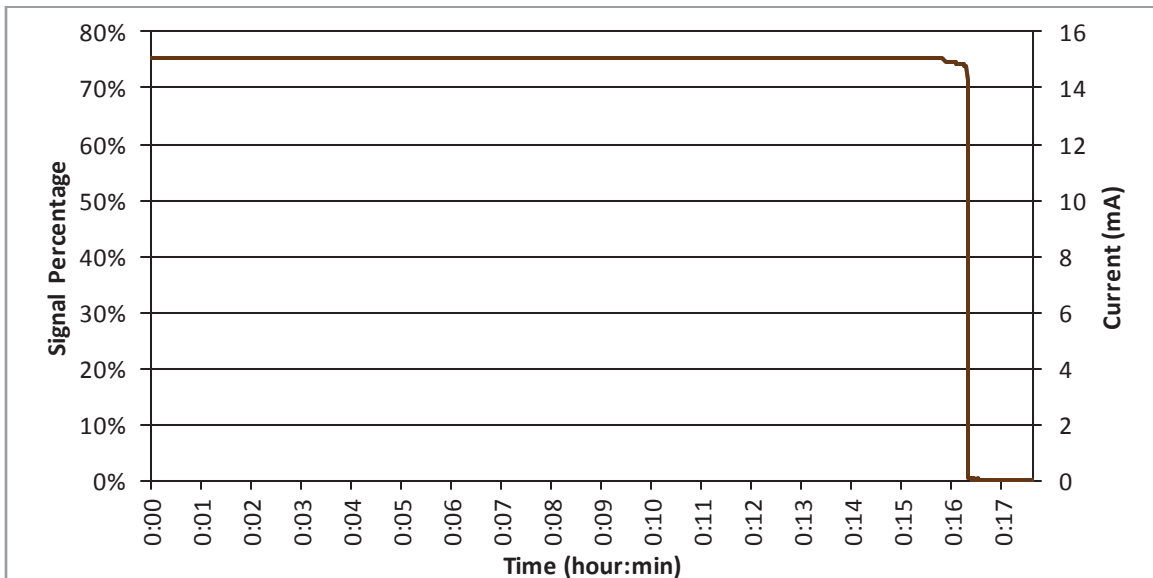
Figure A-10   Test 3 C Signal Percentage and Current

A.6 Test 4 A Results

Test conditions: 2/23/17, 11:59 am
Cable: HW4, 1007, TS, 16-AWG, FR-EP/CPE, 8 twisted pairs, pairs shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
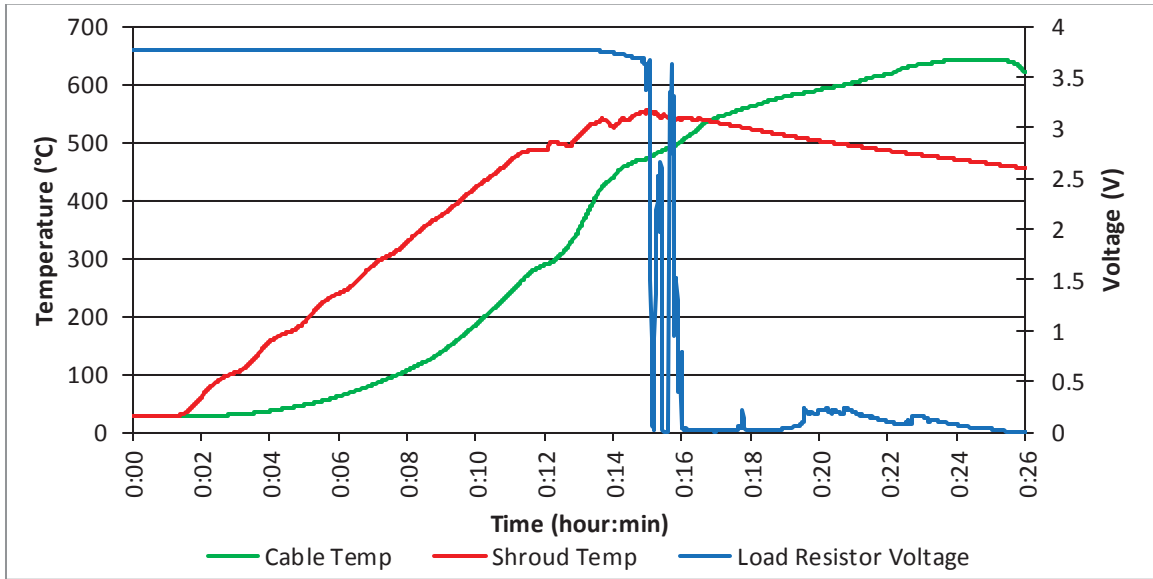Shroud power: Initiated after 60 seconds of baseline data monitoring.
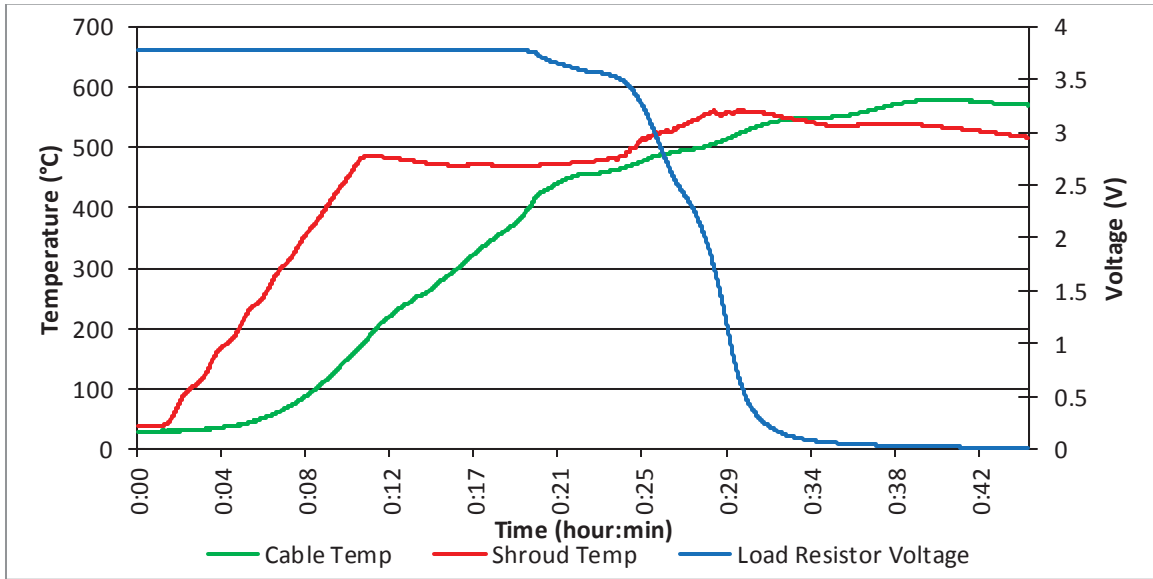
**Figure A-11   Test 4 A Temperature and Voltage**
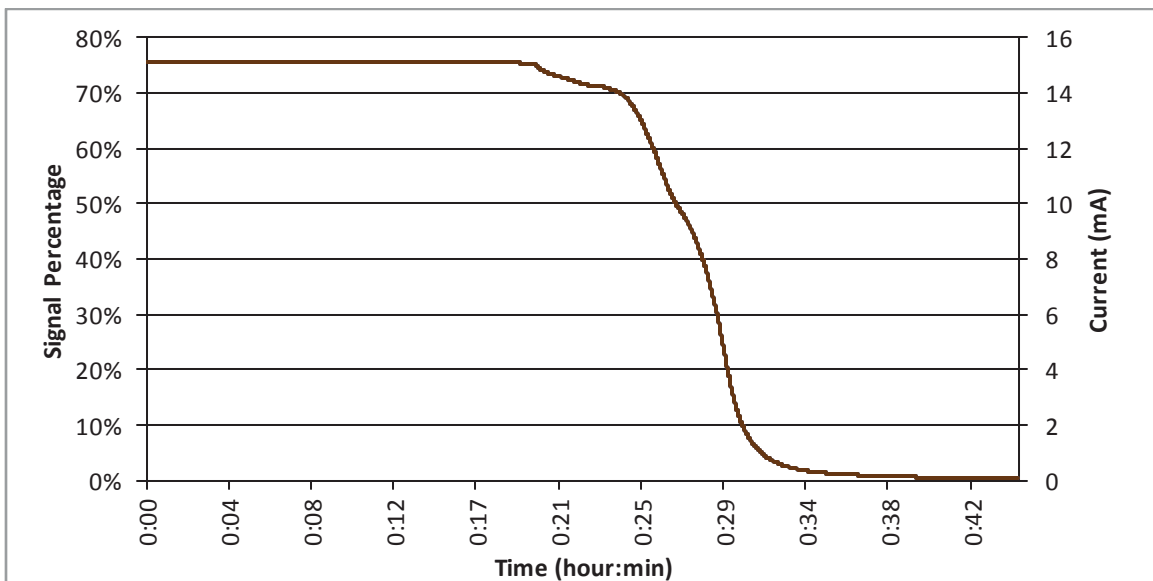
Figure A-12   Test 4 A Signal Percentage and Current

A.7 Test 4 B Results

Test conditions: 2/23/17, 2:30 pm
Cable: HW4, 1007, TS, 16-AWG, FR-EP/CPE, 8 twisted pairs, pairs shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
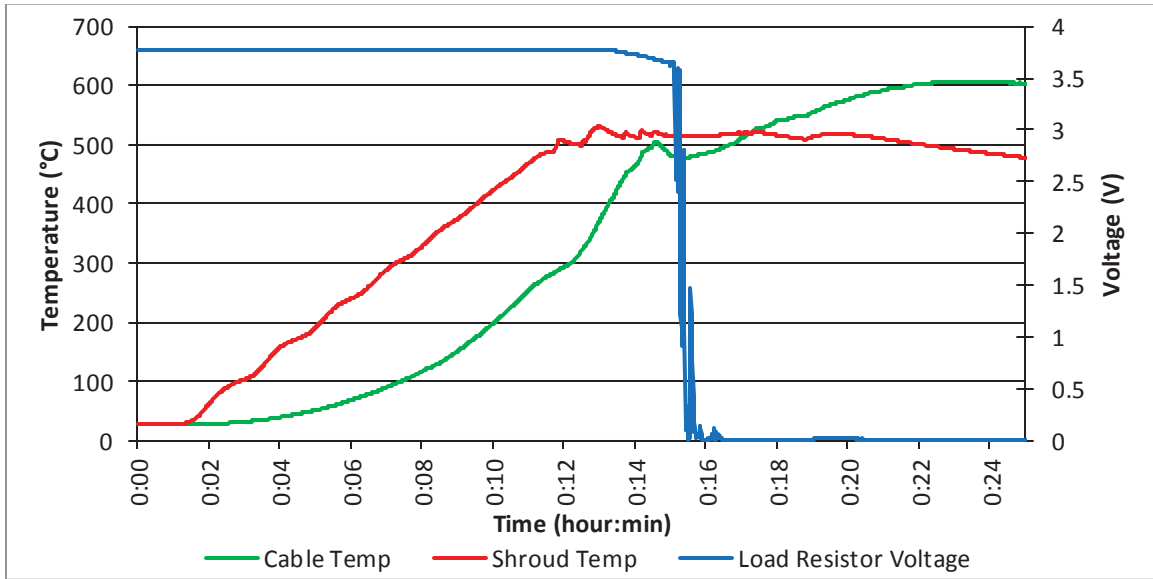Shroud power: Initiated after 60 seconds of baseline data monitoring.
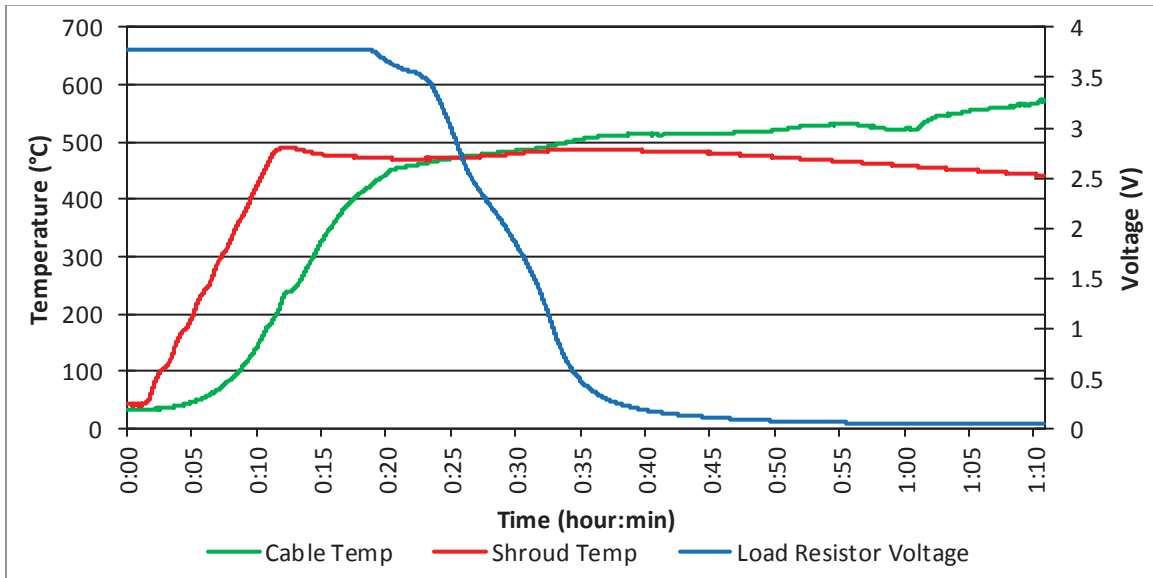
Figure A-13   Test 4 B Temperature and Voltage
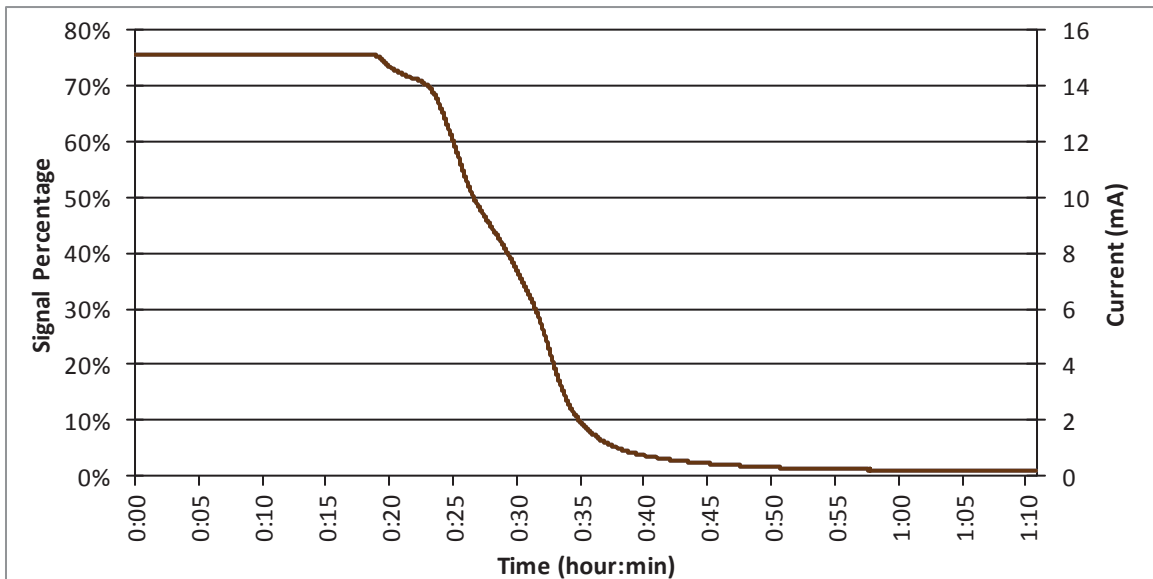
Figure A-14   Test 4 B Signal Percentage and Current

A.8 Test 5 Results

Test conditions: 2/27/17, 8:04 am
Cable: HW5, 1008, TS, 16-AWG, XLP-LSZH, 1 twisted pair, pairs not shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
Shroud power: Initiated after 60 seconds of baseline data monitoring.
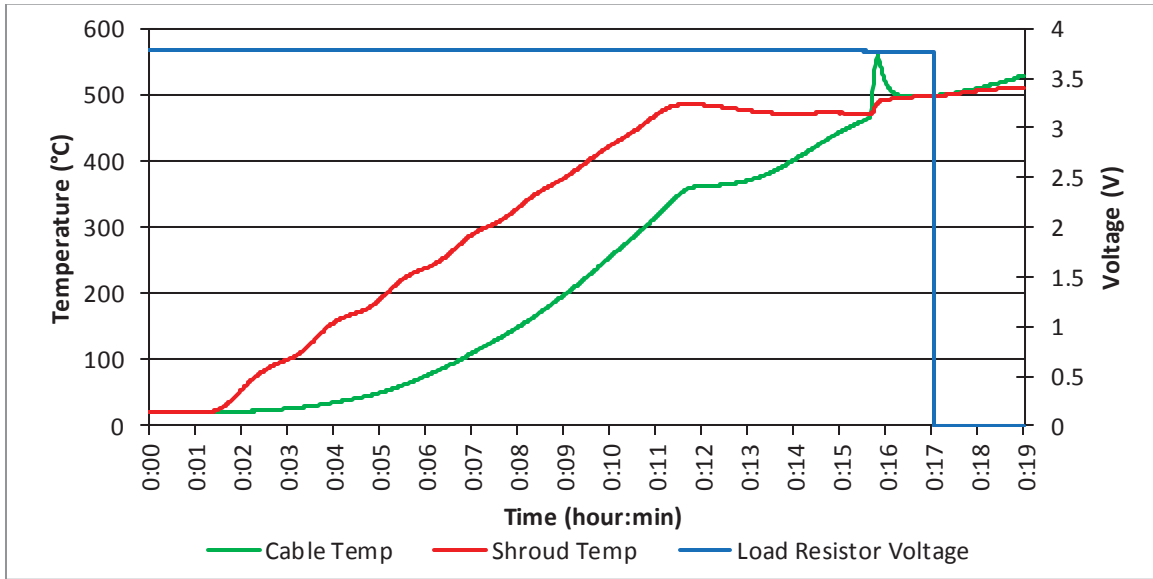
**Figure A-15   Test 5 Temperature and Voltage**
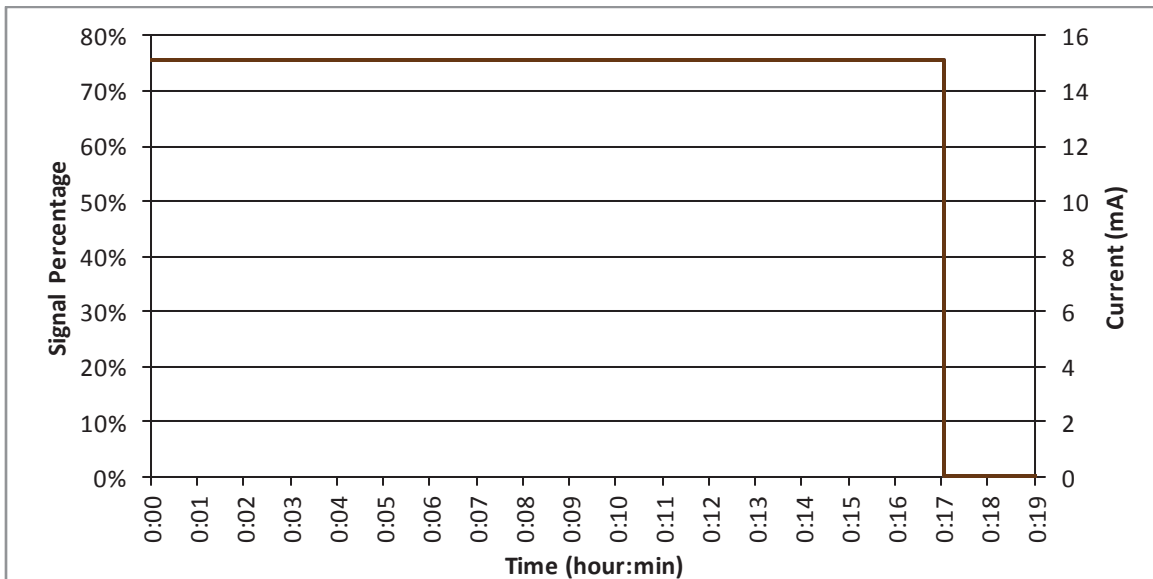
Figure A-16   Test 5 Signal Percentage and Current

A.9 Test 6 A Results

Test conditions: 2/27/17, 9:58 am
Cable: HW6, 1009, TS, 16-AWG, XLP-LSZH, 8 twisted pairs, pairs shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
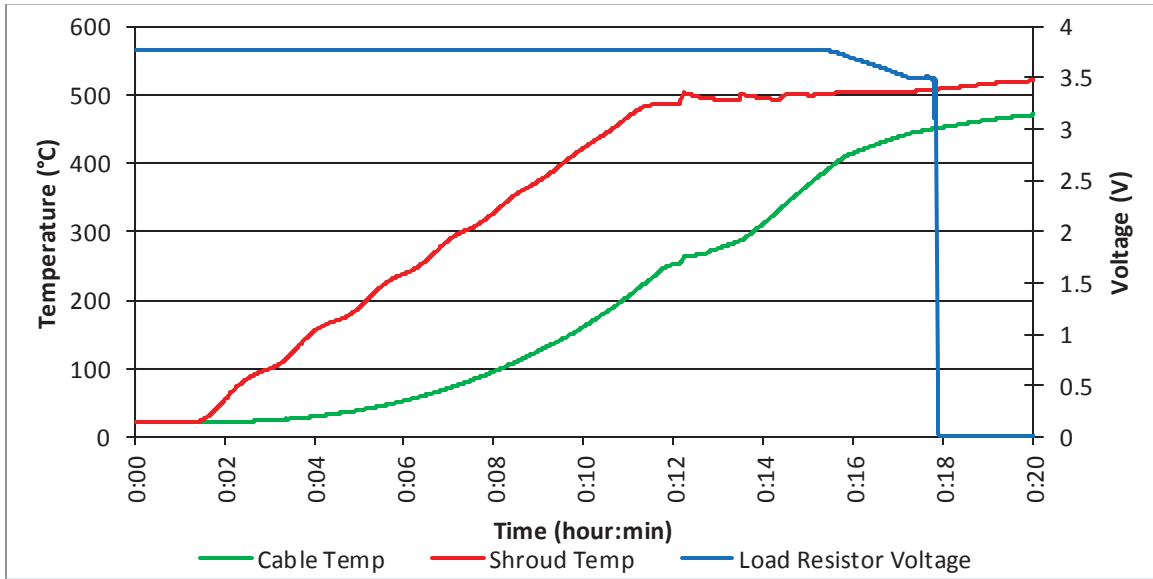Shroud power: Initiated after 60 seconds of baseline data monitoring.
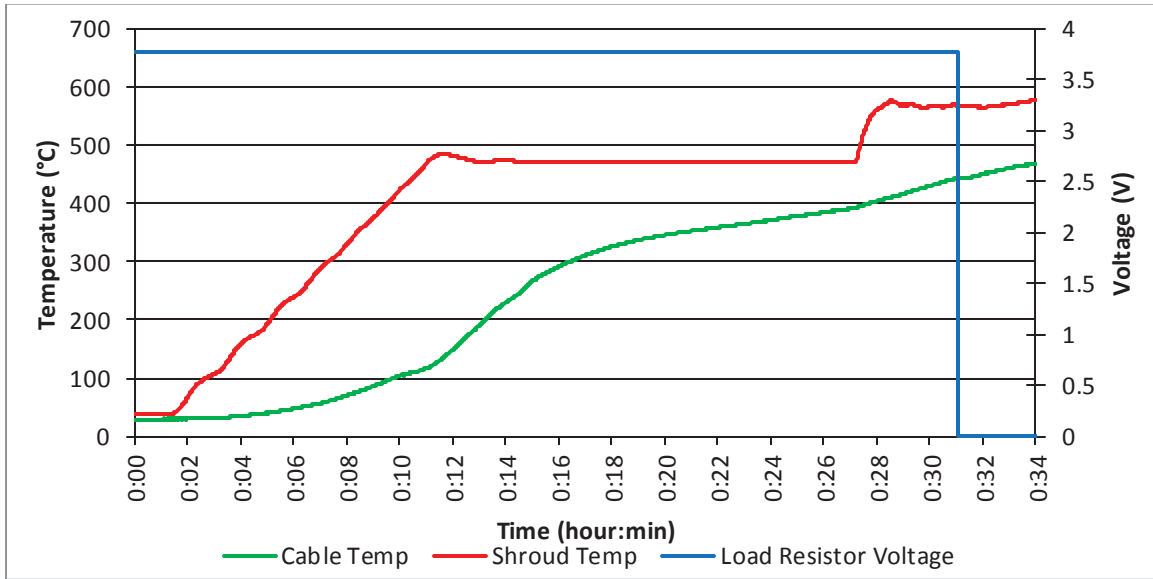
**Figure A-17   Test 6 A Temperature and Voltage**
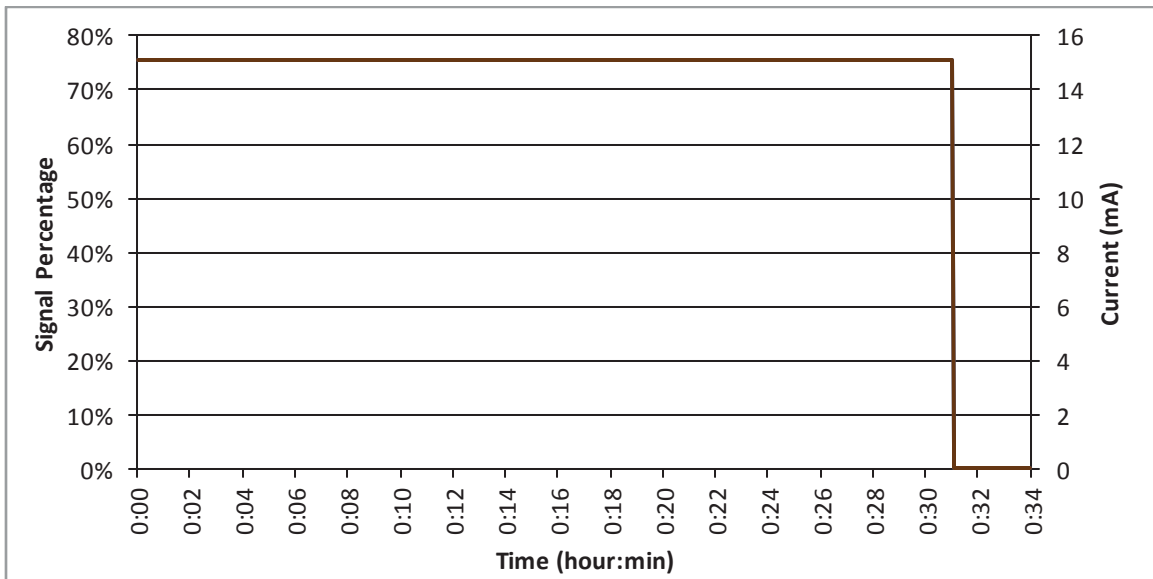
Figure A-18   Test 6 A Signal Percentage and Current

A.10 Test 6 B Results

Test conditions: 2/27/17, 2:30 pm
Cable: HW6, 1009, TS, 16-AWG, XLP-LSZH, 8 twisted pairs, pairs shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
Shroud power: Initiated after 60 seconds of baseline data monitoring.

Figure A-19   Test 6 B Temperature and Voltage
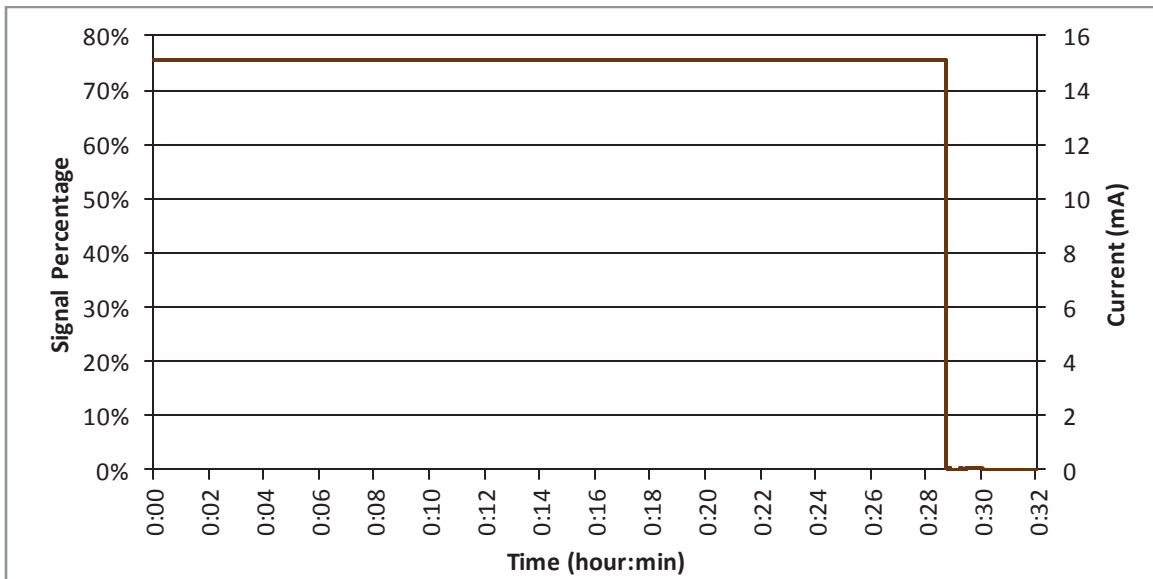
Figure A-20   Test 6 B Signal Percentage and Current

A.11 Test 7 Results

Test conditions: 2/22/17, 8:32 am
Cable: RB1, 1000, TS, 16-AWG, XLPE/CSPE, 2 Conductors, pairs not shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
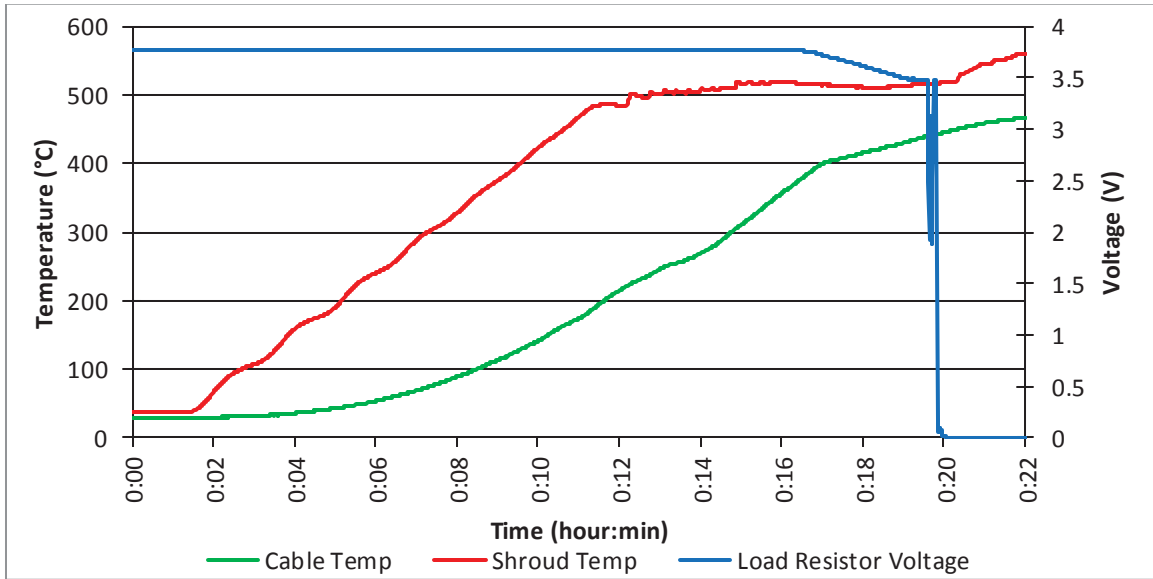Shroud power: Initiated after 60 seconds of baseline data monitoring.

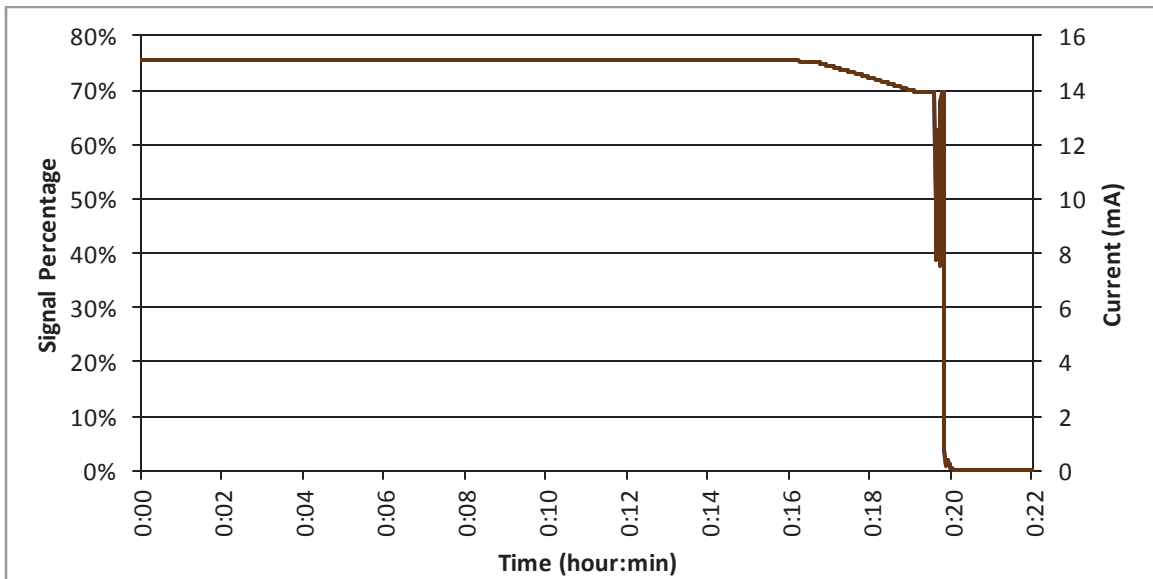**Figure A-21   Test 7 Temperature and Voltage**
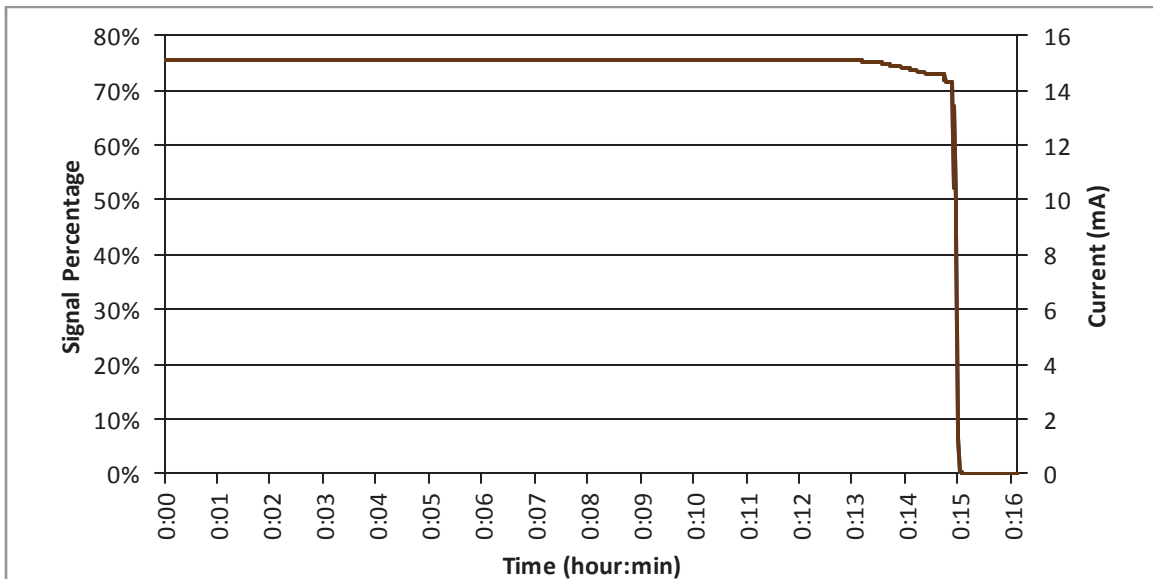
Figure A-22   Test 7 Signal Percentage and Current

A.12 Test 8 A Results

Test conditions: 2/22/17, 1:05 pm
Cable: RB2, 1001, TS, 16-AWG, XLPE/CSPE, 4 Conductors, pairs not shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
Shroud power: Initiated after 60 seconds of baseline data monitoring.

Figure A-23   Test 8 A Temperature and Voltage
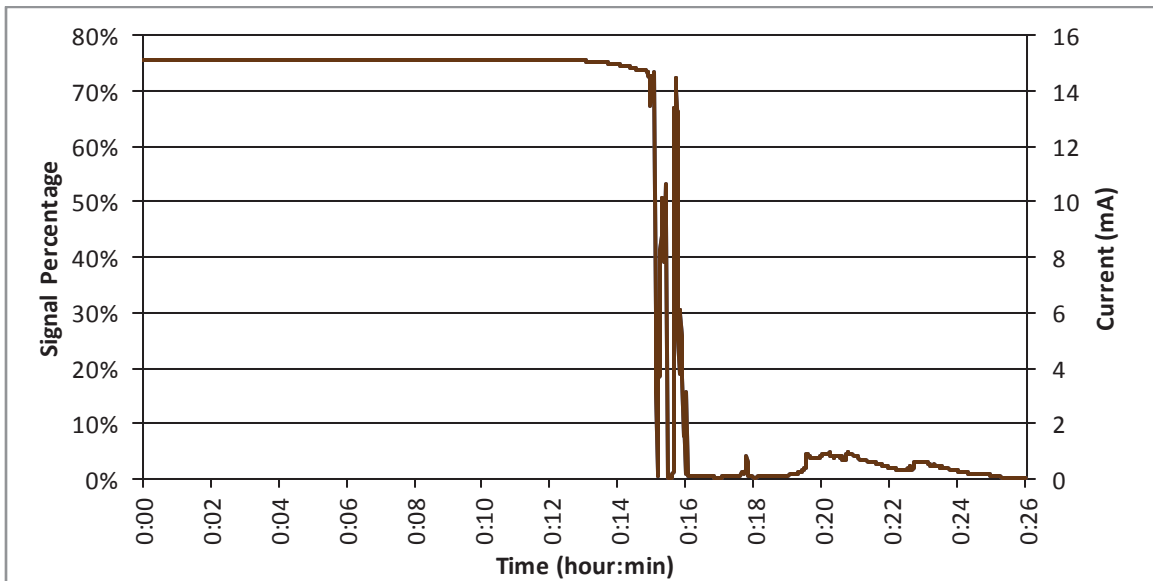
Figure A-24   Test 8 A Signal Percentage and Current

A.13 Test 8 B Results

Test conditions: 2/22/17, 3:30 pm
Cable: RB2, 1001, TS, 16-AWG, XLPE/CSPE, 4 Conductors, pairs not shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
Shroud power: Initiated after 60 seconds of baseline data monitoring.

Figure A-25 Test 8 B Temperature and Voltage
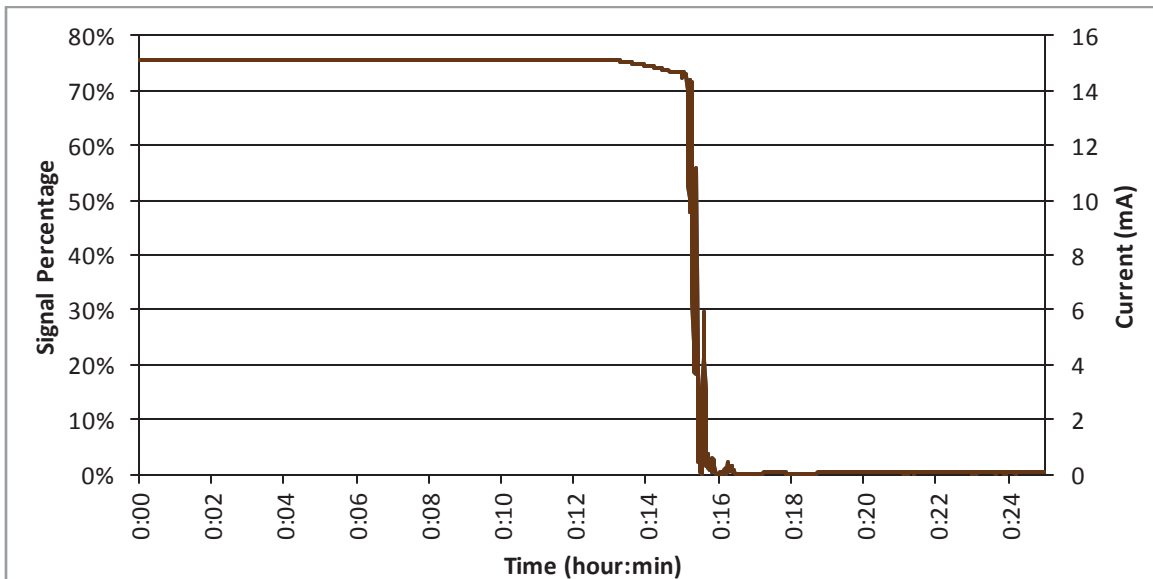
Figure A-26 Test 8 B Signal Percentage and Current

A.14 Test 9 Results

Test conditions: 2/23/17, 8:06 am
Cable: RB3, 1002, TS, 16-AWG, XLPE/CSPE, 2 twisted pairs, pairs shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
Shroud power: Initiated after 60 seconds of baseline data monitoring.
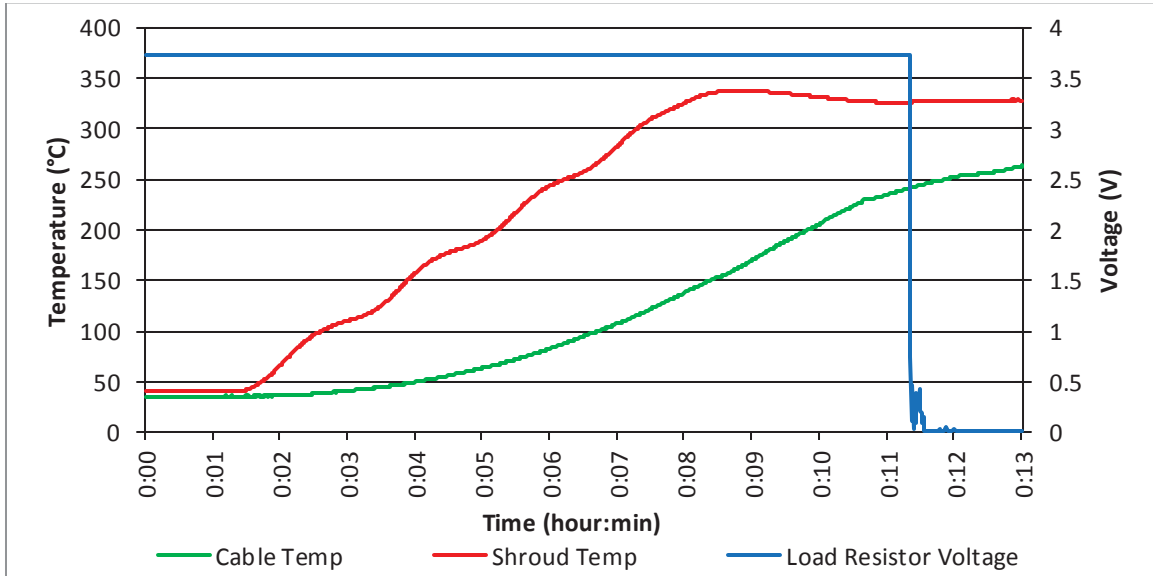

Figure A-27   Test 9 Temperature and Voltage
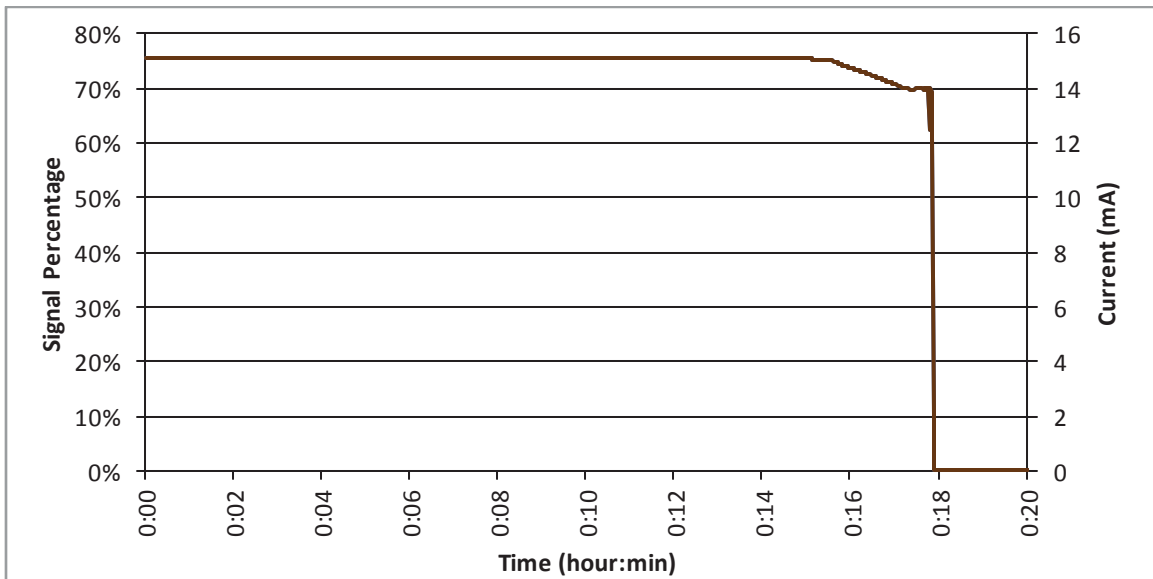
Figure A-28   Test 9 Signal Percentage and Current

A.15 Test 10 Results

Test conditions: 2/23/17, 10:02 am
Cable: RB4, 1003, TS, 16-AWG, XLPE/CSPE, 4 twisted pairs, pairs shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
Shroud power: Initiated after 60 seconds of baseline data monitoring.

Figure A-29   Test 10 Temperature and Voltage

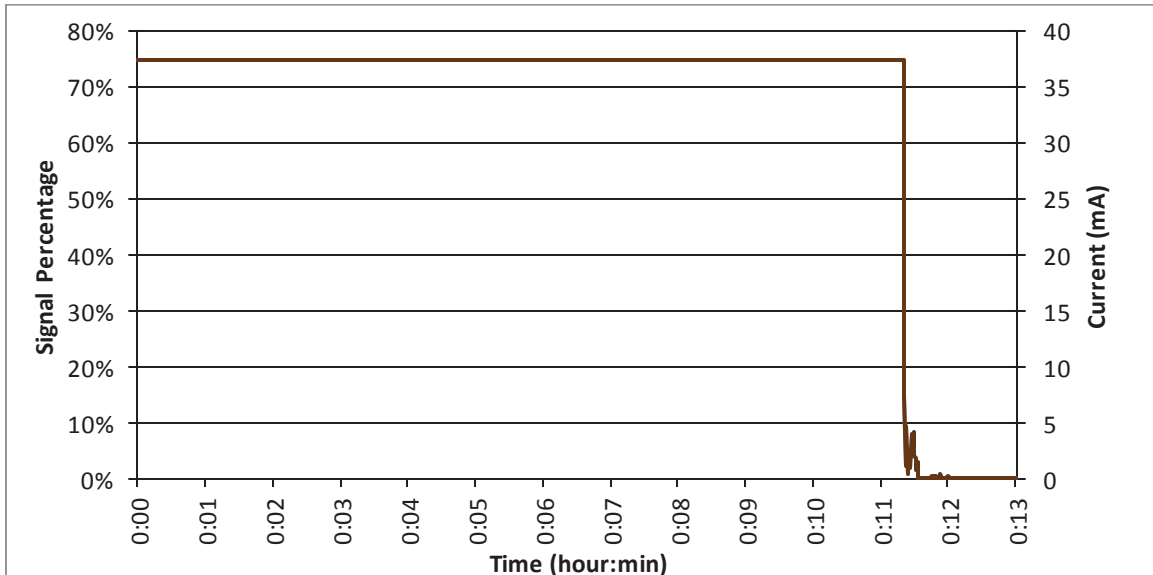**Figure A-30   Test 10 Signal Percentage and Current**

A.16 Test 11 Results

Test conditions: 2/22/17, 10:55 am
Cable: RB1, 1000, TS, 16-AWG, XLPE/CSPE, 2 Conductors, pairs not shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
Electrical response monitoring: Labview modules used to measure current. Cable tray was grounded.
Shields were not grounded, circuit ungrounded to power supply.
Shroud power: Initiated after 60 seconds of baseline data monitoring.
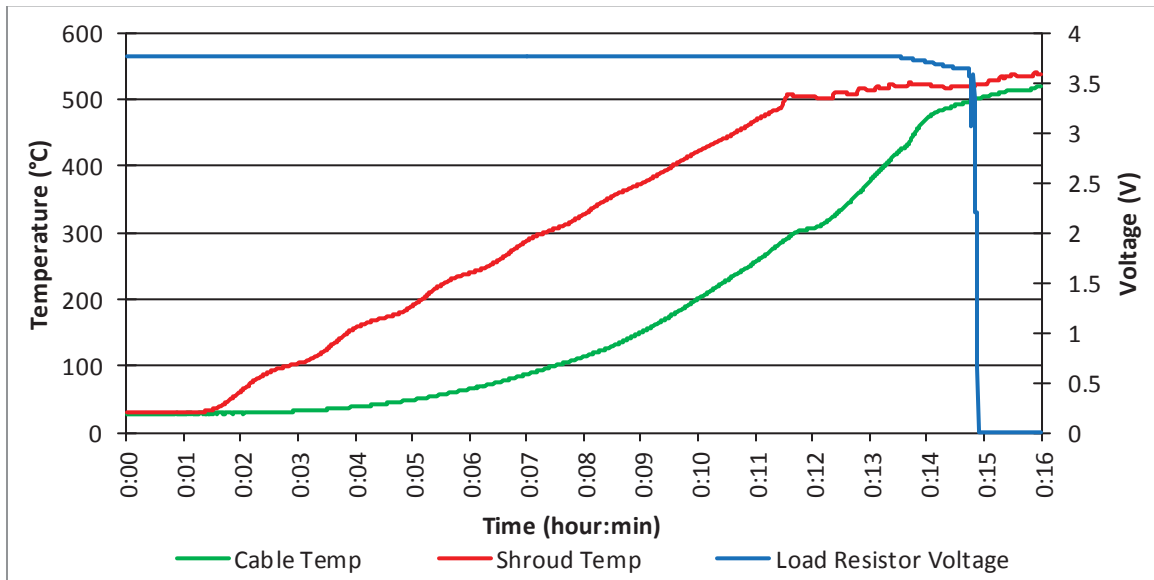
Figure A-31   Test 11 Temperature and Voltage
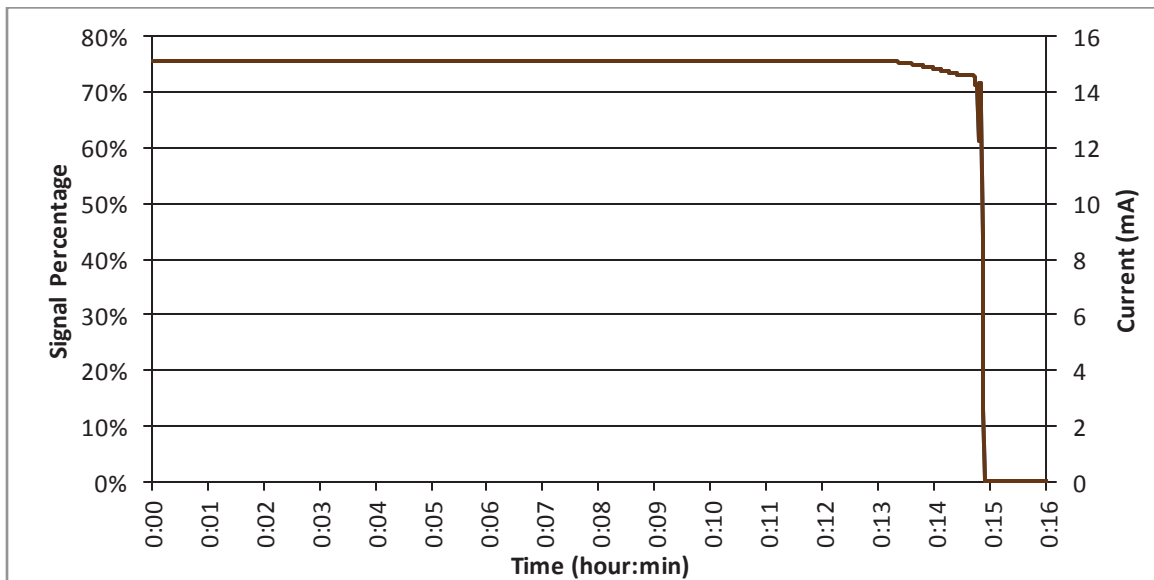
Figure A-32   Test 11 Signal Percentage and Current

A.17 Test 12 Results

Test conditions: 3/2/17, 11:00 am
Cable: HW1, 1004, TP, 16-AWG, PVC/PVC, 2-twisted pairs, pairs not shielded, overall shield.
Exposure conditions: Shroud set to temperature of 325C, with a 45°/min ramp, nominal 6.17 kW/m² flux from shroud.
Shroud power: Initiated after 60 seconds of baseline data monitoring.
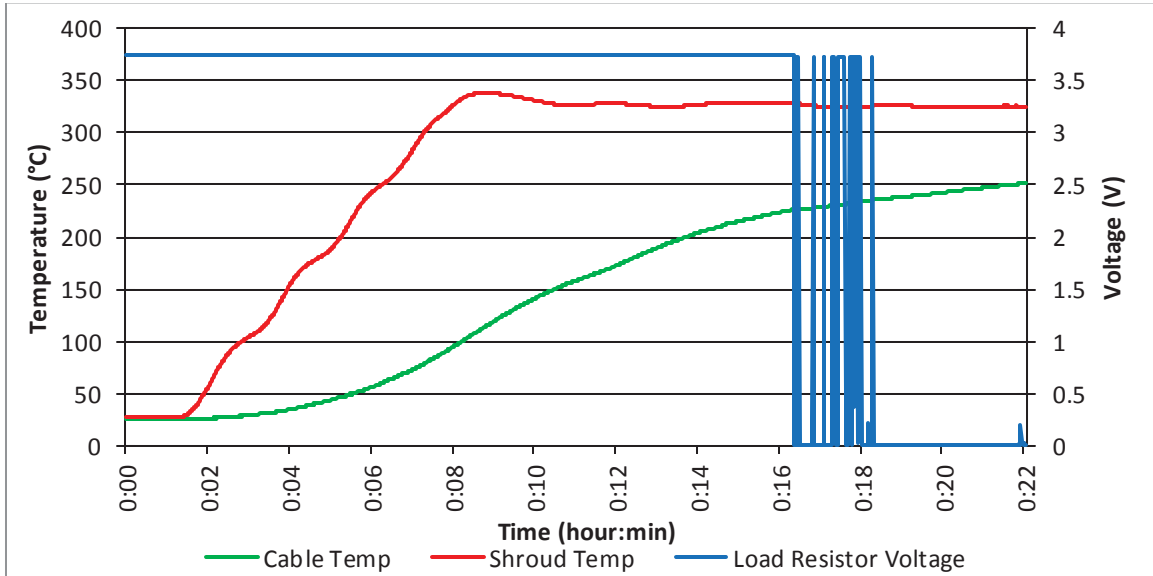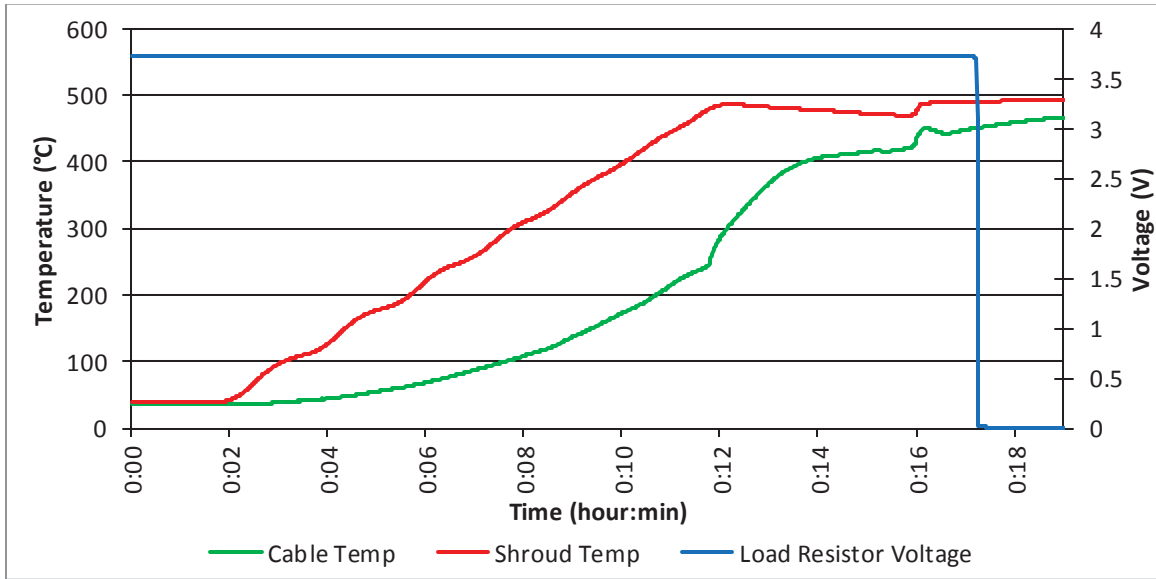

Figure A-33 Test 12 Temperature and Voltage

Figure A-34 Test 12 Signal Percentage and Current

A.18 Test 13 Results

Test conditions: 3/2/17, 1:20 pm
Cable: HW2, 1005, TP, 16-AWG, PVC/PVC, 8-twisted pairs, pairs not shielded.
Exposure conditions: Shroud set to temperature of 325C, with a 45°/min ramp, nominal 6.17 kW/m2 flux from shroud.
Shroud power: Initiated after 60 seconds of baseline data monitoring.

Figure A-35   Test 13 Temperature and Voltage
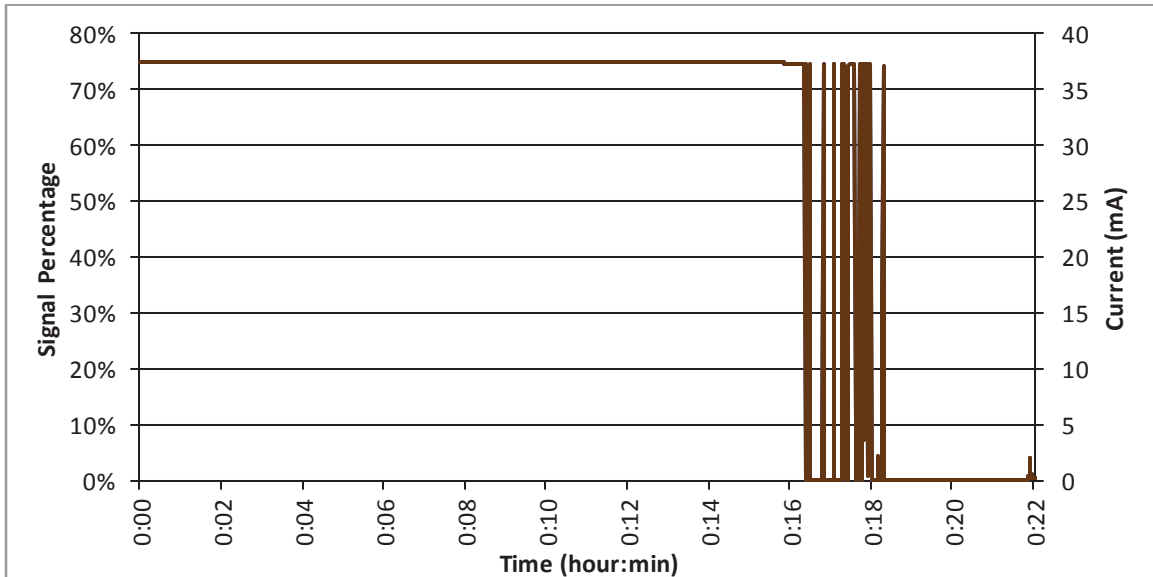
Figure A-36   Test 13 Signal Percentage and Current

A.19 Test 14 Results

Test conditions: 2/28/17, 11:21 am
Cable: HW3, 1006, TS, 16-AWG, FR-EP/CPE, 2-twisted pairs, pairs shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
Shroud power: Initiated after 90 seconds of baseline data monitoring.
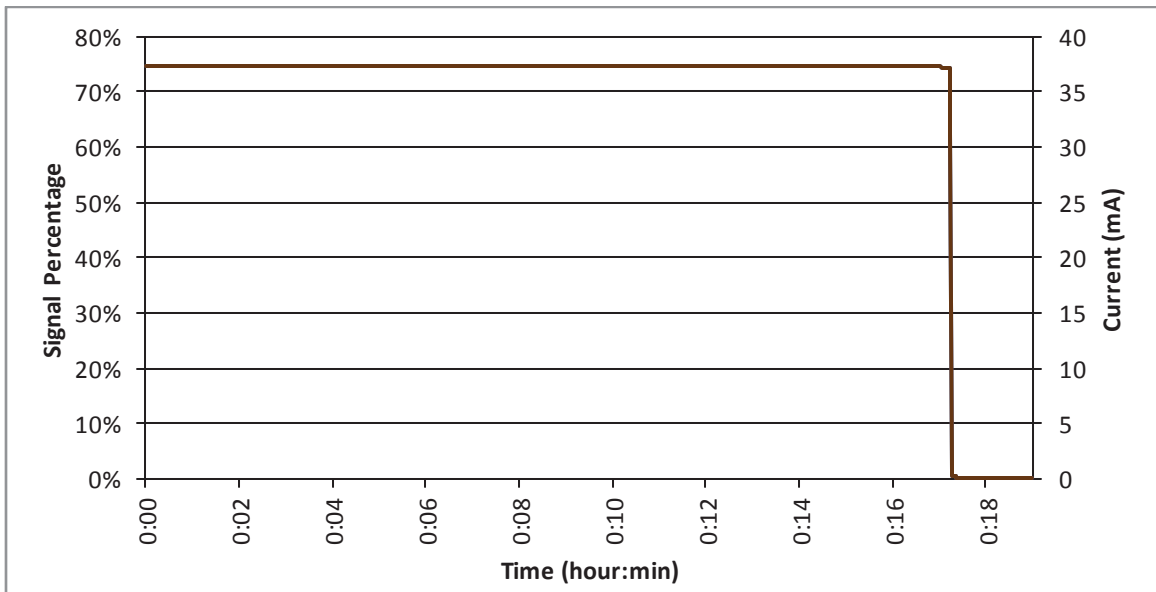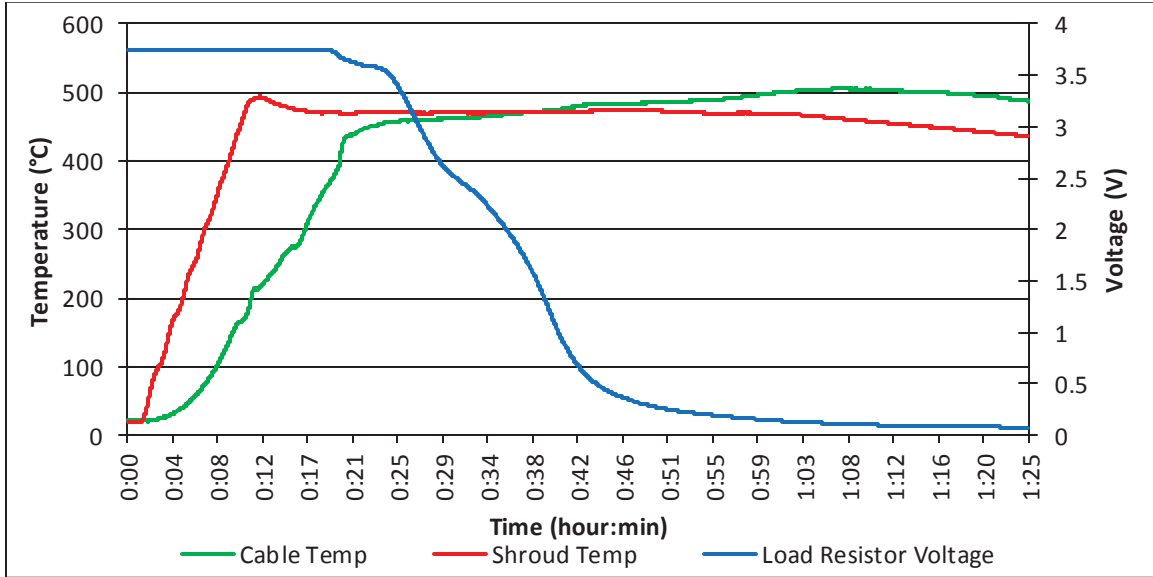

Figure A-37   Test 14 Temperature and Voltage

Figure A-38   Test 14 Signal Percentage and Current

A.20 Test 15 Results

Test conditions: 3/2/17, 8:00 am
Cable: HW4, 1007, TS, 16-AWG, FR-EP/CPE, 8 twisted pairs, pairs shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
Shroud power: Initiated after 60 seconds of baseline data monitoring.

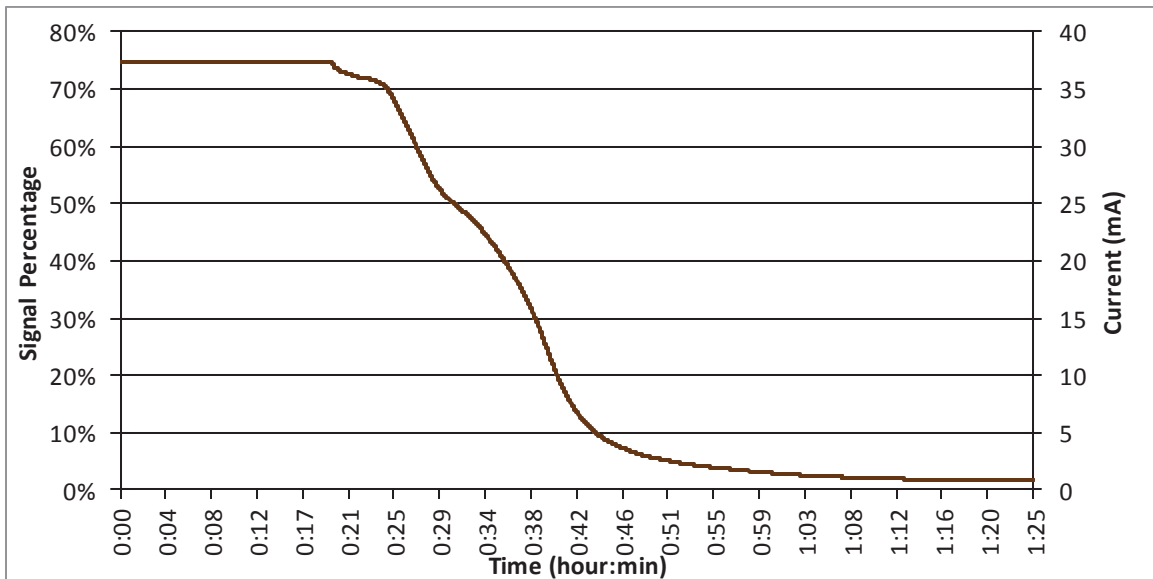
Figure A-39   Test 15 Temperature and Voltage

Figure A-40   Test 15 Signal Percentage and Current

A.21 Test 16 Results

Test conditions: 2/28/17, 1:45 pm
Cable: HW5, 1008, TS, 16-AWG, XLP-LSZH, 1 twisted pair, pairs not shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
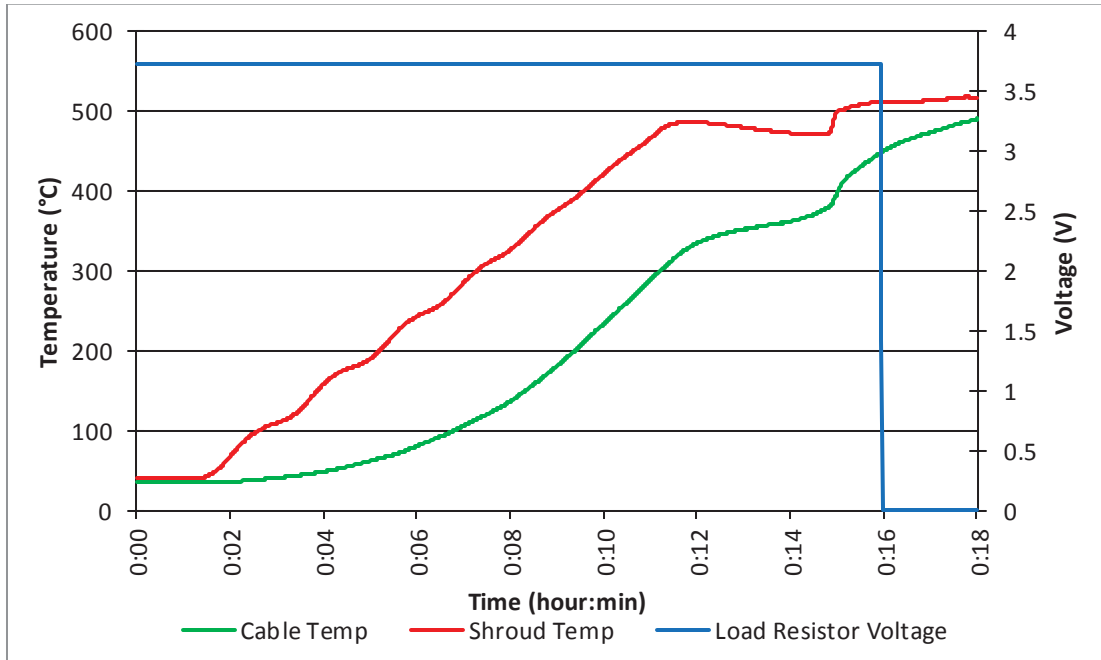Shroud power: Initiated after 60 seconds of baseline data monitoring.

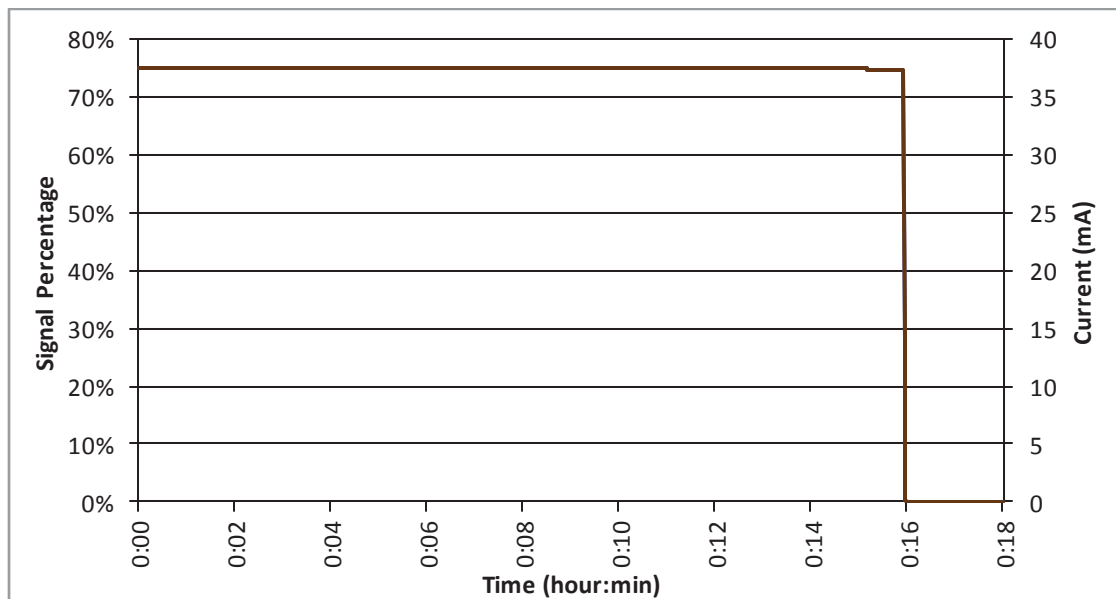**Figure A-41   Test 16 Temperature and Voltage**

Figure A-42   Test 16 Signal Percentage and Current

A.22 Test 17 Results

Test conditions: 3/1/17, 1:40 pm
Cable: HW6, 1009, TS, 16-AWG, XLP-LSZH, 8 twisted pairs, pairs shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
Shroud power: Initiated after 60 seconds of baseline data monitoring.

Figure A-43   Test 17 Temperature and Voltage

Figure A-44   Test 17 Signal Percentage and Current

A.23 Test 18 A Results

Test conditions: 2/28/17, 3:22 pm
Cable: RB1, 1000, TS, 16-AWG, XLPE/CSPE, 2 Conductors, pairs not shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
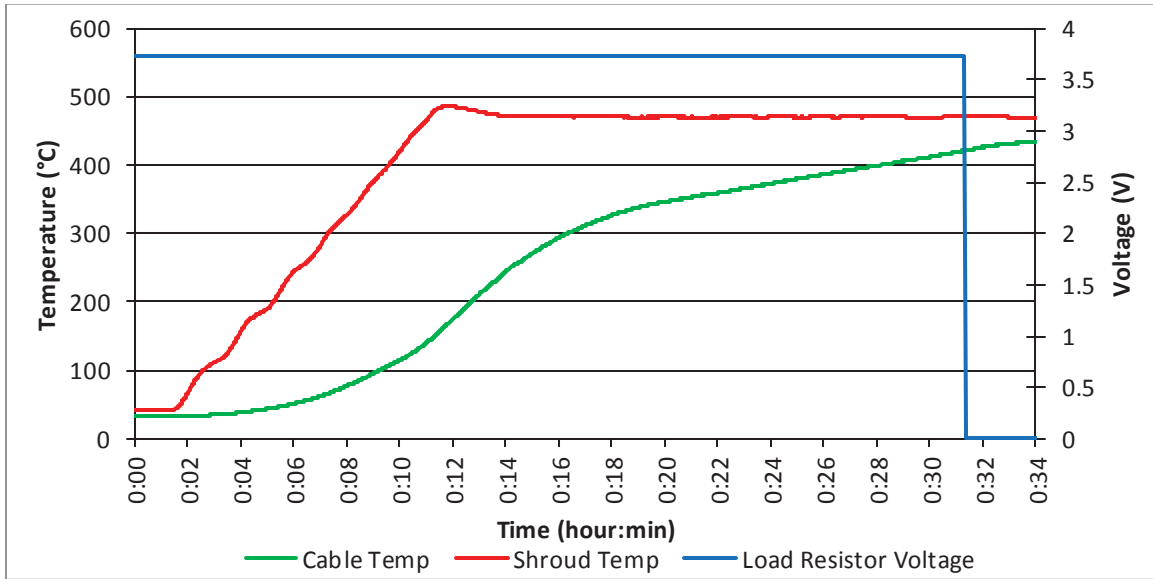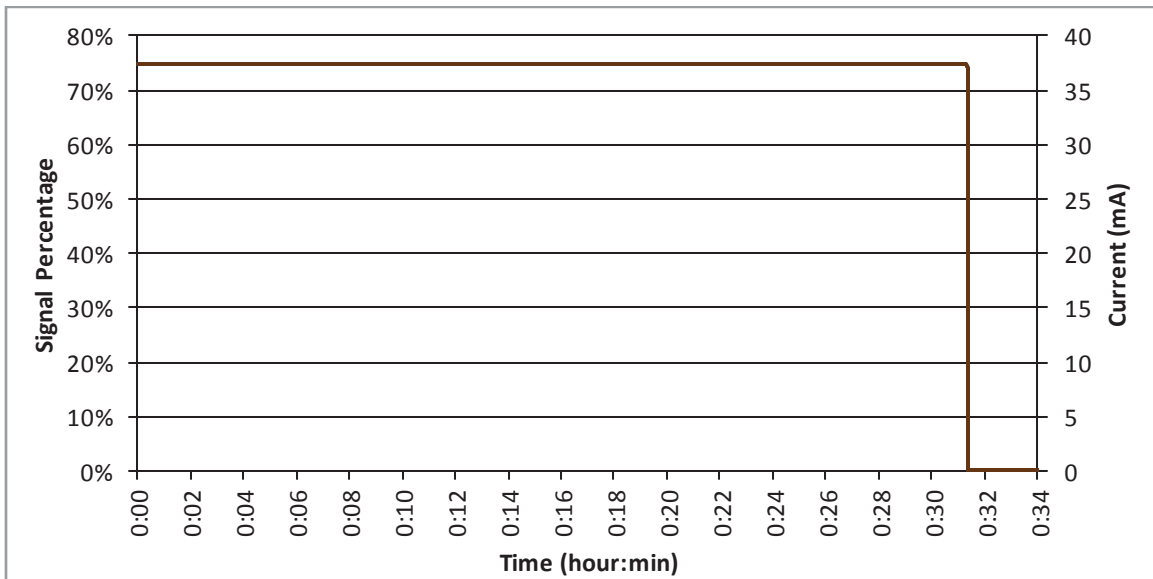Shroud power: Initiated after 60 seconds of baseline data monitoring.

Figure A-45   Test 18 A Temperature and Voltage

Figure A-46   Test 18 A Signal Percentage and Current

A.24 Test 18 B Results

Test conditions: 3/3/17
Cable: RB1, 1000, TS, 16-AWG, XLPE/CSPE, 2 Conductors, pairs not shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
Electrical response monitoring: Labview modules used to measure current. Cable tray was grounded. Shields were grounded, circuit grounded to power supply, circuit includes fuse.
Shroud power: Initiated after 60 seconds of baseline data monitoring.

Figure A-47   Test 18 B Temperature and Voltage

Figure A-48   Test 18 B Signal Percentage and Current

A.25 Test 19 Results

Test conditions: 3/1/17, 7:30 am
Cable: RB2, 1001, TS, 16-AWG, XLPE/CSPE, 4 Conductors, pairs not shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
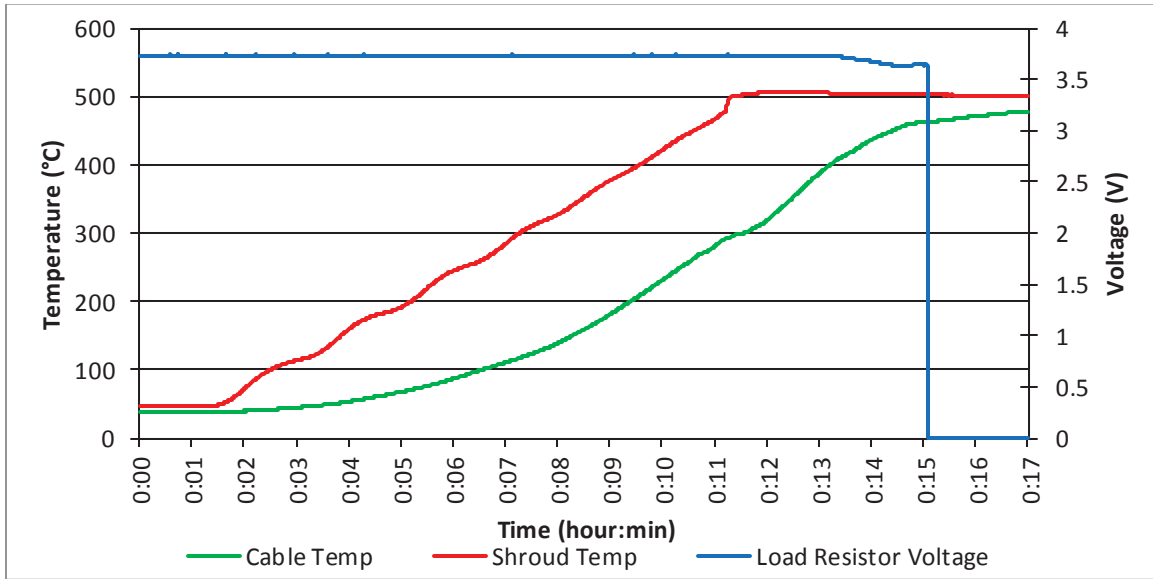Shroud power: Initiated after 60 seconds of baseline data monitoring.

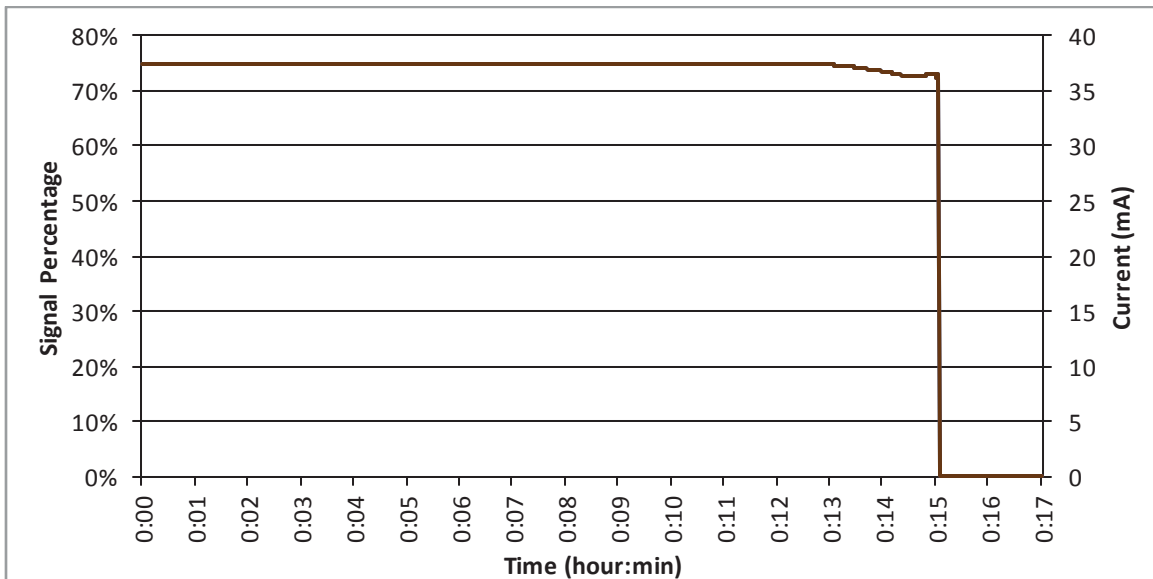**Figure A-49   Test 19 Temperature and Voltage**
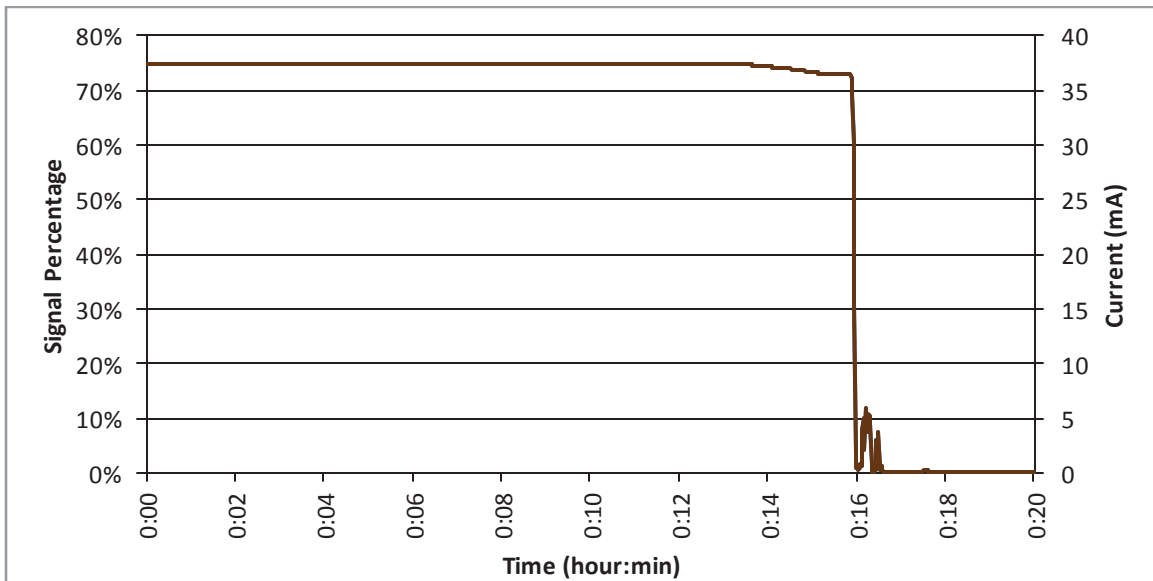
Figure A-50   Test 19 Signal Percentage and Current

A.26 Test 20 Results

Test conditions: 3/1/17, 9:30 am
Cable: RB3, 1002, TS, 16-AWG, XLPE/CSPE, 2 twisted pairs, pairs shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
Shroud power: Initiated after 60 seconds of baseline data monitoring.

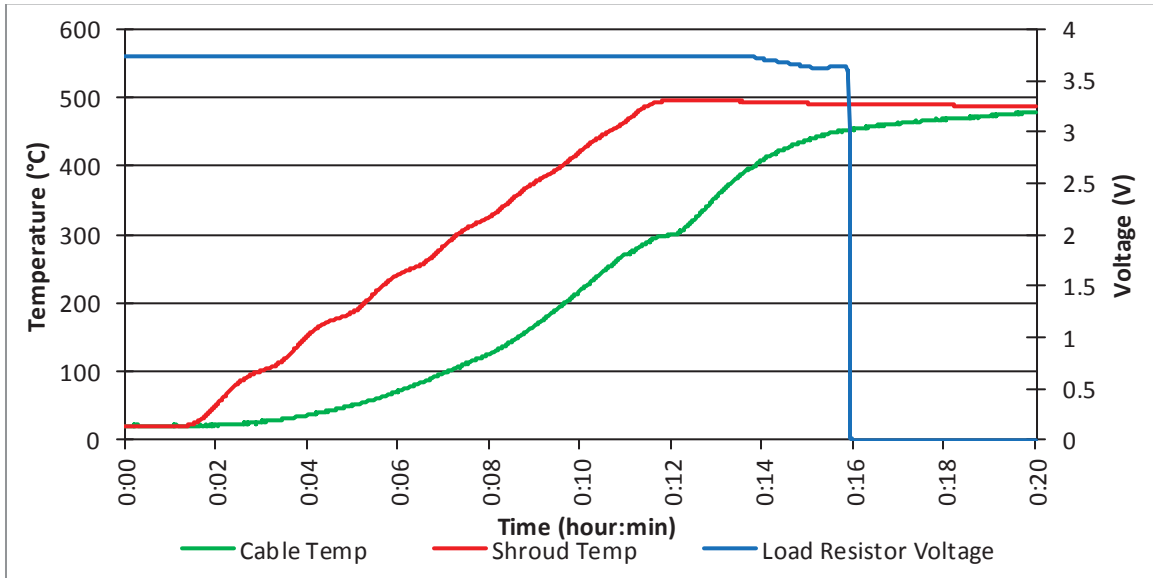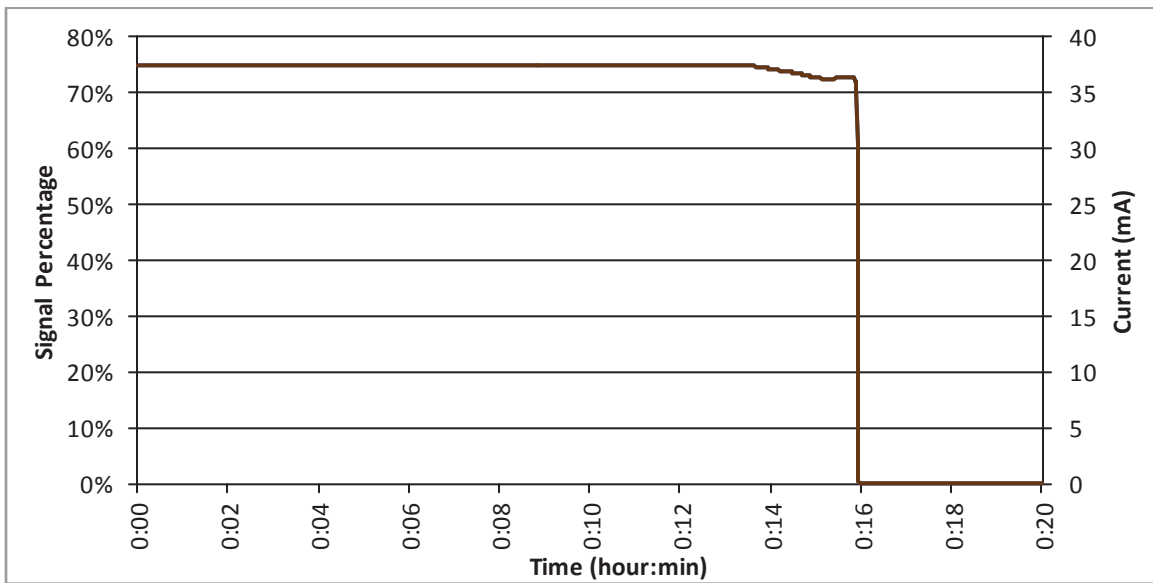**Figure A-51   Test 20 Temperature and Voltage**
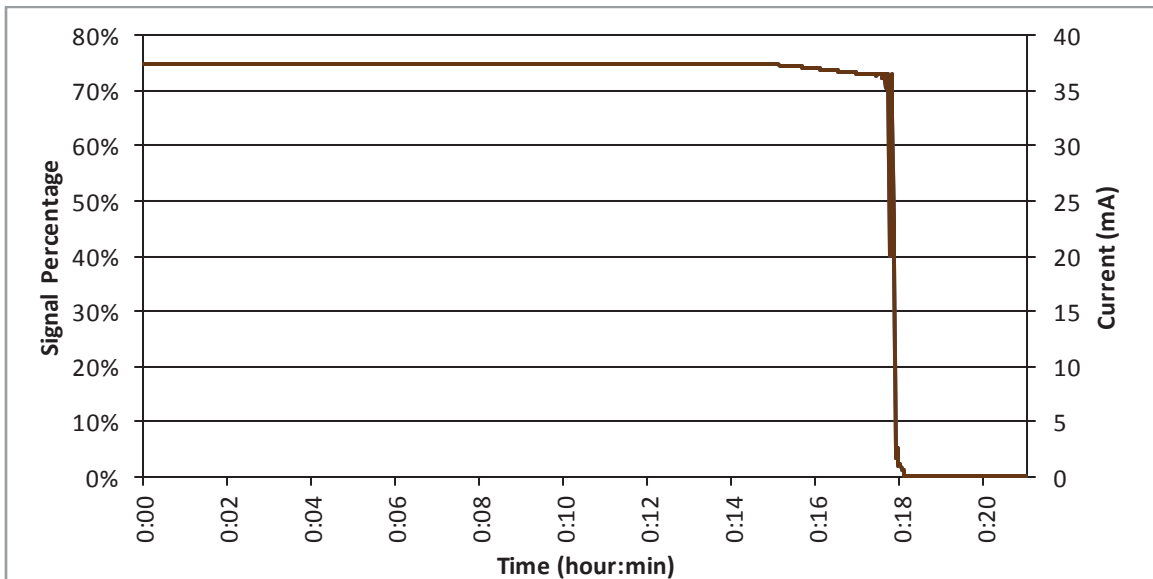
Figure A-52   Test 20 Signal Percentage and Current

A.27 Test 21 Results

Test conditions: 3/1/17, 11:30 am
Cable: RB4, 1003, TS, 16-AWG, XLPE/CSPE, 4 twisted pairs, pairs shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
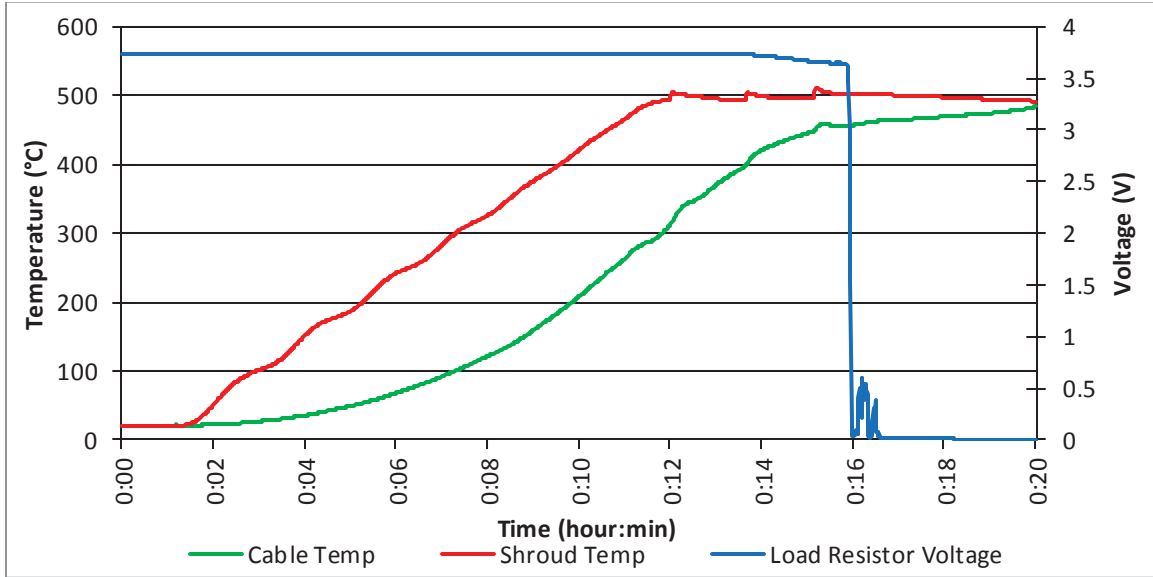Shroud power: Initiated after 60 seconds of baseline data monitoring.

**Figure A-53   Test 21 Temperature and Voltage**
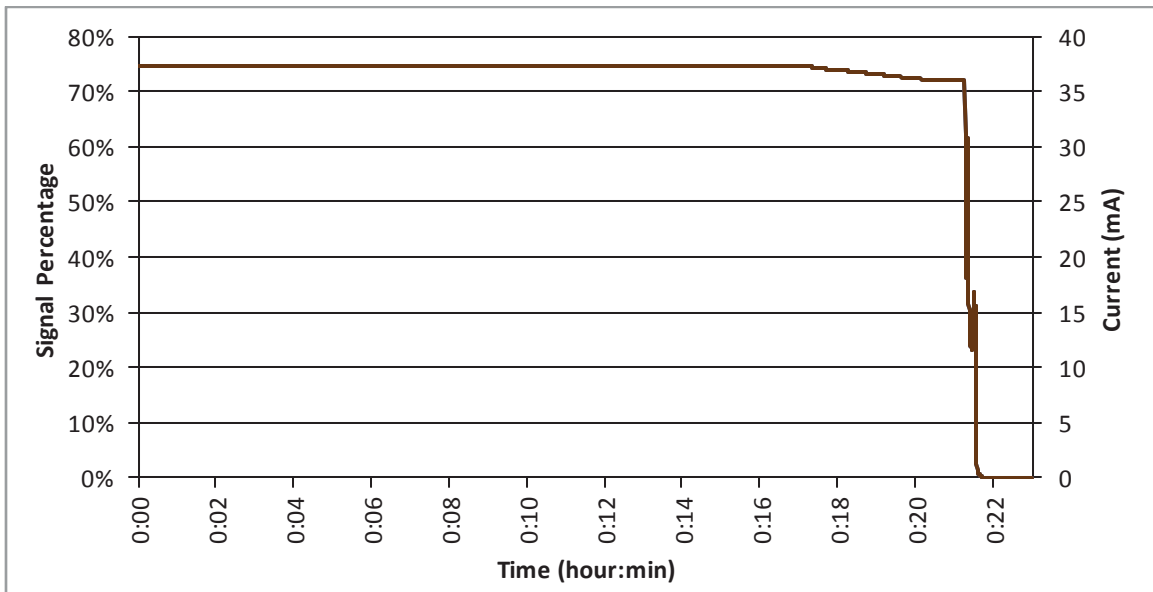
Figure A-54   Test 21 Signal Percentage and Current

A.28 Test 22 Results

Test conditions: 3/6/17, 8:00 am
Cable: HW1, 1004, TP, 16-AWG, PVC/PVC, 2-twisted pairs, pairs not shielded, overall shield.
Exposure conditions: Shroud set to temperature of 325C, with a 45°/min ramp, nominal 6.17 kW/m² flux from shroud.
Shroud power: Initiated after 60 seconds of baseline data monitoring.

Figure A-55   Test 22 Temperature and Voltage

Figure A-56   Test 22 Signal Percentage and Current

A.29 Test 23 Results

Test conditions: 3/6/17, 9:30 pm
Cable: HW2, 1005, TP, 16-AWG, PVC/PVC, 8-twisted pairs, pairs not shielded.
Exposure conditions: Shroud set to temperature of 325C, with a 45°/min ramp, nominal 6.17 kW/m2 flux from shroud.
Shroud power: Initiated after 60 seconds of baseline data monitoring.

Figure A-57   Test 23 Temperature and Voltage
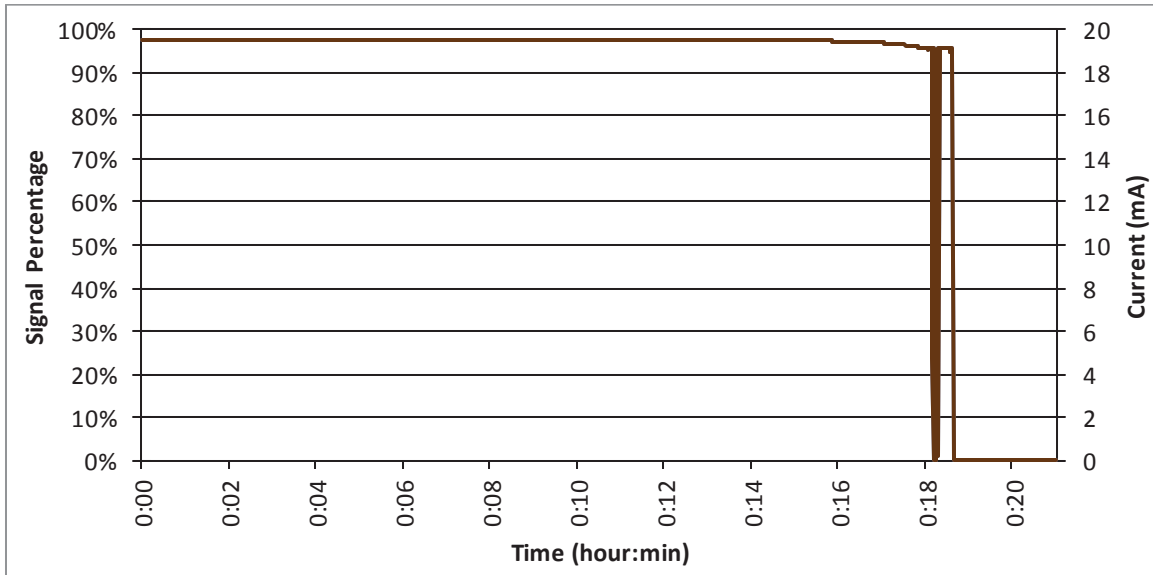
Figure A-58   Test 23 Signal Percentage and Current

A.30 Test 24 Results

Test conditions: 3/6/17, 11:32 am
Cable: HW3, 1006, TS, 16-AWG, FR-EP/CPE, 2-twisted pairs, pairs shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
Shroud power: Initiated after 60 seconds of baseline data monitoring.
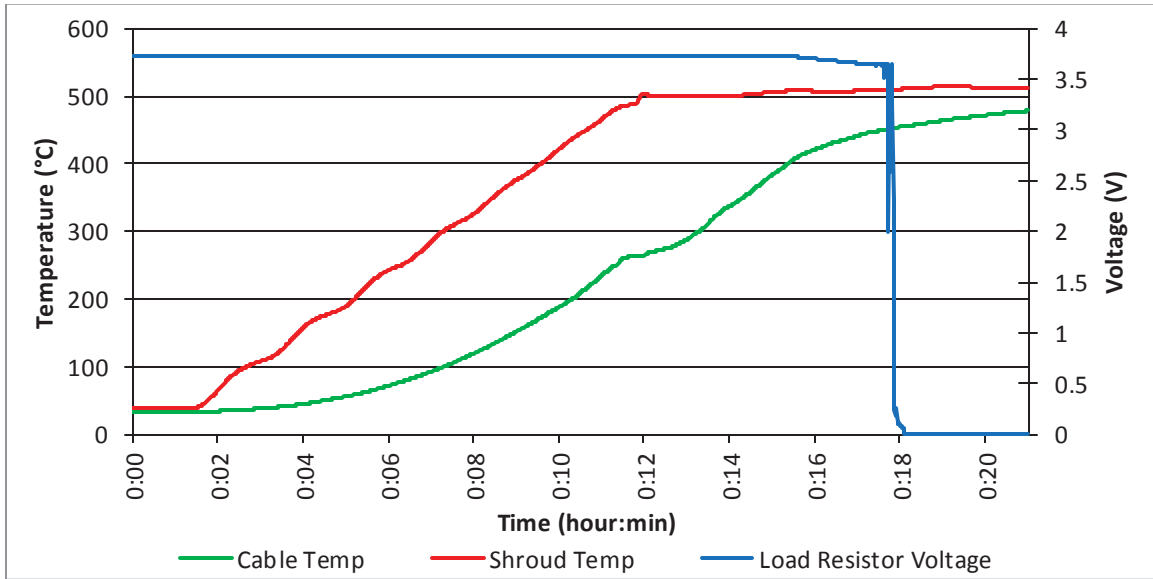

Figure A-59   Test 24 Temperature and Voltage
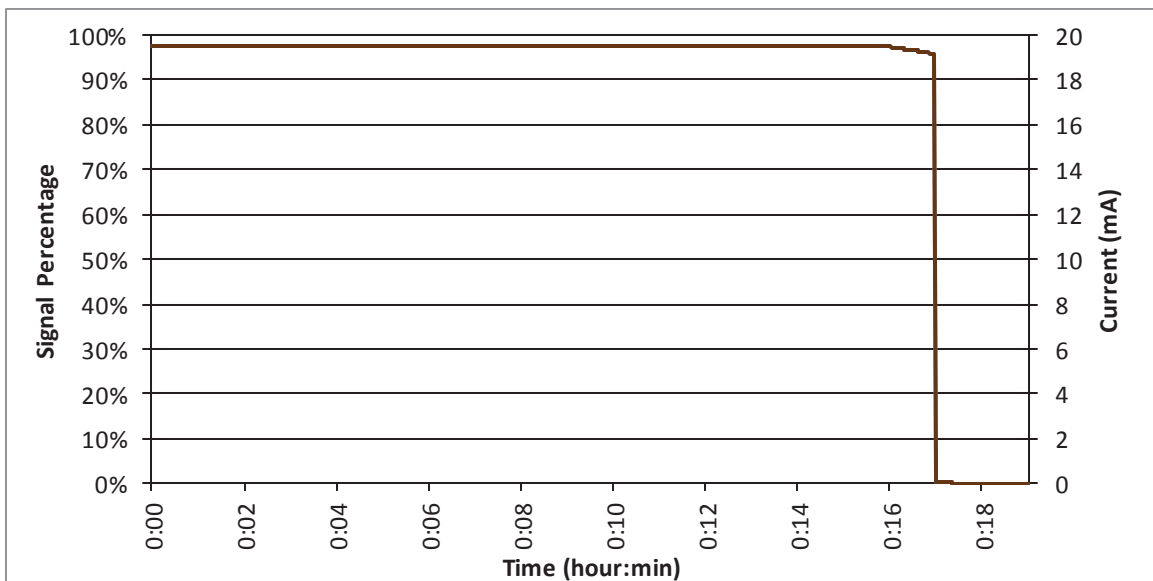
Figure A-60   Test 24 Signal Percentage and Current

A.31 Test 25 Results

Test conditions: 3/7/17, 2:20 pm
Cable: HW4, 1007, TS, 16-AWG, FR-EP/CPE, 8 twisted pairs, pairs shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
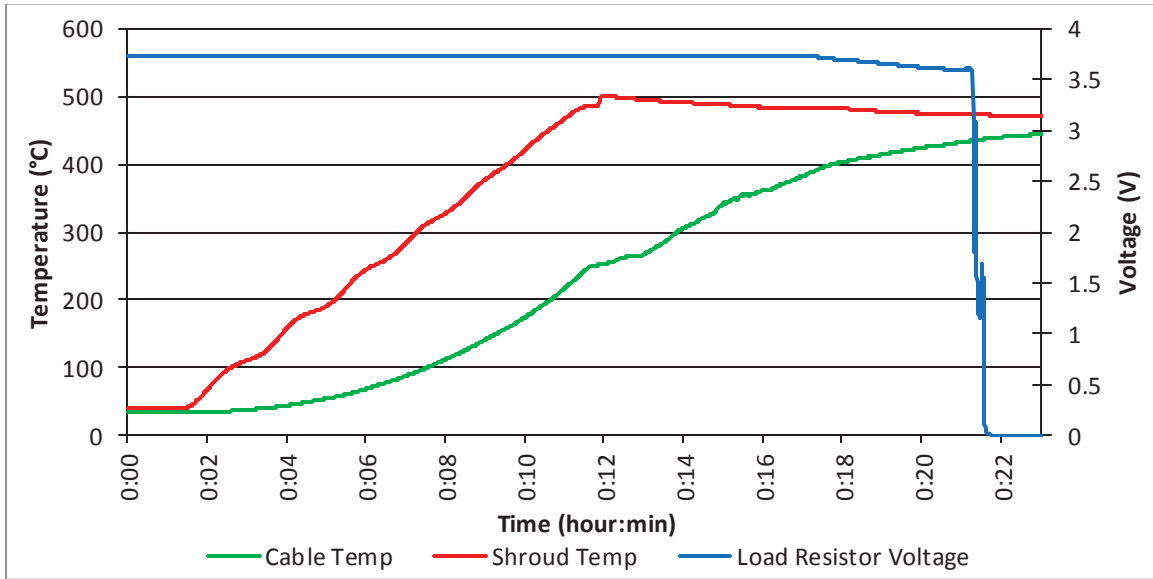Shroud power: Initiated after 60 seconds of baseline data monitoring.

**Figure A-61   Test 25 Temperature and Voltage**
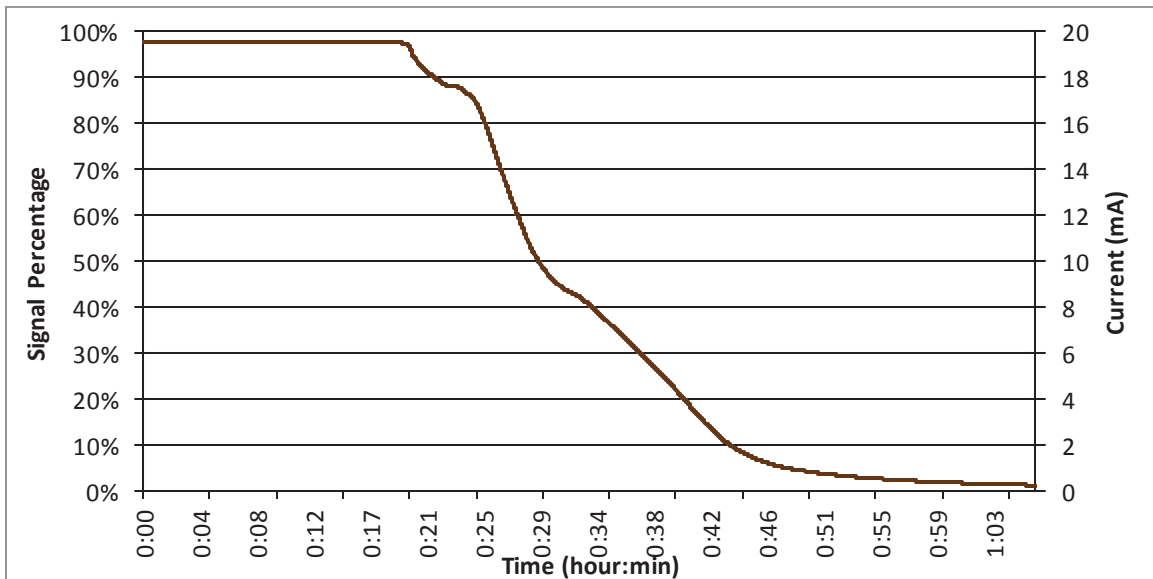
Figure A-62   Test 25 Signal Percentage and Current

A.32 Test 26 Results

Test conditions: 3/6/17, 1:45 pm
Cable: HW5, 1008, TS, 16-AWG, XLP-LSZH, 1 twisted pair, pairs not shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
Shroud power: Initiated after 60 seconds of baseline data monitoring.

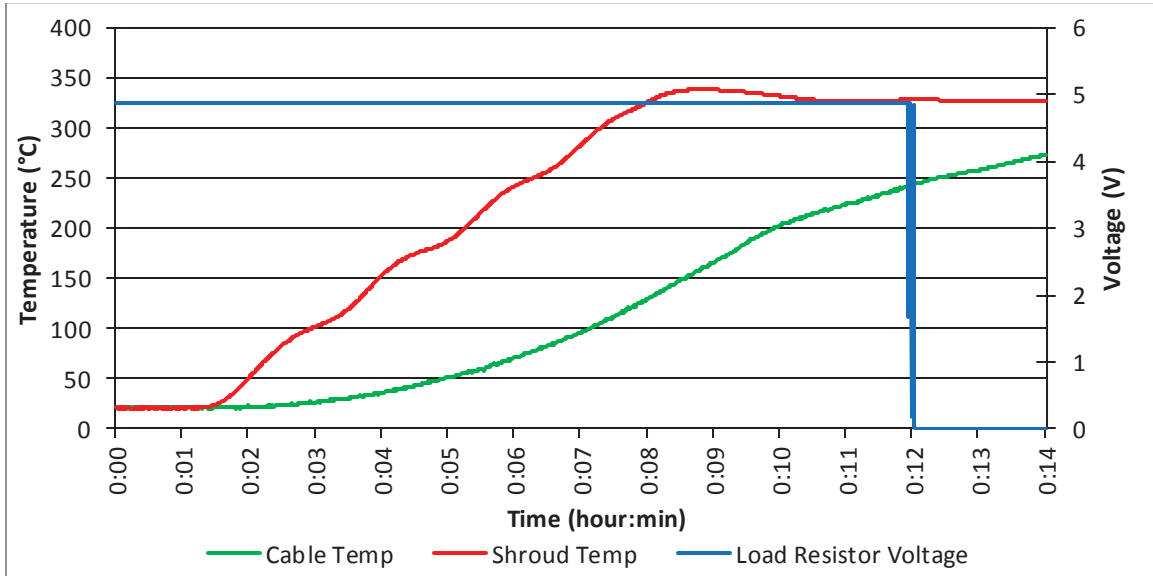**Figure A-63   Test 26 Temperature and Voltage**
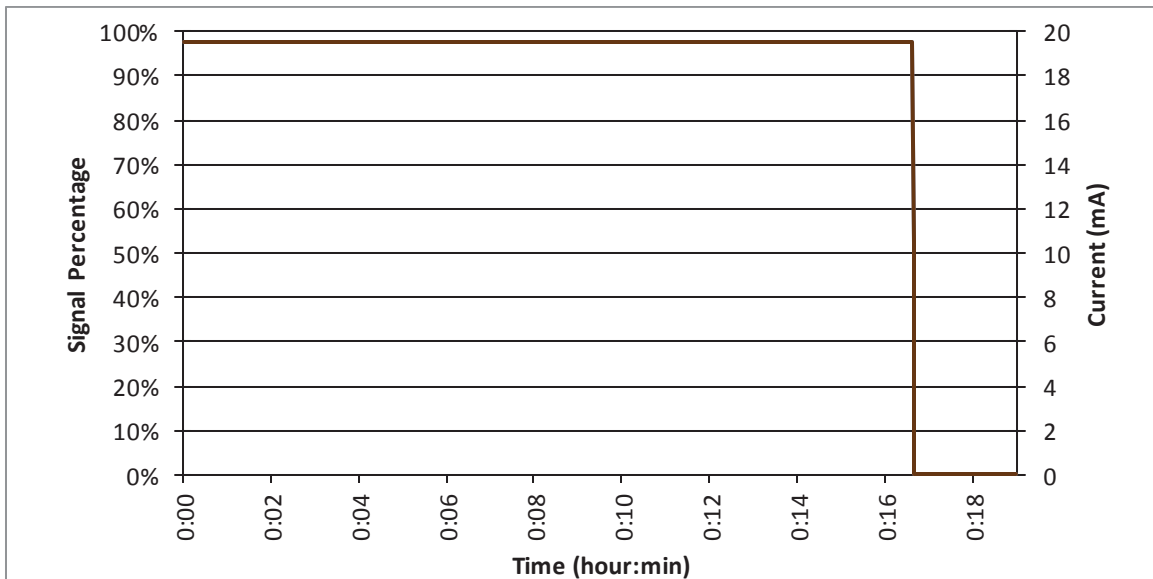
Figure A-64   Test 26 Signal Percentage and Current

A.33 Test 27 Results

Test conditions: 3/8/17, 8:00 am
Cable: HW6, 1009, TS, 16-AWG, XLP-LSZH, 8 twisted pairs, pairs shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
Shroud power: Initiated after 60 seconds of baseline data monitoring.
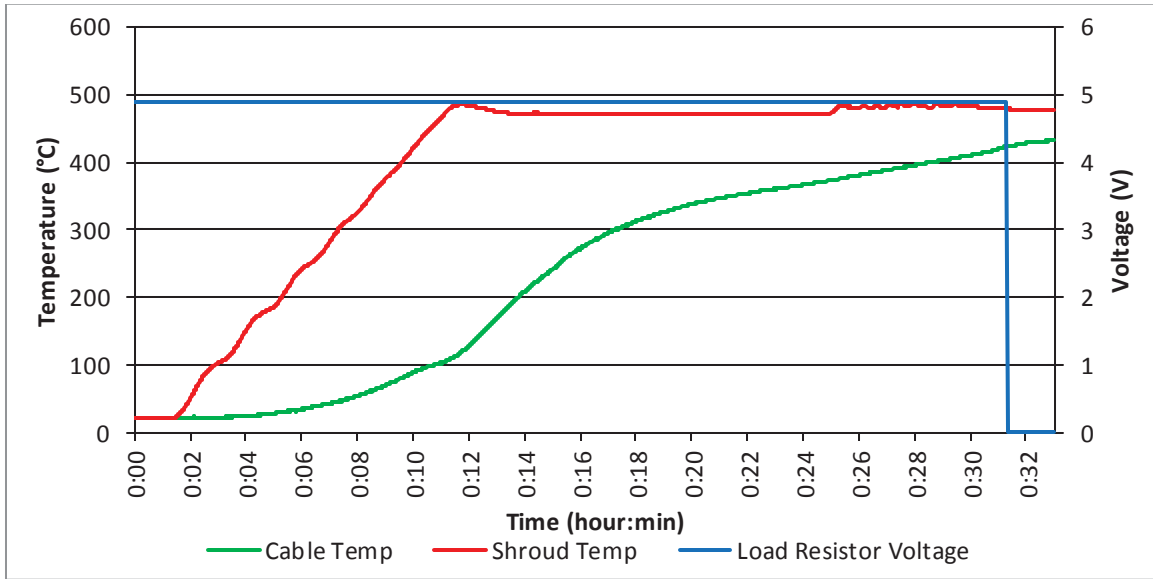
Figure A-65   Test 27 Temperature and Voltage
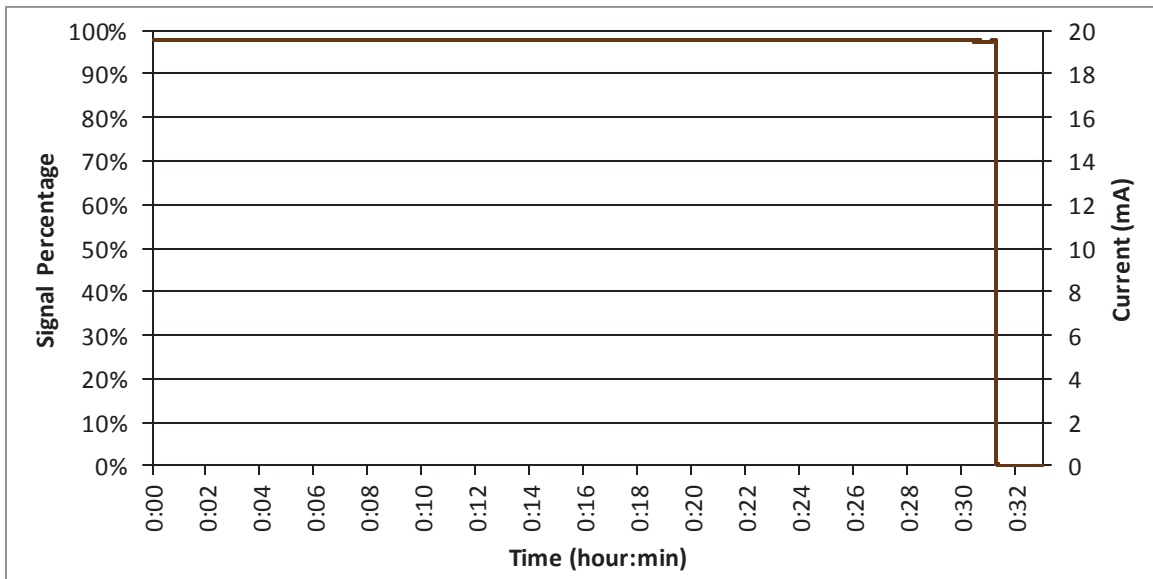
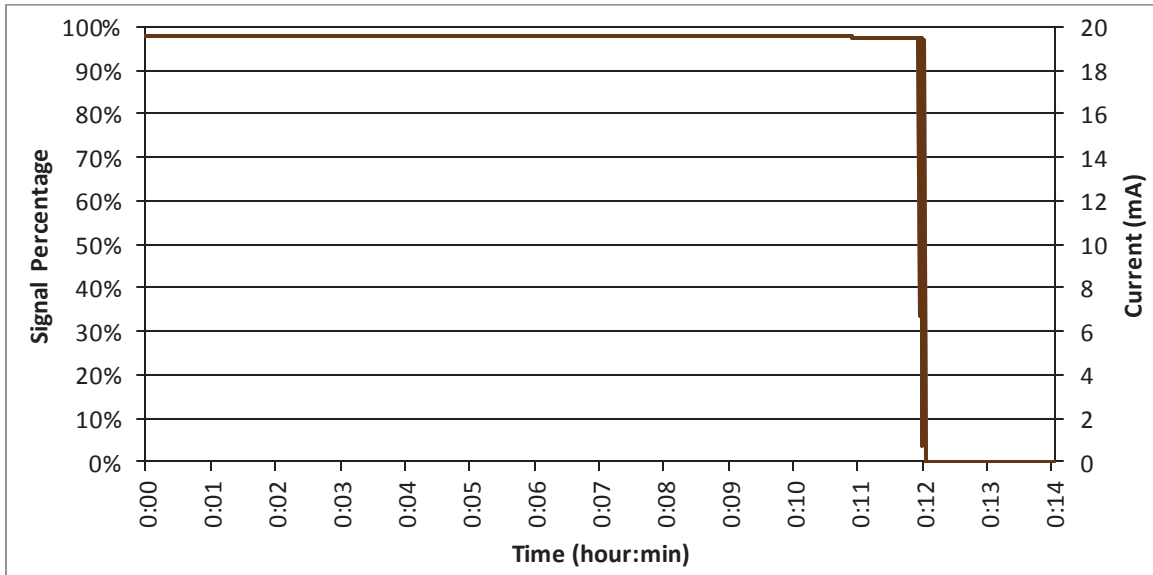**Figure A-66   Test 27 Signal Percentage and Current**

A.34 Test 28 Results

Test conditions: 3/6/17, 3:30 pm
Cable: RB1, 1000, TS, 16-AWG, XLPE/CSPE, 2 Conductors, pairs not shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
Shroud power: Initiated after 60 seconds of baseline data monitoring.
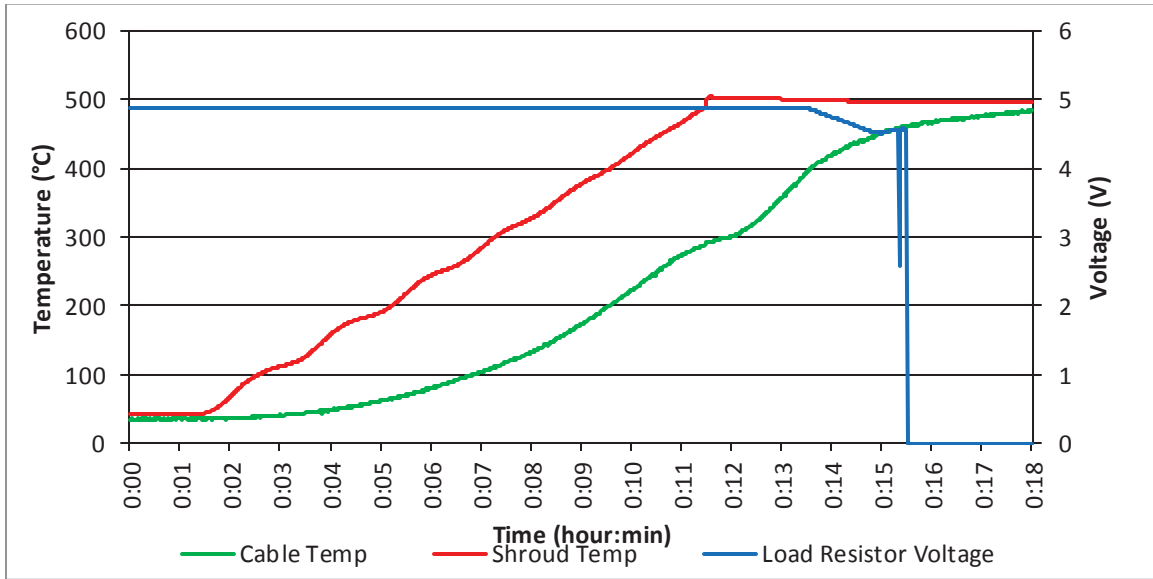
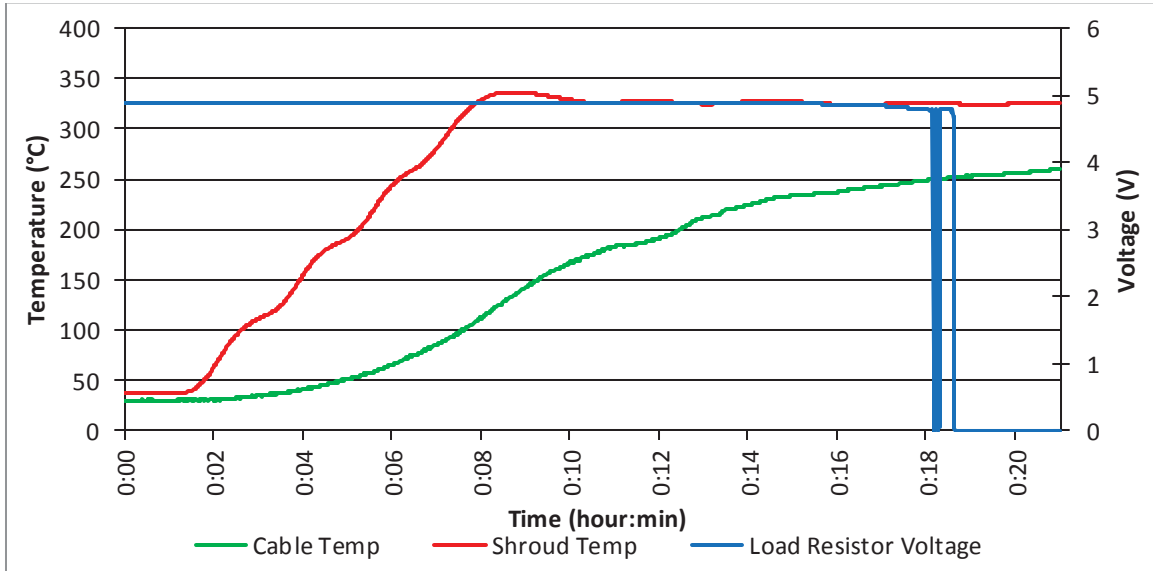**Figure A-67   Test 28 Temperature and Voltage**
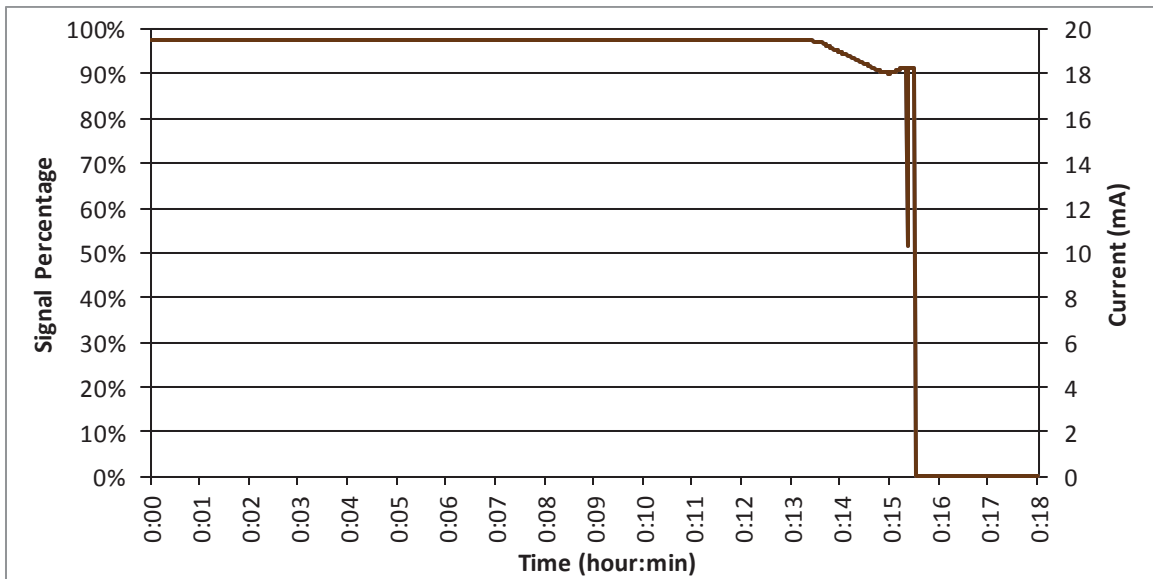
Figure A-68   Test 28 Signal Percentage and Current

A.35 Test 29 Results

Test conditions: 3/7/17, 8:17 am
Cable: RB2, 1001, TS, 16-AWG, XLPE/CSPE, 4 Conductors, pairs not shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
Shroud power: Initiated after 60 seconds of baseline data monitoring.
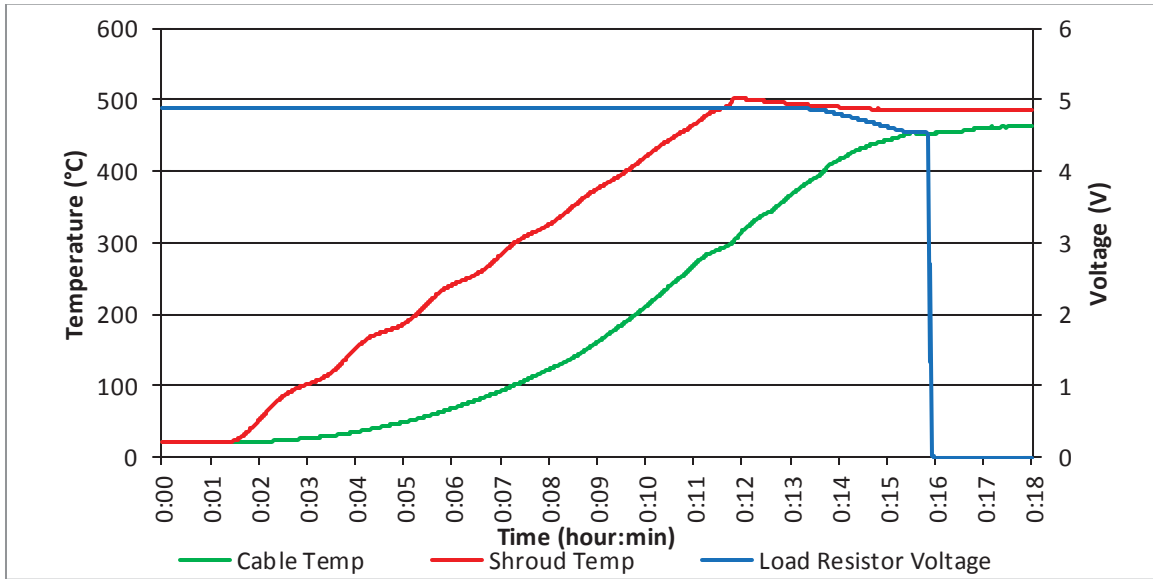
Figure A-69   Test 29 Temperature and Voltage
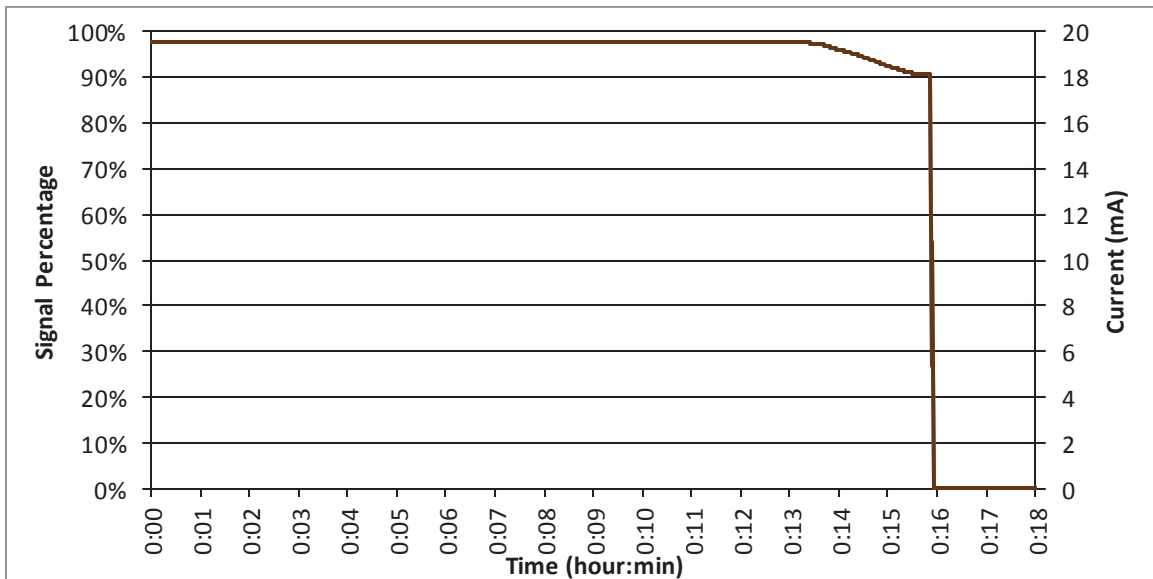
Figure A-70   Test 29 Signal Percentage and Current

A.36 Test 30 Results

Test conditions: 3/1/17, 9:30 am
Cable: RB3, 1002, TS, 16-AWG, XLPE/CSPE, 2 twisted pairs, pairs shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
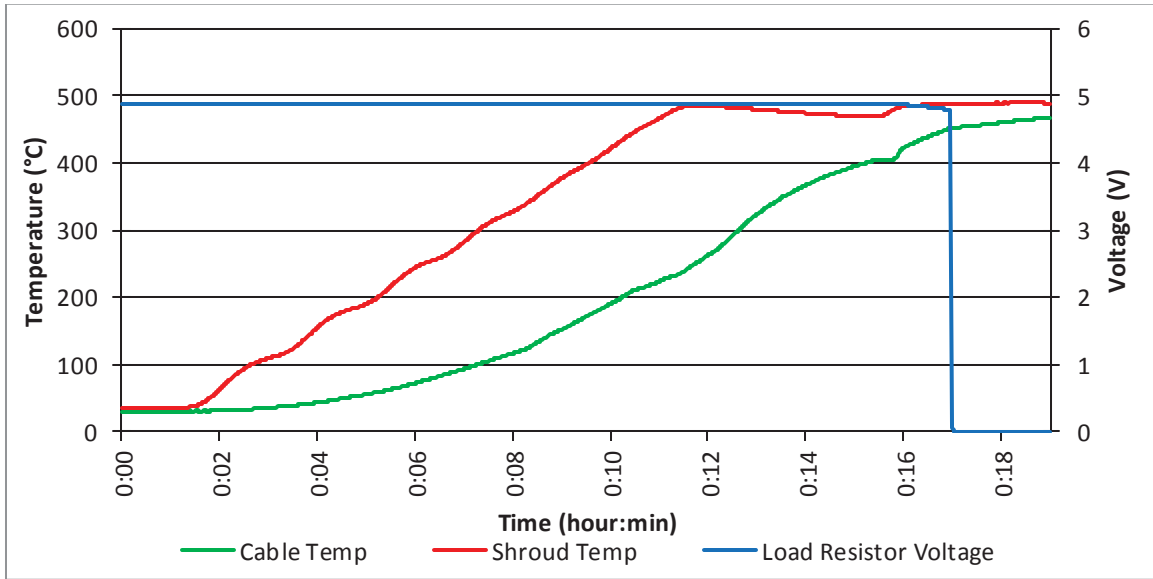Shroud power: Initiated after 60 seconds of baseline data monitoring.
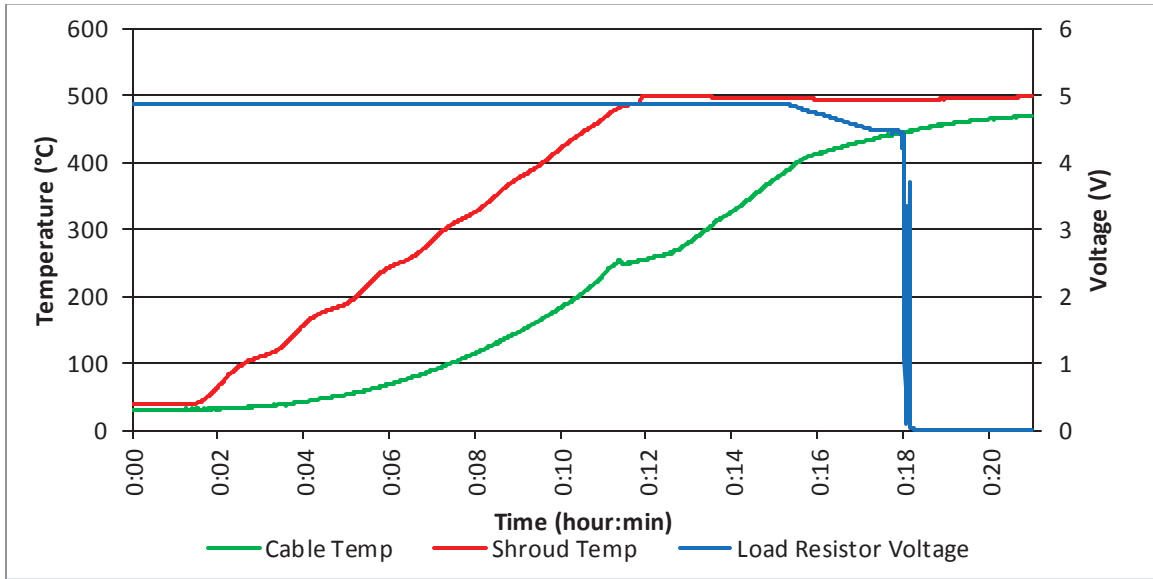
Figure A-71   Test 30 Temperature and Voltage
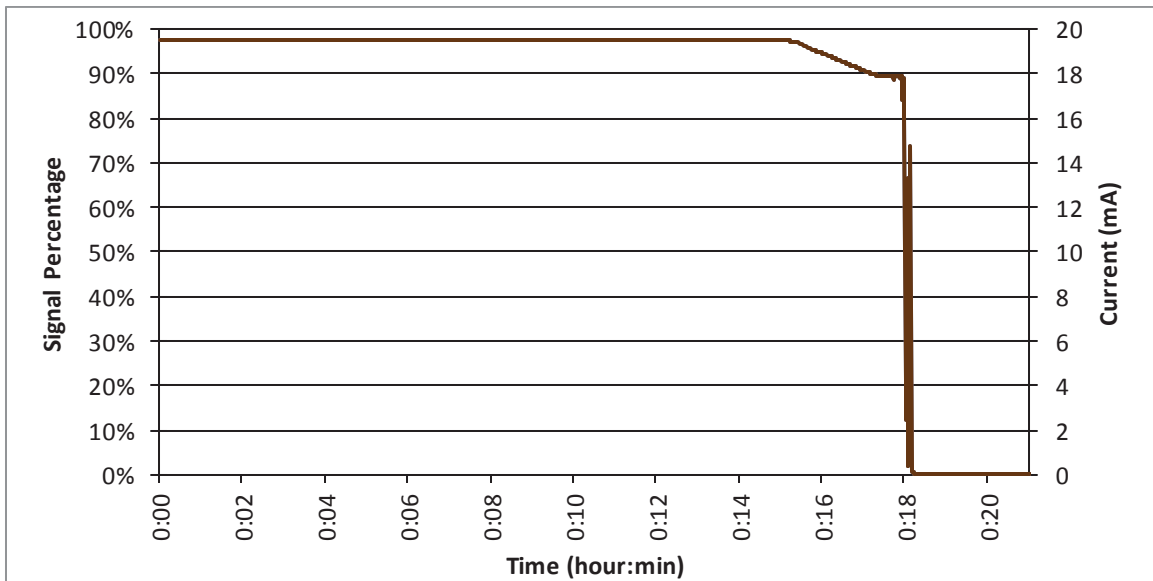
Figure A-72   Test 30 Signal Percentage and Current

A.37 Test 31 Results

Test conditions: 3/7/17, 12:00 pm
Cable: RB4, 1003, TS, 16-AWG, XLPE/CSPE, 4 twisted pairs, pairs shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
Shroud power: Initiated after 60 seconds of baseline data monitoring.
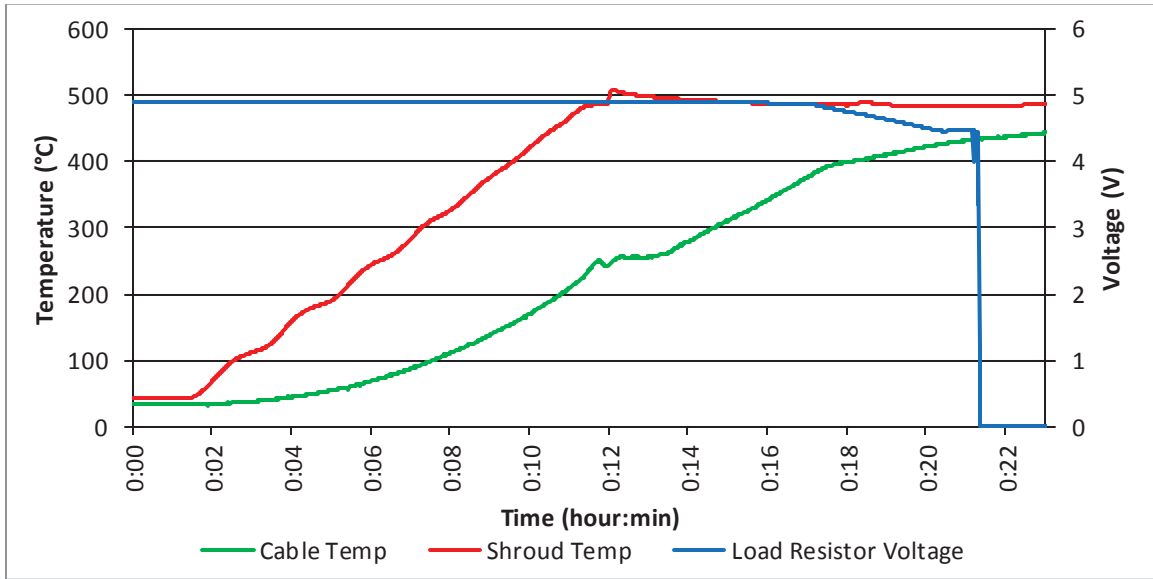
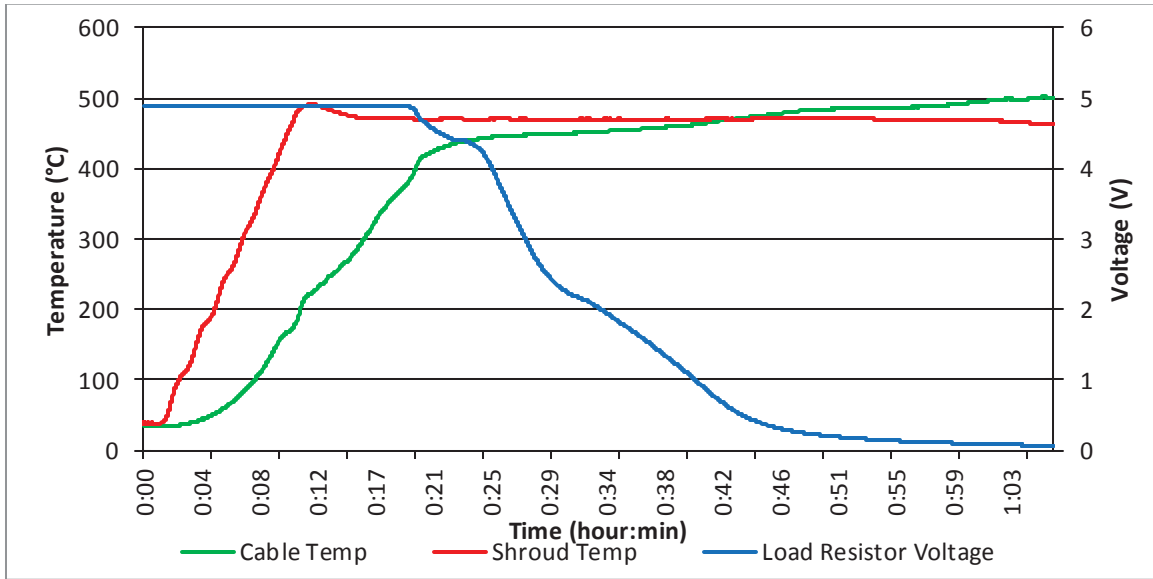**Figure A-73   Test 31 Temperature and Voltage**
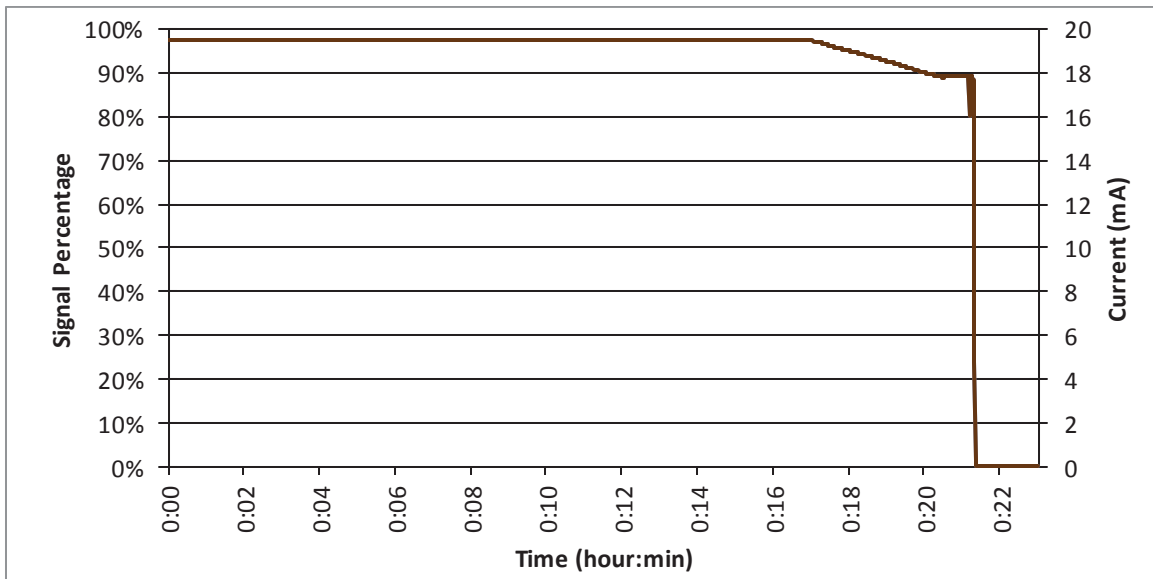
Figure A-74   Test 31 Signal Percentage and Current

A.38 Test 32 Results

Test conditions: 3/8/17, 11:00 am
Cable: CC4, TP, 16-AWG, PVC/PVC, 2/c, pairs shielded.
Exposure conditions: Shroud set to temperature of 325°C, with a 45°/min ramp, nominal 6.17 kW/m² flux from shroud.
Shroud power: Initiated after 60 seconds of baseline data monitoring.
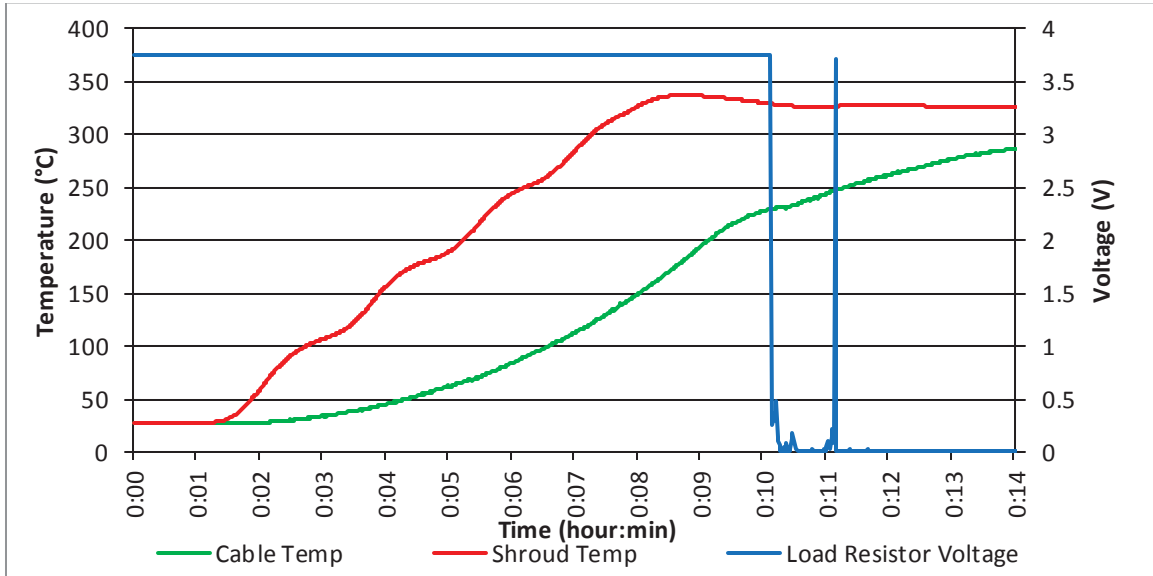
Figure A-75   Test 32 Temperature and Voltage
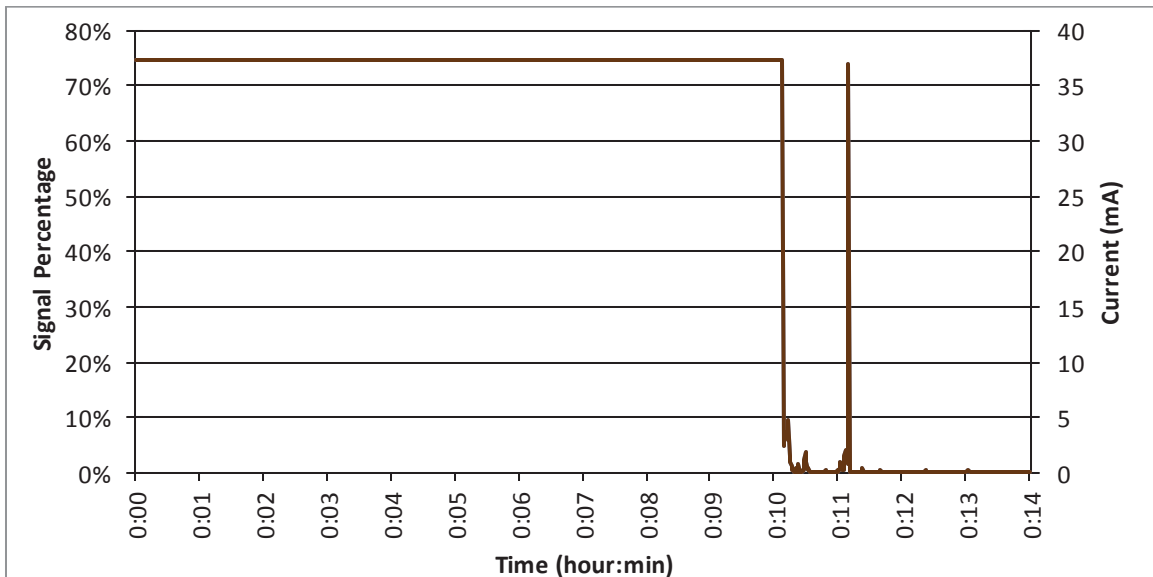
Figure A-76   Test 32 Signal Percentage and Current

A.39 Test 33 Results

Test conditions: 3/8/17
Cable: CC7, TS, 16-AWG, XLPE/CSPE, 2/c, shielded.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
Shroud power: Initiated after 60 seconds of baseline data monitoring.
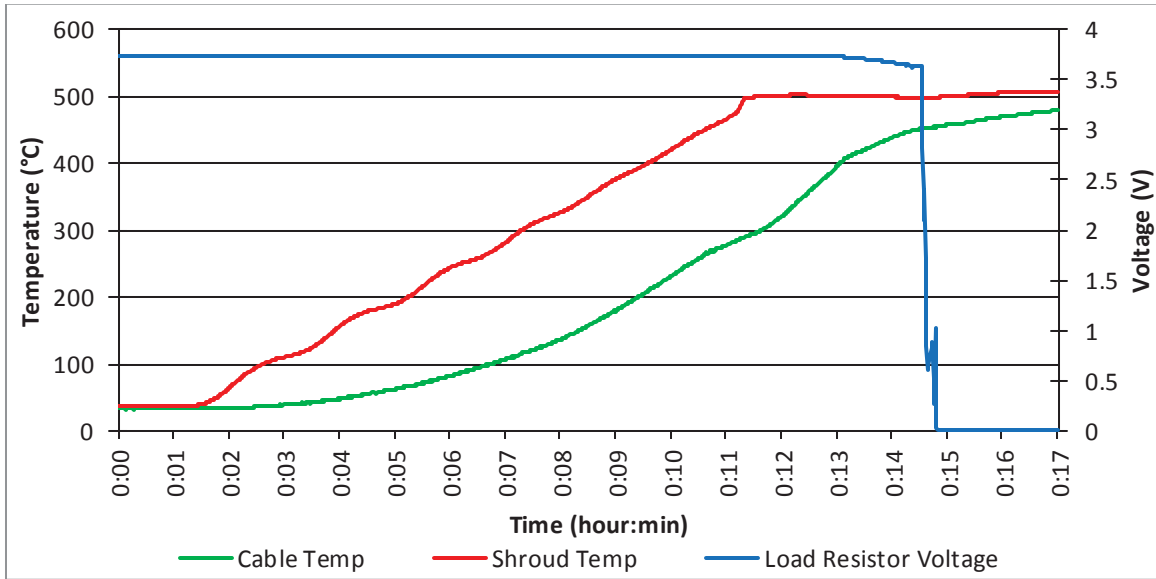
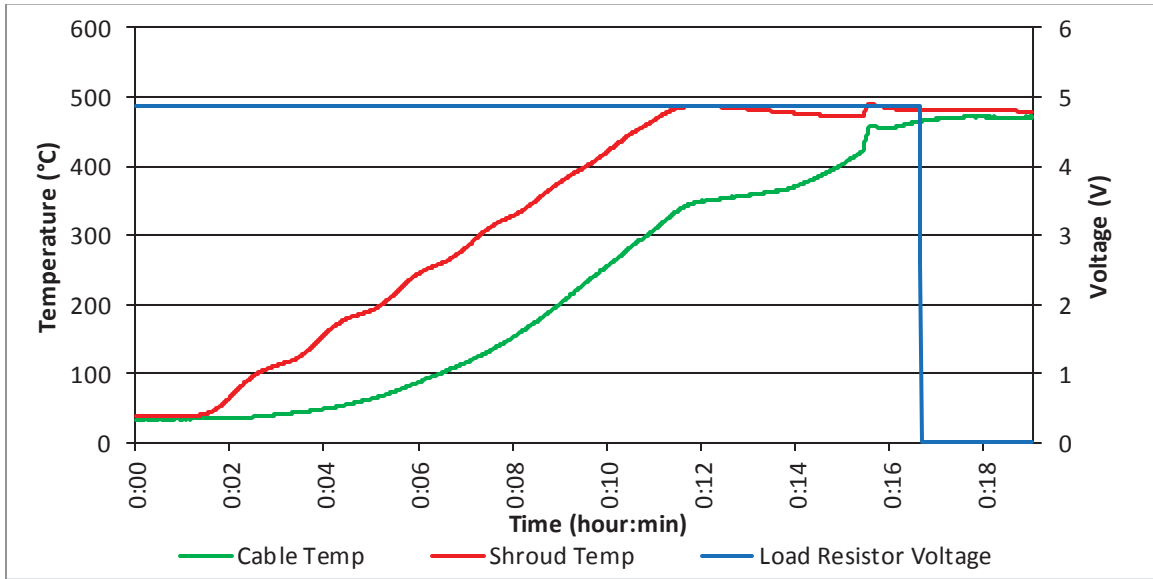**Figure A-77   Test 33 Temperature and Voltage**
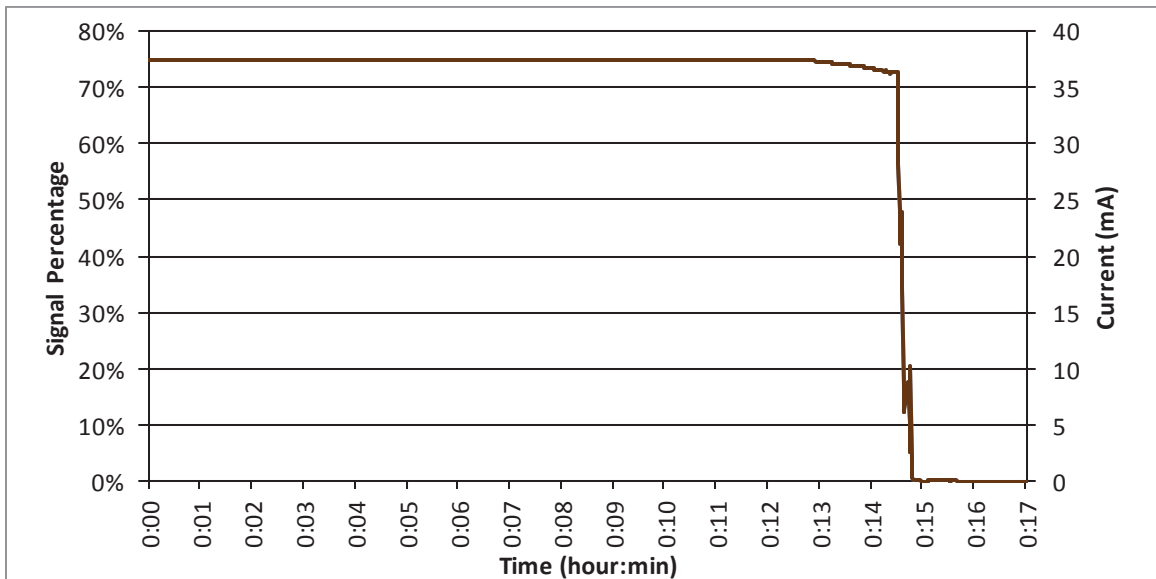
Figure A-78   Test 33 Signal Percentage and Current

A.40 Test 34 TCB Results

Test conditions: 3/9/17, 10:00 am
Specimens present: Two stainless steel rods both analyzed for thermocouple response.
Raceway: 12" B-Line Series 2 tray. One thermocouple was attached to the inner surface of the side of the cable tray.
Exposure conditions: Shroud set to temperature of 470°C, with a 45°/min ramp.
Thermal response monitoring: Two shroud temperatures, one tray temperature, and two cable temperatures were measured by Labview modules for the two stainless steel rods.
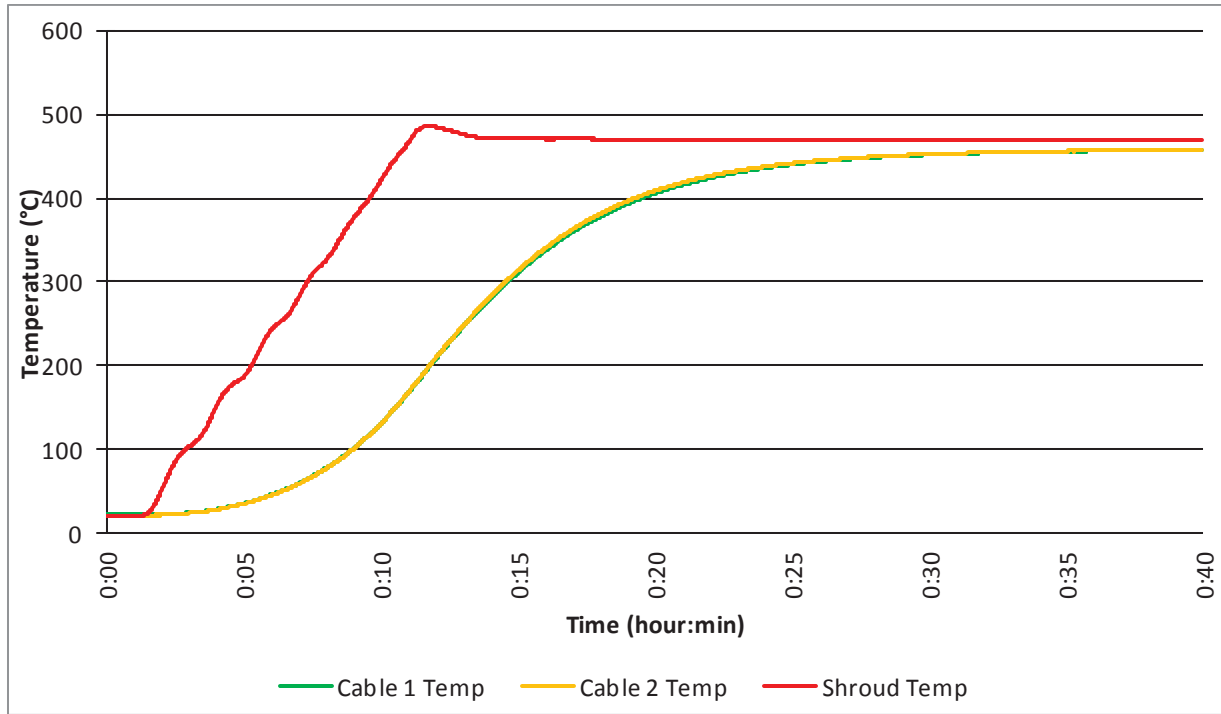
Figure A-79   Test 34 TCB Temperatures

APPENDIX B LITERATURE SEARCH

B.1 Scope of Literature Review

This literature review was undertaken to better understand instrumentation circuit fire testing conducted in the past with regards to time to signal degradation and time to electrical failure of the electrical cables in these circuit designs. 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:

- NUREG/CR-5546, An Investigation of the Effects of Thermal Aging on the Fire Damageability of Electric Cables, May 1991.
- J.M. Such, *Programme Etude probiliste de Surete Incendie,* (translated as: *Probability Study Program on Fire Safety*), EF.30.15.R/96.442, ISPN, April 1997, as summarized in NUREG/CR-6834, *Circuit Analysis - Failure Mode and Likelihood Analysis*, September 2003.
- NUREG/CR-6776, Cable Insulation Resistance Measurements Made During Cable Fire Tests, June 2002.
- NUREG/CR-6931, Cable Response to Live Fire (CAROLFIRE) Volume 1-3, April 2008.
- NUREG/CR-7010, Cable Heat Release, Ignition, and Spread in Tray Instillations During Fire (CHRISTIFIRE), July 2012.
- NUREG/CR-7150, Joint Assessment of Cable Damage and Quantification of Effects from Fire (JACQUE-Fire), Volume 1: Phenomena Identification and Ranking Table (PIRT) Exercise for Nuclear Power Plant Fire-Induced Electrical Circuit Failure, October 2012.

B.2 Cable Aging Effects on Cable Failure Thresholds Tests

These tests were performed as part of the USNRC-sponsored Fire Vulnerability of Aged Electrical Components program. The objective of the test was to investigate the impact of cable aging on cable failure thresholds. During the series of tests, a 2-conductor 16 AWG Boston Insulated Wire (BIW) instrumentation cable with shield and drain was tested. The cable was energized during testing using a three-phase 208V power source and each conductor was connected to one phase of the power source and it was open-circuited at the opposite end. The drain wire was also energized as if it were a third conductor. The leakage currents on each phase/conductor were then monitored over time. Of note, the cables were thermally and electrically isolated from the supporting tray structure during tests which eliminated the potential for either cable-to-cable or conductor-to-tray failures.

The conclusion of the test was that the degradation behavior of the aged BIW sample is more pronounced than that of the unaged BIW sample. During the tests, significant levels of leakage current were observed prior to the onset of catastrophic failure. This phenomenon was not investigated further as the damage threshold and damage times reported were all based on the failure of a 2-ampere fuse in any one leg of the energizing circuitry. The drain wire showed a pronounced tendency to experience the highest leakage currents of the three energized conductors, in most cases nearly twice of the individual insulated conductors. This indicated that for the aged samples there was a pronounced tendency of the insulated conductors to leak current to the shield and drain conductor rather than to each other.

B.2.1 Conclusions

This test introduces the concept that leakage current could occur before the onset of catastrophic failure. However, only one cable was tested and the characterization of the leakage current was not captured.

B.3 Probability Study Program on Fire Safety Tests (French nuclear regulatory, IRSN sponsored testing)

This report documents one cable fire test to assess the flammability behavior of certain specific cable products under fire exposure conditions. The fire test consisted of five cable trays, with each tray holding a single layer of cables arranged across the width of the tray. The source of the fire was 100 liters of light-weight pump lubricating oil pre-heated to 250°C and poured into a round pan with a 1 m^2 surface area. The anticipated burn duration was 91 minutes. One of the five types of cables used was a 2-conductor 20 AWG non-armored instrumentation cable. The cables carried an applied voltage and base current and were monitored for short circuits and leakage to ground.

The instrument cable in each tray was energized using a 12-mA current source, to be representative of the mid-range current on a 4–20 mA device. One side of the supply was connected to the first cable conductor and the second conductor was connected to the return side of the source which was also grounded. The first and second conductors were connected in series through a 250 Ω load resistor. Three of the four circuits showed failure during the test. All illustrated a sharp failure behavior with little degradation noted prior to a circuit trip.

B.3.1 Conclusions

This test is included to note that the instrumentation cables had little degradation noted prior to a circuit trip. Unfortunately, more information about the type of insulation and jacket wasn't provided.

B.4 Cable Insulation Resistance Measurements Made During Cable Fire Tests-Instrumentation Testing

In 2002, Sandia National Laboratories (SNL) participated in six instrument circuit burn tests conducted by industry, simulating a 4 to 20 mA instrument circuit current loop at Omega Point Laboratories. The instrument wire transmitting the signal was exposed to fire environments and the output signal was monitored for degradation of the transmitted signal.

A schematic of the instrument loop circuit used during the six tests is shown in Figure B-2 . The instrument loop circuit consisted of a low-power current source, fuses to protect the components in the event of an unwanted voltage surge, two 10 Ω resistors to simulate a long run of instrument cable (~610 m (2000 ft.) as opposed to the short length exposed during the fire test), a 250 Ω load resistor, and a voltmeter to provide the simulate read-out circuit. The 250 Ω load resistor acts in a way similar to a shunt resistor in an output meter that would convert the 4–20 mA signal into a 1 to 5 V signal. The circuit was driven by a constant current output from a current source of 15 mA.
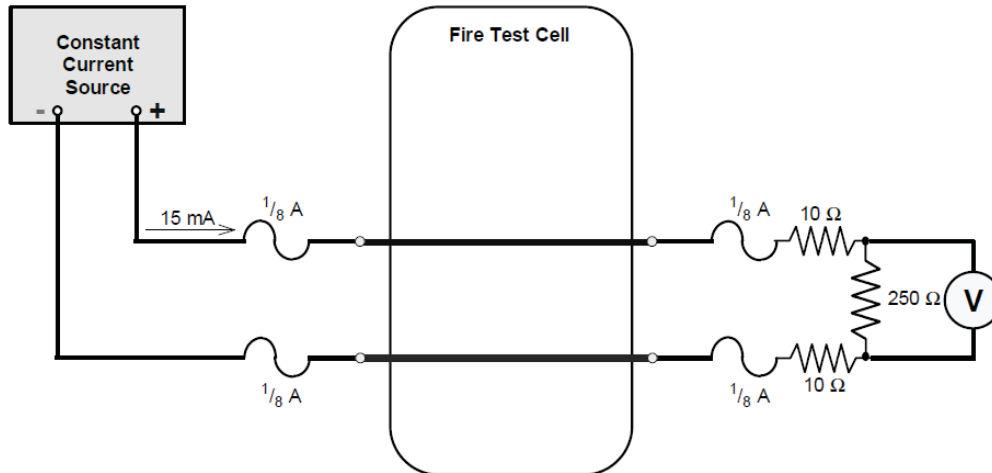
Figure B-1   Instrument Loop Circuit

All tests were conducted in a steel chamber measuring 3 m wide, 3 m deep and 2.4 m high at Omega Point Laboratories, located in Elmendorf, Texas. The chamber had an opening ~76 cm wide by 2.1 m high in the center of one wall. The exposure fire was generated by flowing propane gas through a 30 cm x 30 cm diffusion burner, with a fire intensity ranging from 70 to 350 kW.

The goal of the testing was to monitor the change in conductor IR occurring in at least one cable or bundle to determine the failure mode. During four of the tests for the instrumentation loop (Tests 13, 15, 16 and 17), the IR measurement system was compromised by a wiring fault. One of the instrumentation tests saw no substantive cable failures (Test 14). The IR measurement system was properly working for Test 18 and determined the failure mode to be short-to-ground.

The SNL report does not provide specifics as to the cable manufacturer, instead saying that the cables were standard instrument cables. The instrument loop circuit was independent and separate from the IR measurements made concurrently during the tests; however, the data was gathered and stored by the same computer data acquisition system as the IR data. The current loop data was obtained and analyzed to determine the time of signal degradation and the time of signal loss. The actual measured voltage was converted to an equivalent 0 to 100% process variable scale to ease the interpretation of the results, for example an output reading of 1V corresponds to zero on the process variable scale and an output reading of 5 V corresponds to 100%. The results of the tests are listed in Table B-1 Instrument Loop Test Data.

Table B-1   Instrument Loop Test Data

Test Number	Cable Material	Raceway Type	Heat Release Rate of Flame (kW)	Time of Signal Degradation (s)	Time of Signal Loss (s)
13	TS	Horiz. Tray	350	1100	2390
14	TP	Conduit	145	—	2225
15	TS	Horiz. Tray	Variable (350/200/450)	1100	1500
16	TP	Horiz. Tray	145	—	100

Table B-1   Instrument Loop Test Data (Cont'd.)

17	TS	Vert. Tray	200	930	1600
18	TS	Conduit	250	1140	1325

B.4.1 Conclusions

This test demonstrated that there are pronounced behavior differences observed between the failure of the TP and TS cables. TP cables generally displayed no characteristics of signal degradation prior to complete loss of signal. TS cables displayed some substantial amount of signal degradation for a relatively prolonged time period prior to the total loss of the signal, shown in Figure B-2. As demonstrated in the TS tests, prolonged signal degradation could provide an operator with misleading information. Also noted was that instrument cables failed earlier than co-located control cables during the testing.
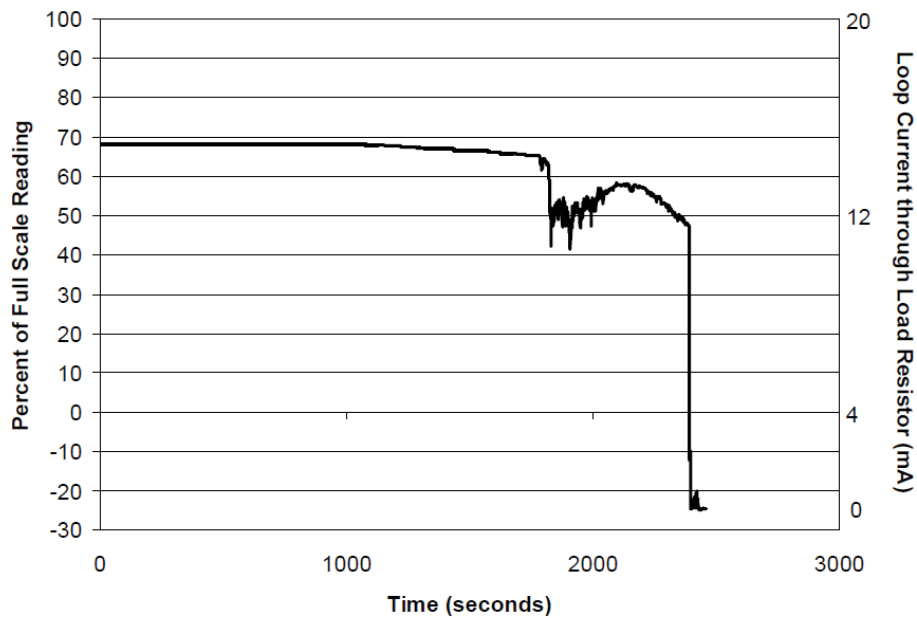
Figure B-2   Current Loop Data from Thermoset Test Number 13

B.5 Cable Response to Live Fire (CAROLFIRE) Instrumentation Cable Testing

During the Cable Response to Live Fire (CAROLFIRE) series of tests, a limited number of tests on instrumentation cables were performed. The two instrumentation cables tested were a 12-conductor 18 AWG instrument cable and a 2-conductor 16 AWG instrument cable. These cable configurations were included primarily to support the fire model improvement need area. A detailed description of the cables tested is shown in Table B-1.

The results of the tests are found in Table B-2. For Tests 62 and 64, both TS cables, the thermal response cable ignited prior to electrical failure. Electrical failure for the CAROLFIRE tests is defined as a conductor to conductor short or short to ground. Because no temperature at failure was reported for these cases, the case was considered indeterminate and was not included in the resulting CAROLFIRE analysis. The TS cable experienced spontaneous ignition early in the test, compared to larger cables of the same insulation and jacket material, and did not have the same

prolonged time to signal loss shown in the 2001 test. For Test 65, the thermal response cable ignited prior to electrical failure but the case met the criteria for inclusion in this analysis as described in CAROLFIRE, Vol. 2.

B.5.1 Conclusions

Because of the indeterminate conclusion of Tests 62 and 64, they were not included in determining threshold temperature for TS cables in CAROLFIRE Vol. 3. Tests 63 and 65, which failed at 205 and 225 °C respectively, aligned with the threshold temperature chosen for TP cables: 200 °C.

Table B-2   Physical Characteristics of the CAROLFIRE Instrumentation Cables

Short Description	Manufacturer	Part Number	Cond. Count	Cond. Size AWG	Insulation Type	Jacket Type	Notes
PVC/PVC, 16 AWG, 2/C SH	General Cable	230830	2	16	TP	TP	Contains a foil shield
PVC/PVC, 18 AWG, 12/C	General Cable	236120	12	18	TP	TP	
XLPE/CSPE, 16 AWG, 2/C SH	Rockbestos-Surprenant	146-0021	2	16	TS	TS	Contains a foil shield.
XLPE/CSPE, 18 AWG, 12/C	Rockbestos-Surprenant	157-0120	12	18	TS	TS	

Table B-3   Summary of CAROLFIRE Test Results for Instrumentation Cables

Test Number	Cable Insulation and Jacket Material	Conductor Count	Conductor Size (AWG)	Shroud Temperature °C (°F)	Raceway Type	Time of First Observed Electrical Failure (s)	Cable Temp.at Failure °C (°F)
62	XLPE/CSPE (TS/TS)	12	18	475 (887)	Tray	502	n/a
63	PVC/PVC (TP/TP)	12	18	325 (617)	Tray	333	205-208 (401-406)
64	XLPE/CSPE (TS/TS)	2	16	470 (878)	Tray	348	n/a
65	PVC/PVC (TP/TP)	2	16	325 (617)	Tray	258	225 (437)

B.6 Cable Heat Release, Ignition, and Spread in Tray Instillations during Fire (CHRISTIFIRE) Tests

The goal of the Cable Heat Release, Ignition, and Spread in Tray Instillations during Fire (CHRISTIFIRE) program was to provide data for the development of fire models that can predict the heat release rate of a cable fire. One instrumentation cable was tested during this program, a Brand-Rex XLPE/XLPE 18/c. This cable was tested with a mixture of other cables. Due to the nature and configuration of the tests, the results are not applicable to this project.

B.7 Phenomena Identification and Ranking Table (PIRT) Exercise

This report documented the results of a PIRT exercise that was performed on fire-induced electrical circuit failures that may occur in nuclear power plants as a result of fire damage to cables. The electrical expert PIRT panel was comprised of a group of electrical and fire protection experts sponsored by NRC and EPRI. Due to the lack of fire test data, the PIRT panel could not rank the parameters influencing hot short-induced spurious operations in a similar manner as for the control circuits. The panel recommended future research in areas where the configurations were common and the consequences of fire-induced failures could be high.

The PIRT panel discussed several different types of instrumentation control circuits and ruled out a number of them for further consideration and research for several reasons. Table B-4 gives a synopsis of the different types of circuits that the panel evaluated. The table briefly describes the configuration of each instrument control circuit, its usages in the nuclear industry, and the panel's recommendations for future research.

As shown in Table B-4, the panel was primarily concerned about testing instrument current loops and determining the failure modes and effects on those instrument circuits, which could be substantially different than those on control circuits. Some of the panel's specifically identified instrumentation concerns on cable failures are listed below:

- If the power for the loop is provided by a power supply that is physically independent of the loop's transmitter, a conductor-to-conductor short across the transmitter possibly could drive the loop current high (20+ mA). The effect of this failure mode is contrary to the belief that loop currents cannot be driven high by intra-cable shorting.

- Depending upon the electrical relationship of the shield with respect to the signal conductors, it may be possible for leakage to occur between the two. This may occur as a result of intra-cable shorts, or a combination of intra- and inter-cable shorts. It even may be possible to re-reference a shield, via an inter-cable short, to allow the flow of current from one loop to another through the shield or ground plane. This failure mode would challenge the concept that the shield would protect the target loop from the influences of external loops.

- The leakage of signal current could be induced by intra-cable short(s) between the signal conductors within a shielded, twisted pair cable. Due to low- energy characteristics of instrumentation circuits, a prolonged short condition might be established, producing an erroneous signal, fixed or variable, that is in the high-, low- or midscale-range. This failure mode would be contrary to the concept that internal shorting is always of low impedance, and will quickly drive the circuit to a single-failure state.

B.7.1 Conclusions

Due to the low state of knowledge and potentially high consequences of fire-induced failure on instrumentation current loop circuits, the PIRT panel recommended that additional testing be conducted and the following circuits should be included in testing:

- 10 mA to 50 mA instrumentation circuits
- 4 mA to 20 mA instrumentation circuits
- 1 VDC to 5 VDC instrumentation circuits

Table B-4   PIRT Panel Table

No.	Instrumentation Control System Type	Description	Usage in Nuclear Industry	PIRT Panel Recommendation
1	Current Loop	In a current loop instrumentation control-system, the current produced by the loop's power supply is sent around the loop, flowing through every device and load resistor in the circuit. Variations in the loop current are determined by changes in the process parameter, as measured by the instrument. The transmitter produces the output signal, either in the form of a 4–20 mA or a 10–50 mA current that can be used for indication, operation, and other functions.	Current loops are used throughout the industry in a variety of control applications. The most common instrument loops in the nuclear industry are the 4–20 mA ones.	Since the 4–20 mA current loop is prevalent in the industry, and the signal is transmitted through an electrical cable, very little prior testing has been conducted on the effects fire on the cables. Therefore, the PIRT panel highly recommended undertaking further research. Testing on the 10–50 mA current loop, although not as prevalent at NPPs, was also recommended.
2	Full Pneumatic	Full pneumatic-control systems utilize mechanical transducers to convert the process variable into a pneumatic signal for transmission around the plant via pneumatic tubing. Control pressures generally are 3-15 psig but can be amplified via mechanical amplifiers to greater pressures and volumes for the purposes of opening valves.	Used before the advent of the current loop (pre-1950s). Found later in some commercial nuclear power plants for the trip logic of the emergency diesel generator.	Since these systems do not use electrical wiring, the PIRT panel did not recommend their future testing.

Table B-4   PIRT Panel Table (Cont'd.)

No.	Instrumentation Control System Type	Description	Usage in Nuclear Industry	PIRT Panel Recommendation
3	Electro-Pneumatic	Electro-pneumatic control systems use an electrical process variable signal and convert it to a proportional pressure signal via an electro-mechanical transducer.	Used extensively for valve control.	Electrical portion is similar to the current loop in that a 4–20 mA signal is transmitted through a cable. Future research recommended by the PIRT panel is addressed in number 1 above under Current Loop. Since the pneumatic portion does not employ electrical cabling, the PIRT panel did not recommend this type of system for future testing.
4	Electro-Hydraulic	Electro-hydraulic systems employ a standard electrical control system via transducers. A typical example would be the conversion of an electrical process variable into a proportional hydraulic pressure for moving valves such as in the turbine control system.	Electro-hydraulic controls are found throughout the nuclear industry in the turbine control system and in the control system for many turbine driven pumps.	Electrical portion is similar to the current loop; therefore, future research is recommended by the PIRT panel and is addressed in number 1 above, Current Loop. Since the hydraulic portion does not employ electrical cabling, the PIRT panel did not recommend this type of system for future testing.

Table B-4   PIRT Panel Table (Cont'd.)

No.	Instrumentation Control System Type	Description	Usage in Nuclear Industry	PIRT Panel Recommendation
5	Digital Control	Digital-control systems employ high-order communication protocols, often with complex error-checking and loop-regeneration capabilities. In general, the cabling is shielded, twisted pair, or more recently, specialty cabling that can carry power and other signals within the same cable. Sophisticated isolation and synchronizing- capabilities often ensure seamless transfer when a fault is detected on a cable. Some protocols support the programming of loops so that they enter a "hold last state" mode upon loss of communications.	While digital-control systems are frequently used in non-nuclear industrial applications, they are not as common in the nuclear industry. This is primarily due to the complexity of the systems, and as a result, the uncertainty of, and vulnerability to, common-cause failures due to software related problems. Digital systems primarily are used in non-safety and important- to-safety applications, such as feedwater-control and turbine-control systems. (use same type as in rest)	Because of the many variations of standards, protocols, cable media, adaptability, and programmability, a bounding testing- configuration for digital systems would be difficult to establish. Additionally, error-checking schemes are employed by digital- control schemes that largely decrease the likelihood of fire- induced cable faults. Consequently, the PIRT panel does not recommend testing the cabling of digital- control systems. However, overheating effects of digital devices due to a fire may be a concern. It is important to understand the potential effects of exceeding the temperature ratings of the digital devices and the ultimate effects to the system that is being controlled.
6	Combination Analog and Digital	In this control system, digital data is carried over the same wires that the analog loop utilizes for control purposes with the digital signal riding in the carrier analog signal. Generally, the digital data is used to convey data such as system/device health, and environmental information.	While this type of device is "state-of-the-art" and often used in the nonnuclear industry, the PIRT panel was not aware of any nuclear plant that presently employs this type of system.	Since this type of system is rarely, if ever, used in the nuclear industry, the PIRT panel does not recommend further research.

B.8   General Test Conclusions

The limited testing performed in 2002 demonstrated that there are pronounced behavior differences observed between the failure of the TP and TS cables. The instrumentation cables tested during CAROLFIRE tests led to more insight into the failure time for TP cables only. The need to fully understand TS cables and the differences between them and TP cables was highlighted in the PIRT exercises conducted in 2012.

B.9   Summary of NRC, IEEE and Industry Standards

This section summarizes NRC, IEEE, and other industry standards applicable to the protection of instrumentation circuits.

- GL 81-12 describes the systems and instrumentation that are generally necessary for achieving post fire safe shutdown for existing PWRs and BWRs.
- IN 84-09 lists the minimum monitoring instrumentation needed to achieve safe shutdown for both PWRs and BWRs.
- RG 1.189 states that a fire hazard analysis should identify and provide appropriate protection for locations where the loss of instrumentation circuits important to safety can occur.
- ANSI/ISA-50.00.01-1975 (R2012) applies to analog dc signals use din process control and monitoring systems to transit information between subsystems or separated elements of systems. The goal of the document is to provide for compatibility between subsystems. It provides standard signals for transmitters and receivers. Applicable to this project, the standard output signal of the transmitter should have a range of 4–20 mA. The receiver should have a standard current input signal of 4–20 mA and a standard voltage input signal of 1-5 VDC. It also states that the source resistance shall be no higher than 250 Ω. This information is applicable for the 4–20 mA circuit.
- IEEE Std. 379-2014 states, "The principle of independence is basic to the effective use of single-failure criterion. The design of a safety system shall be such that no single failure of a component will interfere with the proper operation of an independent redundant component or system."
- IEEE Std. 384–2008 "Required independence. Physical separation and electrical isolation shall be provided to maintain the independence of Class 1E circuits and equipment so that the safety functions required during and following any design basis event can be accomplished."

B.10   References

1. NUREG/CR-5546, *An Investigation of the Effects of Thermal Aging on the Fire Damageability of Electric Cables,* May 1991.
2. J.M. Such, *Programme Etude probiliste de Surete Incendie*, (translated as: *Probability Study Program on Fire Safety*), EF.30.15.R/96.442, ISPN, April 1997, as summarized in NUREG/CR-6834, Circuit Analysis- Failure Mode and Likelihood Analysis, September 2003.
3. NUREG/CR-6776, *Cable Insulation Resistance Measurements Made During Cable Fire Tests,* June 2002.

4. TR-1003326, *Characterization of Fire-Induced Circuit Faults – Results of Cable Fire Testing*, EPRI, Palo Alto, CA, Dec. 2002.

5. NUREG/CR-6931, Vol. 1, *Cable Response to Live Fire (CAROLFIRE) Volume 1: Test Descriptions and Analysis of Circuit Response Data*, April 2008.

6. NUREG/CR-6931, Vol. 2, *Cable Response to Live Fire (CAROLFIRE) Volume 2: Cable Fire Response Data for Fire Model Improvement*, April 2008.

7. NUREG/CR-6931, Vol. 3, *Cable Response to Live Fire (CAROLFIRE) Volume 3: Thermally-Induced Electrical Failure (THIEF) Model*, April 2008.

8. NUREG/CR-7010, Vol. 1, *Cable Heat Release, Ignition, and Spread in Tray Instillations During Fire (CHRISTIFIRE), Phase 1: Horizontal Trays*, July 2012.

9. NUREG/CR-7010, Vol. 2, *Cable Heat Release, Ignition, and Spread in Tray Instillations During Fire (CHRISTIFIRE), Phase 2: Vertical Shafts and Corridors*, December 2013.

10. NUREG/CR-7150, *Joint Assessment of Cable Damage and Quantification of Effects from Fire (JACQUE-Fire), Volume 1: Phenomena Identification and Ranking Table (PIRT) Exercise for Nuclear Power Plant Fire-Induced Electrical Circuit Failure,* October 2012.

B.11   Regulatory Requirements Reviewed

A. ANSI/ISA-50.00.01-1975 (R2012), *"Compatibility of Analog Signals for Electronic Industrial Process Instruments,"* 17 July 2012.

B. ANSI/ISA-67.01.01-2002, "*Transducer and Transmitter Installation for Nuclear Safety Applications*," 16 September 2002.

C. IEEE Std. 323, "*IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations,*" January 2004.

D. IEEE Std. 379, "*Application of the Single-Failure Criterion to Nuclear Power Generating Station Safety Systems,*" May 2014.

E. IEEE Std. 384, "*Criteria for Independence of Class 1E Equipment and Circuits,*" December 2008.

B.12   Documents Reviewed, but not Summarized in the Report

A. Andrews, Ian, "Trends in Nuclear Instrumentation." Electronics & Power. August 8, 1974.

B. Becker, P.H.B.; Gardos, M.; Hollenthoner, S.; Tanpraphan, T.; and Markowicz, A., "*More than 20 years of Experience of the IAEA in Providing Training on Nuclear Instrumentation for Developing Countries*," Advancements in Nuclear Instrumentation Measurement Methods and their Applications (ANIMMAA) 2009 Conference.

C. DOE Standard 1162-2013, "*Instrumentation and Control Functional Area Qualification Standard.*" June 2013.

D. IAEA-TECDOC-363, "*Selected Topics in Nuclear Electronics*." January 1986.

E. IAEA-TECDOC-426, "*Troubleshooting in Nuclear Instruments*." June 1987.

F. IAEA-TECDOC-530, "*Nuclear Electronics Laboratory Manual*." October 1989.

G. IAEA-TECDOC-932, "*Pilot Study on the management of ageing of instrumentation and control cables*." March 1997.

H. IAEA-TECDOC-1188, *Assessment and management of ageing of major nuclear power plant components important to safety: In-containment instrumentation and control cables,* December 2000.

APPENDIX C   FINAL TEST PLAN

C.1 OBJECTIVES, TECHNICAL BACKGROUND, AND APPROACH

C.1.1 Objectives

The objective of this research is to better understand the fire-induced failure modes of instrumentation cables and evaluate the potential effect those failure modes could have on plant instrumentation circuits (i.e., circuit, component, and/or system response). In particular, this research is intended to better quantify the signal leakage that may occur before catastrophic failure in instrumentation circuits. This work is intended to support future revisions to guidance (e.g., RG 1.189, NUREG/CR-6850) related to circuit analysis.

This test plan has been developed by Sandia National Laboratories (SNL) and sponsored by the US Nuclear Regulatory Commission (NRC), Office of Regulatory Research (RES) Fire and External Hazards Analysis Branch.

C.1.2 Technical Background

In 1990, the NRC sponsored a series of tests at SNL to investigate the effects of thermal aging on fire damageability, documented in NUREG/CR-5546, "An Investigation of the Effects of Thermal Aging on the Fire Damageability of Electric Cables." An instrumentation cable was tested to determine the failure time and temperature for both aged and unaged cables. During the testing, levels of leakage current, on the order of 15 mA, were observed prior to the onset of catastrophic failure. This phenomenon was not explored further as the damage thresholds and damage times were only based on the failure of a 2-ampere fuse in the circuit.

In 2001, the Nuclear Energy Institute (NEI) and the Electric Power Research Institute (EPRI) and hereafter referred to as "industry," conducted a series of cable fire tests designed to address specific aspects of the cable failure and circuit fault issues of concern.[6] The NRC was invited to observe and participate in the 2001 tests by including supplemental cable performance monitoring equipment during the tests. The NRC contracted with SNL who provided instrumentation designed to monitor cable degradation through the measurement of insulation resistance (IR) for several of the NEI/EPRI tests. In addition to the IR tests, a separate surrogate instrument circuit was fielded by NRC/SNL in six of the NEI/EPRI tests. This circuit simulated a 4-to-20 mA instrument circuit loop with a constant current source set to 15 mA. The instrument wire transmitting the signal was exposed to fire conditions and the output signal was monitored for degradation of the transmitted signal. These tests were documented in NUREG/CR-6776, "Cable Insulation Resistance Measurements Made During Cable Fire Tests."

These tests concluded that there are pronounced behavior differences observed between the failure of the thermoplastic (TP) and thermoset (TS) cables. TP cables generally displayed no characteristics of signal degradation prior to complete loss of signal. TS cables displayed a substantial amount of signal degradation for approximately ten minutes prior to the total loss of the signal, shown in Figure C-1. If a fire affected a TS instrument cable, it could cause the indicator to read an intermediate, but not obviously erroneous, value. This misleading indication could potentially cause operators to take an action based on faulty information (depending on the nature of the signal and the direction of the signal leakage). In contrast, a fire affecting a TP cable would

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[6] "Issues of concern" refers to the problems associated with post-fire safe-shutdown circuit analysis, as presented in Information Notice 99-17, "Problems Associated with Post-Fire Safe-Shutdown Circuit Analyses."

likely cause an abrupt and obviously faulty off-scale indication. This would be far less likely to mislead operators who would likely diagnose the instrumentation failure.
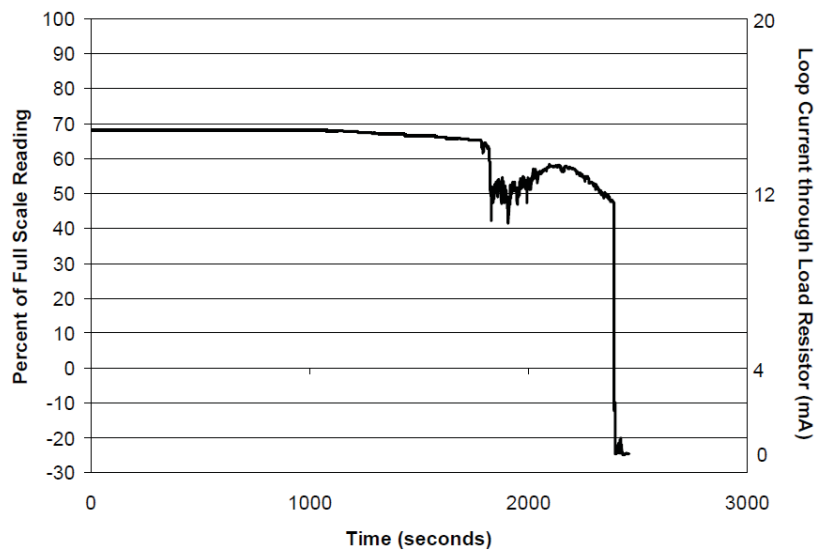
Figure C-1   Degradation of Signal Data from Thermoset Test

These early tests identified potential issues that are unique to instrumentation cables; however, the parameters influencing hot short-induced spurious operations could not be identified and ranked in the same manner as control circuits, which have been evaluated in a more thorough manner.

C.1.3 General Approach

The tests described in this test plan focus on the failure modes for instrumentation cables. The tests were designed to determine the failure modes, time of failure, and temperature at electrical failure. The tests are intended to supplement the 2001 testing done on instrumentation cables documented in NUREG/CR-6776 and to advance the state of knowledge, which has been determined to be low from a phenomena identification and ranking table exercise (NUREG/CR-7150, Volume 1). For the purposes of this test, there are two concerns for instrumentation readings. First, an instrumentation reading for a component that an operator has to react to within a set time could cause unanalyzed problems if the time for the signal to fail is delayed. Second, instrumentation readings that automatically actuate an event are also of interest, since instrumentation circuits can be tied to component start/stop logic.

To meet these objectives, SNL will perform a series of tests involving the following variables: cable manufacturers, insulation types, conductor sizes, number of twisted pairs or multi-conductor cables, and shielding variations. The tests are designed such that cable and instrumentation configuration changes can be made with little effort, allowing for flexibility as the testing progresses. The tests will utilize a ceramic fiber heater for the heating apparatus. This test plan will be reviewed by an NRC/RES and EPRI oversight panel and peer reviewed. Subsequent full-scale testing is planned to be performed by the National Institute of Standards and Technology (NIST).

C.2 Cable Selection

C.2.1 Instrumentation Circuit Background

Instrument circuits (also known as instrumentation and control circuits) provide critical information regarding the status of plant conditions to operators. Circuit fault effects on instrument systems are unique and more complex than power and control circuits. Instrument sensors typically convert process variable values (temperature, pressure, level, flow, etc.) to an electric signal (e.g., voltage/current) for transmission to a remote readout or display. Instrumentation readings can also be used to automatically actuate an event, since instrumentation circuits can be tied to process equipment, such as the reactor protection system and engineering safeguard feature actuation system (ESFAS). The current loop typically exists in two forms: 10–50 mA (old standard) and 4–20 mA (new standard). The 4–20 mA became the industry standard because it has lower circuit voltages and current levels so there is less chance for personal shock injury or the generation of sparks.

In either case, the principle of operation is the same: current produced by the loop power supply is sent around the loop, flowing through every device and load, or burden device, in the circuit. The current is modulated into a process variable by a transmitter which converts a sensor's measurement into a current signal and amplifies and conditions the output. A sensor typically measures temperature, humidity, flow, level or pressure. The current loop also has a receiver which is a device that interprets the current signal into units that can be easily understood by the operators. It converts the 4–20 mA current back into a voltage which can be displayed or actuate another component based on its start/stop logic. In this setup, 4 mA represents 0 percent of the measurement, 20 mA represents 100 percent and when the current is between 4 mA and 20 mA the voltage across the resistor is in direct proportion to that current. See Figure C-2 for an example current loop with components listed.

Current loops are extremely robust systems as they are impervious to electrical noise, and routing the signal through shielded, twisted pair cables further reduces noise. Grounding the negative of the power supply to the shield provides additional noise protection. It is ideal for long distances as current does not degrade over long connections, unlike voltage which can degrade over long distances. It is also simple to detect a fault in the system. For example, a loss of power would indicate 0 mA, instead of the expected 0 percent output of 4 mA for a typical 4–20 mA design. Some designs of instrumentation circuits fail high, where a break in the circuit would read greater than 20 mA.

One downside for the current loop design is that it can only transmit one particular process signal. However programmable logic controllers or other digital control systems are designed to take inputs from multiple current loops.
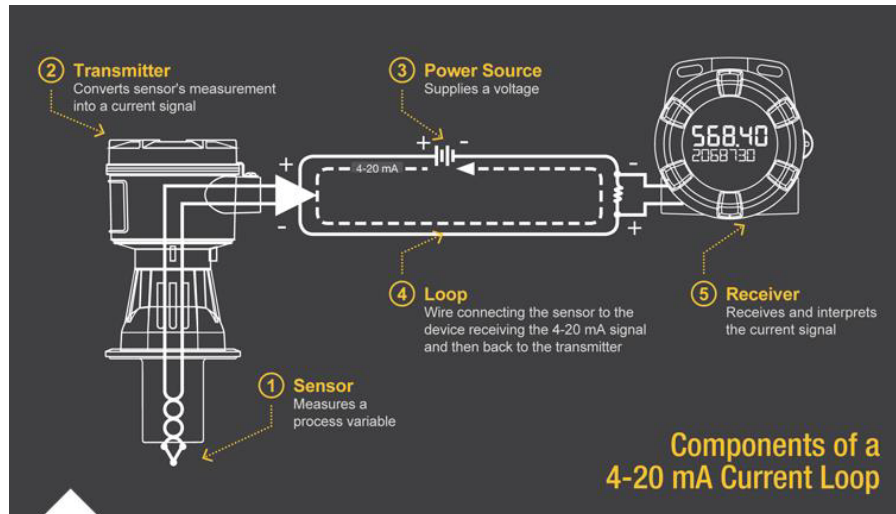
Figure C-2   4–20 mA Current Loop Example[7]

C.2.2 Instrumentation Cable Background

Instrument cables transmit low-level signals from the instrument sensor to an indicator, controller, or recorder. Instrumentation cables are low voltage, low ampacity cables (SAND 96-0344). They are used for digital or analog transmission from various types of transducers. Resistance temperature detectors, pressure transducers and thermocouples are usually of a shielded twisted pair configuration whereas radiation detection and neutron monitoring circuits often use coaxial or triaxial shielded configurations (SAND 96-0344). Instrument cables typically use single, twisted shielded pair conductor cables or much larger multi-conductor cables consisting of 50 or more conductors. Each instrument conductor typically is size 16 AWG or smaller. These cables frequently enclose several shielded twisted pairs of conductors contained within a protective outer jacket. The twisting of conductors reduces magnetic noise, while the shield and drain wire reduce electrostatic and radio-frequency interference. The shield consists of a conductive material that is wrapped around the twisted pair of conductors. The uninsulated drain wire, which is in physical and electrical contact with the shield, provides for easier termination of the foil shield to a common ground point.

C.2.3 Cable Failures and Circuit Faults

C.2.3.1 Cable Failures

Cable failures and subsequent circuit faults are discussed in this section. Cable failure implies that the cable is no longer able to perform its intended function which is to maintain the electrical integrity and electrical continuity of the associated circuit sufficient to ensure proper operation of the circuit (NUREG/CR-6834). For a cable to perform its intended function, each individual conductor within the cable must maintain both electrical integrity and continuity. Hence, cable failure implies that one or more of the cable conductors have lost electrical integrity or continuity. Cables can fail in the following ways.

Open Circuit: An open circuit is failure condition that results when a circuit (either a cable or individual conductor within a cable) has a loss of continuity (RG 1.189). Such failures would likely

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[7] Source: https://www.predig.com/indicatorpage/back-basics-fundamentals-4–20-ma-current-loops

be diagnosed as a circuit fault by operators. However, a complete loss of several signals may mean that operators would not know the actual reactor status, dependent on independent and redundant sensors available.

Short Circuit: A short circuit is an abnormal connection (including an arc) of relatively low impedance, whether made accidentally or intentionally, between two points of different potential (RG 1.189). This scenario does not involve an external ground. Twisted pairs, especially shielded twisted pairs, would be more likely to short-to-ground rather than form a short circuit given the proximity of the ground. If the power for the current loop is provided by a power supply that is physically independent of the loop's transmitter, a conductor-to-conductor short across the transmitter could possibly drive the loop current high and give a false reading. Both intra-cable and inter-cable faults are possible, but again the possibility decreases with the addition of shielding (properly grounded) protecting the twisted pairs and/or the cables. It could be possible to re-reference a shield, via an inter-cable short, to allow the flow of current from one loop to another through the shield or ground plane.

Hot Short: Hot shorts are where individual conductors of the same or different cables that come in contact with each other and may result in an impressed voltage or current on the circuit being analyzed (RG 1.189).

Short-to-Ground: A short-to-ground is a short circuit between a conductor and a grounded reference point (e.g., grounded conductor, conduit or other raceway, metal enclosure, shield wrap, or drain wire within a cable) (RG 1.189). Twisted pairs, shields for the pairs, and overall shields can be grounded in instrumentation circuits, so shorts-to-ground may occur more than hot shorts.

C.2.3.2 Circuit Faults

A circuit fault is undesired or unplanned behavior in an electrical circuit induced by the failure of one or more elements of the circuit, in particular, including the failure of an associated electrical cable (NUREG/CR-6834). For the purposes of this test plan, this term refers to effects that postulated cable failures have on the associated electrical circuits and components. Circuit faults that could be applicable to instrumentation circuits are:

Loss of circuit operability: Some cable failures may lead to a total loss of circuit operability. This may result from failures involving instrumentation and control interlocks and permissive signals. For example, the failure of an oil pressure signal cable in such a manner that a false-low oil pressure was indicated may lead to the loss of function of an associated pump or motor due to an oil pressure interlock (NUREG/CR-6834).

Loss of indication: Cable failures may leave a system or component nominally operational, but will compromise the indication functions of the circuit. This may lead, for example, to status-indicating lights going dark (NUREG/CR-6834).

Inaccurate indications: Some cable failures may result in misleading or even conflicting instrument signals. For instrumentation circuits a relatively low level of degradation in the IR of signals carrying conductors may be sufficient to substantially bias an instrument's readout (NUREG/CR-6834). For example, a false low water level signal could lead operators to activate additional water sources leading to overcooling of the reactor vessel. A false high reading could lead operators to shut down or throttle coolant injection systems potentially leading to voiding of the core (Draft NUREG-1778).

Spurious operation**:** Spurious operation is the undesired or unplanned operation or activation of a system or component. Spurious operations are most commonly associated with cable hot short failures, although various cable failure modes may lead to spurious operations (depending on circuit design) and not all hot shorts will lead to spurious operations (NUREG/CR-6834).

The functional impact of the cable failures and circuit faults on the plants systems, components, and functions can vary. This unpredictability in the state of the process variable as a result of cable failures may elicit undesired automatic- or human-responses that may complicate or compromise the overall response to the effects of fire.

The other unknown is determining the change of voltage that would indicate a change of state to the operator, if the signal has a binary output. For example, if a valve position indicator could only alert the operator if the valve is open or closed. If a voltage change is minimal for a long period of time, the operator may not know something is wrong until several minutes have passed. If controlled by a digital device, like the Dynamix 1444 Series Monitoring System, the operator setting up the system will determine the voltage or amperage at which to indicate a system problem. Because the digital transmitter set points will vary by plant, they will not be analyzed during the test. The overheating of digital devices themselves may also be a concern, but is not in the scope of this test.

C.2.3.3 Instrumentation Needed for Safe Shutdown

For the purposes of this test, there are two concerns for instrumentation readings. First, an instrumentation reading for a component that an operator has to react to within a set time could cause unanalyzed problems if the time for the signal to fail is delayed. Second, instrumentation readings that automatically actuate an event are also of interest. For example, a pump (dependent on the operation of a lubrication system) commonly has a permissive tie to an oil pressure reading. If the instrument cable failure led to an inaccurate indication of a loss of oil pressure, the pump may trip or fail to start on demand (NUREG/CR-6834).

Information Notice 84-09, titled "Lessons Learned from NRC Inspections of Fire Protection Safe Shutdown Systems" provides guidance for licensees implementing requirements of 10 CFR 50, Appendix R. Section III.L.1 of Appendix R requires that alternative shutdown capability achieve and maintain subcritical reactivity conditions in the reactor for III.G.3 fire areas. Section III.L.2 requires provision for direct readings of the process variables necessary to perform and control the reactor shutdown function. The minimum process monitoring capability described in IN 84-09 includes the following instruments:

Instrumentation Needed for PWRs

- Pressurizer pressure and level
- Reactor coolant hot leg temperature or exit core thermocouples, and cold leg temperature
- Steam generator pressure and level (wide range)
- Source range flux monitor
- Diagnostic instrumentation for shutdown systems
- Level indication for all tanks used (e.g., CST)

Instrumentation Needed for BWRs

- Reactor water level and pressure
- Suppression pool level and temperature

C-6

- Emergency or isolation condenser level
- Diagnostic instrumentation for shutdown systems
- Level Indication for all tanks used

Diagnostic instrumentation is instrumentation needed to ensure the proper actuation and functioning of safe-shutdown equipment and associated support equipment (e.g., flow rate, pump discharge pressure). The diagnostic instrumentation needed is plant-specific and should be based on the design of the alternative shutdown capability.

C.2.4 Cable Identification

Surveys conducted under the equipment qualification (EQ) research programs in the 1980's and 1990's were an important factor in determining cable insulation materials for the Cable Response to Live Fire (CAROLFIRE) and Direct Current Electrical Shorting in Response to Exposure Fire (DESIREE-Fire) tests. Instrumentation circuits were also analyzed in the EQ program and composed almost 20% of the various types of circuits found at one nuclear power plant during this study[8]. The NRC EQ inspections identified that a common instrumentation cable is a 2-conductor, twisted shielded pair, 16 AWG (SAND 89-2369).

During the industry cable tests, manufacturers and specific cable properties were not included in the documentation. The types of cable insulations and jackets, which were recorded, are listed below:

- Ethylene-propylene rubber (EPR)/Chloro-Sulphonated Polyethylene (CSPE) 8/Conductor armored cable
- Polyethylene (PE)/ Polyvinyl Chloride (PVC) 2/Conductor shielded cable
- PVC/PVC
- Ethylene Propylene Diene Monomer (EPDM)/CSPE

None of the common suppliers of EPR cables still advertise these cables, according to the CAROLFIRE project plan. The CAROLFIRE project explored a wide range of cable types and the results indicated that TS and TP insulated cables behaved differently; however, the various thermoset cable types behaved similarly, as did the various TP cable types. The four instrumentation cables tested during the CAROLEFIRE project include:

- Cross-linked Polyethylene (XLPE)/CSPE, 16 AWG, 2/Conductor, Shielded Rockbestos-Surprenant Cable
- XLPE/CSPE, 18 AWG, 12/Conductor, Rockbestos-Surprenant Cable
- PVC/PVC, 16 AWG, 2/Conductor, Shielded General Cable
- PVC/PVC, 18 AWG, 12/Conductor General Cable

These cables were chosen to analyze the insulation and cable jacket material for a smaller cable, given that the bulk of CAROLFIRE tests were performed on 7-conductor 12 AWG cables.

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[8] There were a number of USNRC-sponsored cable aging research efforts at Sandia National Laboratories in the 1980's associated with the Nuclear Plant Aging Research (NPAR) programs, and at EPRI and the U.S. Department of Energy relative to Plant Life Extension (PLEX) programs. The work cited here can be found in the reference SAND 96-0344, "Aging Management Guideline for Commercial Nuclear Power Plants – Electrical Cable and Terminations," September 1996.

The CAROLFIRE report stated that the single most popular insulation material used in the US nuclear power industry is the TS material XLPE. The most popular jacket with the XLPE insulation type is CSPE, also known by the trade name Hypalon. The most common TP insulation material in use at US NPPs is polyethylene (PE), however another very popular material is PVC. Given the unavailability of the types of cables from the 2001 tests, instrumentation cables from Rockbestos and General Cable manufacturers will be tested.

To meet the goals of the project, tests will be performed on a variety of instrumentation cable types, sizes, and numbers of twisted pairs or conductors. This includes testing of both TS and TP types of cable insulations. The goal is to make these tests as broadly applicable as possible while establishing reasonable limits on the range of cables and configurations to be used in testing.

C.3 Test Apparatus and Experimental Setups

C.3.1 Heating Apparatus

C.3.1.1 General Description of Ceramic Fiber Heaters

A ceramic fiber heater will be used as the heating apparatus for this series of tests. Volume 2 of the CAROLFIRE (NUREG/CR-6931) report provides a detailed description of the small-scale test facilities and the general test protocols that will be utilized during this series of tests.

The ceramic fiber heater that will be used is constructed of ceramic fiber insulation which isolates the heating chamber from the outside. The heater is lightweight, and its low-density properties make it ideally suited for high temperature applications requiring low thermal mass. The heaters can be customized provide the same cylindrical ring that the Penlight heating apparatus utilized in previous testing. Penlight consisted of a cylindrical ring of 0.61 m (24") long water-cooled quartz lamps with a stainless cylindrical shroud 0.46 m (18") in diameter and 0.6 m (24") long. The ceramic fiber heater will have an inner diameter of 0.41 m (16") and will be 0.6 m (24") long. Similar to Penlight, the heat transfer will transfer heat radially onto the surface of the cables. This 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. The ceramic fiber heater will simulate these conditions with the shroud temperature and shroud heat flux, assuming a constant emissivity of 0.85, shown in Table C-1. The heater will have a high emissivity coating which provides it the constant emissivity, shown in Figure C-3.

The plan for this series of testing is to lay the cables on a ladder-back style cable tray suspended through the center of the ceramic fiber heating shroud. The other physical test conditions are effectively identical to those used in CAROLFIRE (NUREG/CR-6931).
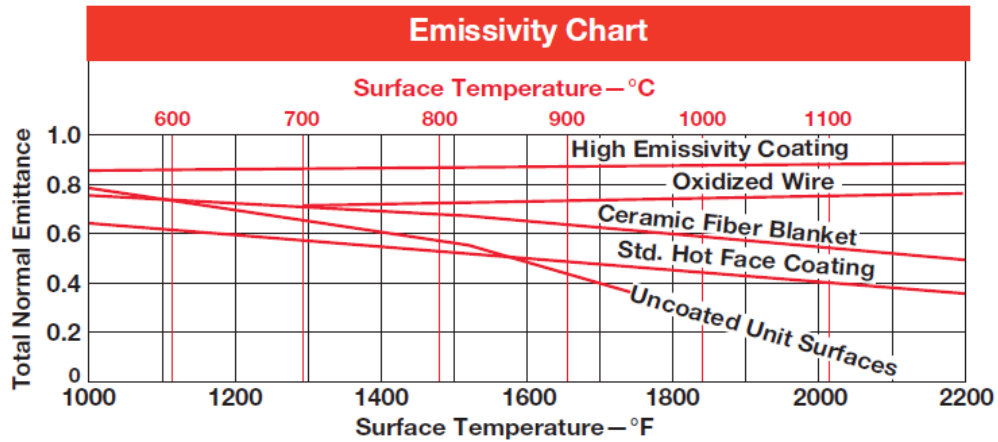
Figure C-3   Emissivity of Heat Surface for Watlow Ceramic Fiber Heater [9]

Table C-1   Relationship between the Ceramic Fiber Heater Shroud Temperature and Radiant Heat Flux Based on Measured Emissivity of 0.85.

Temperature (°C)	Heat Flux (kW/m²)
200	2.42
225	2.97
250	3.61
275	4.35
300	5.20
325	6.17
350	7.27
375	8.51
400	9.90
425	11.45
450	13.18
475	15.10

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[9] Source: Performance Data for Ceramic Fiber Heaters, Watlow Heaters
http://catalog.watlow.com/Asset/Performance-Data-for-Ceramic-Fiber-Heaters.pdf

Table C- 1   Relationship between the Ceramic Fiber Heater Shroud Temperature and Radiant Heat Flux Based on Measured Emissivity of 0.85 (Cont'd.)

Temperature (°C)	Heat Flux (kW/m²)
500	17.22
525	19.56

C.3.1.2 Temperature Heating Profiles

For comparison purposes, the heat profile information for the 2001 tests is included here because this objective of this test plan is to confirm the circuit behavior demonstrated in the 2001 tests. The 2001 testing took place in a 10' x 10' steel enclosure test chamber. A diffusion flame burner was used for all tests, with the radiant heat flux, shown in Table C- 2, calculated using the Oxygen Consumption Calorimetry principle described in ASTM E 1537. The cables were tested on a horizontal raceway in either a plume exposure where the burner is placed directly under the cables or a hot gas layer exposure where the burner is offset approximately two feet toward the center of the room. Tests 14 and 16 were in the plume exposure; tests 13, 15 and 18 are in the hot gas layer exposure. One instrumentation test, test 17, was tested vertically with a radiant exposure. More details on test exposures can be found EPRI TR-1003326.

The CAROLFIRE and DESIREE-fire series of tests used *Penlight* which has a maximum shroud temperature of about 900°C. Although one test was conducted at this temperature during the CAROLFIRE project, the rest of the tests used shroud temperatures ranging from 260-675°C to gauge when failure occurs. The instrumentation cables that were tested during the CAROLFIRE project were tested with a shroud temperature of 325°C for the TP cables, and 470 and 475°C for the two TS cables. The TP cables failed at around 205-225°C. The thermal response cable for the TS cables ignited prior to electrical failure.

Table C- 2   Heat Fluxes and Temperatures from Previous Instrumentation Cable Testing

Test	Cable Description	Radiant Heat Flux Tested (kW/m²)	Shroud Temperatures (CAROLEFIRE) (°C)	Cable Temperature at Failure
IRMS_13	EPR/CSPE 8/c Armored (TS/TS)	350	n/a	unknown
IRMS_14	PE/PVC 2/c Shielded (TP/TP)	145	n/a	unknown
IRMS_15	Thermoset	Variable (350/200/450)	n/a	unknown
IRMS_16	PVC/PVC (TP/TP)	145	n/a	unknown
IRMS_17	EPDM/CSPE (TS/TS)	200	n/a	unknown
IRMS_18	EPR/CSPE (TS/TS)	250	n/a	unknown
CAROLFIRE_62	XLPE/CSPE 12/c 18 AWG (TS/TS)	14.5	475	n/a
CAROLFIRE_63	PVC/PVC 12/c 18 AWG (TP/TP)	5.9	325	205
CAROLFIRE_64	XLPE/CSPE 2/c 16 AWG (TS/TS)	14.1	470	n/a
	PVC/PVC 2/c 16 AWG (TP/TP)	5.9	325	225

As in previous tests, it is desirable to monitor the degradation of cable integrity and behavior over relatively long times (nominally on the order of 10-30 minutes). This amount of time to failure was selected given the nature of typical NPP fires and the types of fire scenarios found to be important in risk analysis, according to the CAROLFIRE report.

TP cables failed electrically when their inner (under the jacket) temperatures reached somewhere between 200°C and 250°C, according to the CAROLFIRE results (NUREG/CR-6931, Vol. 3). The failure temperature of 200°C is used in the NRC Thermally-Induced Electrical Failure (THIEF) Model (NUREG-1805) for TP instrumentation cables. In order to achieve this failure within the target time frame (of 10-30 minutes), a ramp-and-hold profile will be used. The intent of the ramp-and-hold profile is not to explicitly represent any particular fire profile but to generically represent typical fire behavior. The temperature of the heating shroud was 325°C for TP cables in the DESIREE-Fire series of tests. This temperature provides a heat flux of 5.9 kW/m^2 and is expected to cause longer TP failure times. When this testing was done the heating apparatus was set to the desired temperature, which it achieved quickly, and held. Times to failure are expected to be longer than the CAROLFIRE and DESIRE-Fire results due to the gradual increase in temperature which is more representative of fire behavior.

The ceramic fiber heater will start at ambient temperature, around 20°C (68°F). The first test for both TP and TS cables is intended to determine the appropriate temperature to achieve failure within the target time frame (10-30 minutes) and will be performed at lower temperature levels. The damage criteria for generic electrical cables in a fire probabilistic risk assessment is listed as 205°C for TP cables and 330°C for TS cables, according to the EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities (NUREG/CR-6850). The heating profiles for these two temperatures are shown in Figure C-4 and Figure C-5.
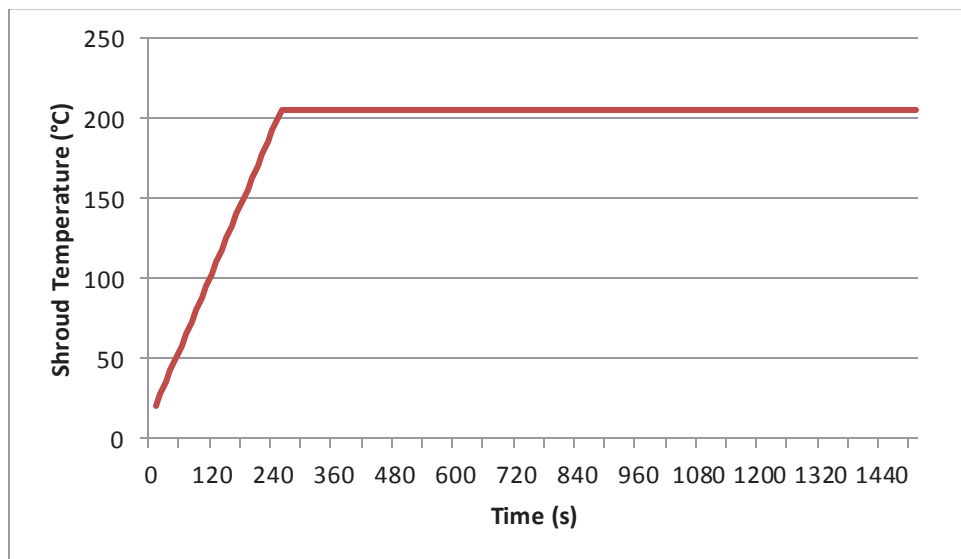

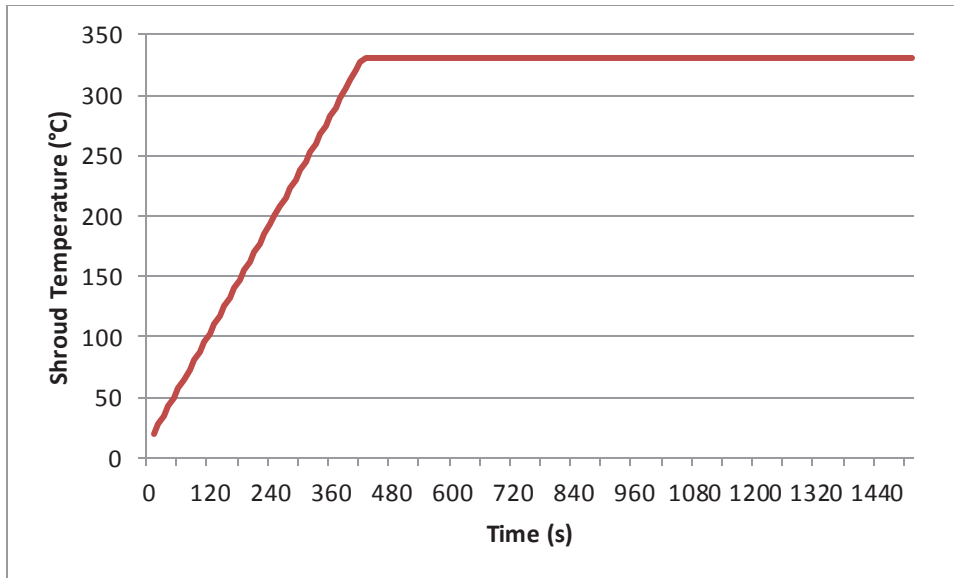**Figure C-4   Thermoplastic Cable Heating Profile - 205°C**

Figure C-5   Thermoset Cable Heating Profile- 330°C

If ignition does not occur within an hour for either of these heating profiles, the temperature will increase until failure is observed. The next set heating profiles were based on the CAROLFIRE and DESIREE-Fire results, but will be altered based on results seen from the first tests.

For TP cables, the primary exposure profile will then begin with a ramp from 20°C to 325°C at the rate of 45°C (113°F) per minute, reaching the maximum temperature at 410 seconds (6.8 minutes). The temperature will be held constant at this temperature until failures are observed. Note that time t=0 is defined as the time when the primary ramp is initiated.
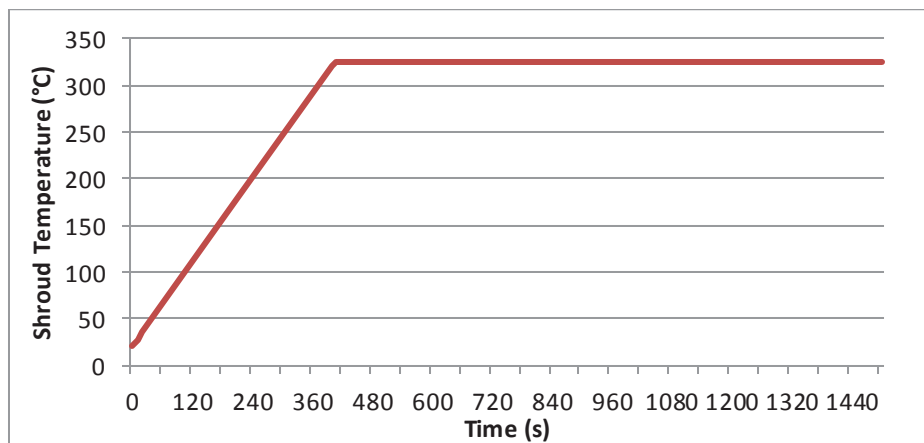
Figure C-6   Thermoplastic Cable Heating Profile- 325°C

To test the TS cables, a similar heating profile was created. TS cables failed electrically when their inner (under the jacket) temperatures reached somewhere between 400°C and 450°C (NUREG/CR-6931, Vol. 3). The failure temperature of 400°C is used in the NRC Thermally-Induced Electrical Failure (THIEF) Model (NUREG-1805) for TP instrumentation cables. The temperature of the heating shroud was 470°C for TS cables in the DESIREE-Fire series of tests. This temperature provides a heat flux of 14.1 kW/m^2 and is expected to cause longer TP failure

times. TS cables will fail earlier than the desired time at a heat flux of 26.9 kW/m² (600°C), according to the DESIREE-Fire report.

The ceramic fiber heater will, again, start at ambient temperature, around 20°C (68°F). The ramp will begin from 20°C to 470°C at the rate of 45°C (113°F) per minute. The shroud should reach 470°C at 600 seconds (10 minutes). The higher temperatures for TS cables correspond to the higher temperature failure rates observed in the CAROLFIRE series of tests. Again, time t=0 is defined as the time when the primary ramp was initiated and the maximum temperature (470°C) will be held until failures are observed.
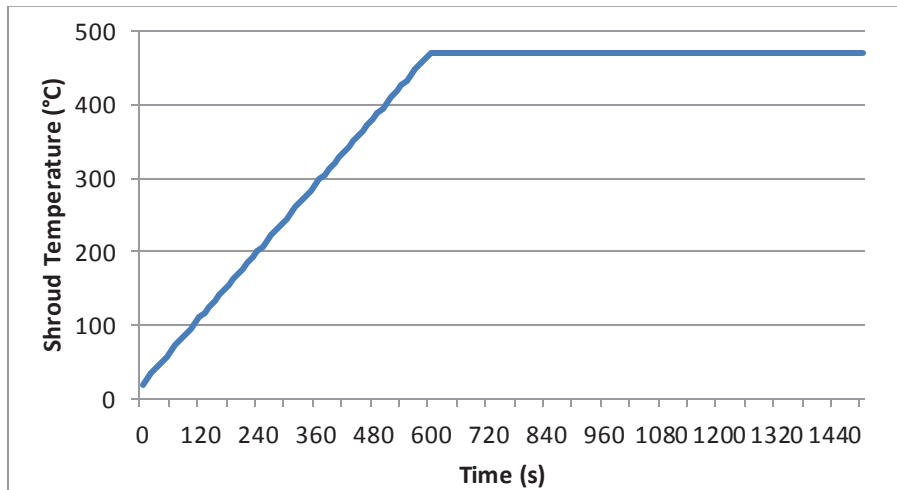

Figure C-7   Thermoset Cable Heating Profile- 470°C

The maximum temperature values are intended to be flexible and will be updated based upon results seen from testing.

C.3.2 Experimental Setups

C.3.2.1 Instrumentation Circuits

Instrument Loop: 4–20 mA Grounded and Ungrounded

A schematic representation that simulates a typical 4–20 mA current loop is shown in Figure C-8. Figure C-9 illustrates the same 4–20 mA current loop, but not connected to a ground. The 4–20 mA current loop is the most popular instrumentation circuit design in many industries given its insensitivity to electrical noise. This is also the standard output signal, according to ANSI/ ISA-50.00.01-1975 (R2012), "Compatibility of Analog Signals for Electronic Industrial Process Instruments." The instrument loop design in this test plan consists of a low-power current source, two 10 Ω resistors to simulate a long run of instrument cable, in this case 610 m (2000 ft), as opposed to the short length exposed during the fire test, a 250 Ω load resistor, and a voltmeter to provide the simulated readout circuit. Note that the 250 Ω load resistor is analogous to a shunt resistor in an output meter that would convert the 4 to 20 mA signal into a 1 to 5 V signal. Use of such a shunt resistor at the output device is typical of many instrumentation circuit designs and 250 Ω is the maximum for a 4 to 20 mA standard current input (ANSI/ ISA-50.00.01-1975
(R2012)). Although not shown on the diagram, if the cable has a shield, it will be grounded at the meter consistent with common practice. The drain wire will also be grounded, which mirrors

typical practice for a shielded cable which is to ground the shield/drain. If twisted pairs have a shield, it will be grounded at one end, and not both ends, based on discussions with the industry working group for the project who determined this was a common industry practice.

The circuit will be driven by a constant current output from the current source of nominally 15 mA. In typical instrumentation circuits, a DC voltage would be converted to a current at the transmitter based on the signal from the sensor. In order to simulate this, a current source will be used instead of adding another variable to the fire test. A fire is assumed to only affect the instrumentation cable, not the transmitter or receiver which are assumed to be located in other rooms. Because of this, a constant current is expected from the transmitter, which is emulated by using a current source.

As the fire degrades the instrument cable, some current can leak between the cable conductors resulting in an apparent drop in the instrument signal at the display device. That is, portions of the fixed 15 mA current signal may leak directly from conductor to conductor bypassing the load/shunt resistor. This behavior will be reflected as an inaccurate reading at the load resistor/voltmeter assembly.

Note that in presenting the data from this device, the actual measured output voltage can be converted to an equivalent 0 to 100 percent process variable scale to ease the interpretation of the results. That is, an output reading of 1 V corresponds to 0 percent on the process variable scale, and an output reading of 5 V corresponds to 100 percent on the process variable scale. Given the 15 mA constant input current, a reading of about 68 percent on the process variable scale is expected. If the two conductors form a "hard" (or very low impedance) short, the reading would go off-scale low on the process variable scale (i.e., a zero voltage would be off-scale low because the minimum anticipated current load under normal circuit conditions is 4 mA).

Since the circuit is of such a simplistic nature, robust circuit simulators that Sandia has used in the past, specifically Surrogate Circuit Diagnostic Unit (SCDU), are not necessary. Rather, the instrument loop will be implemented directly as shown.
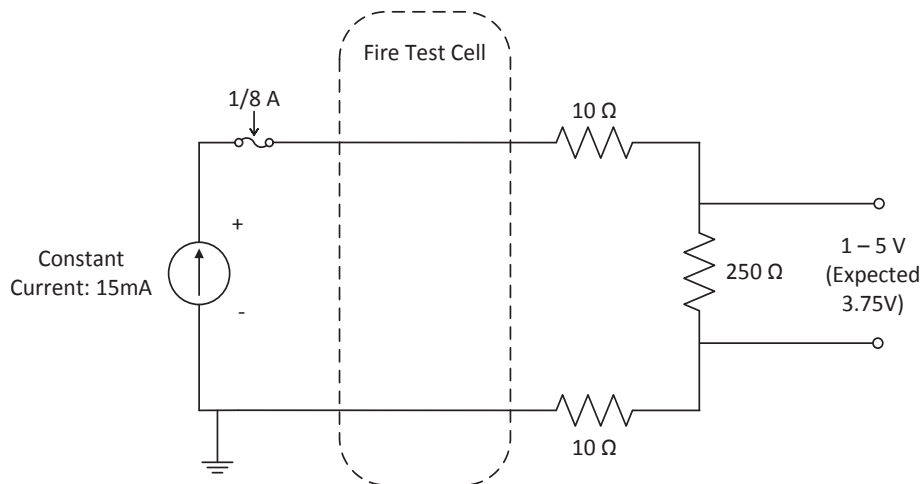

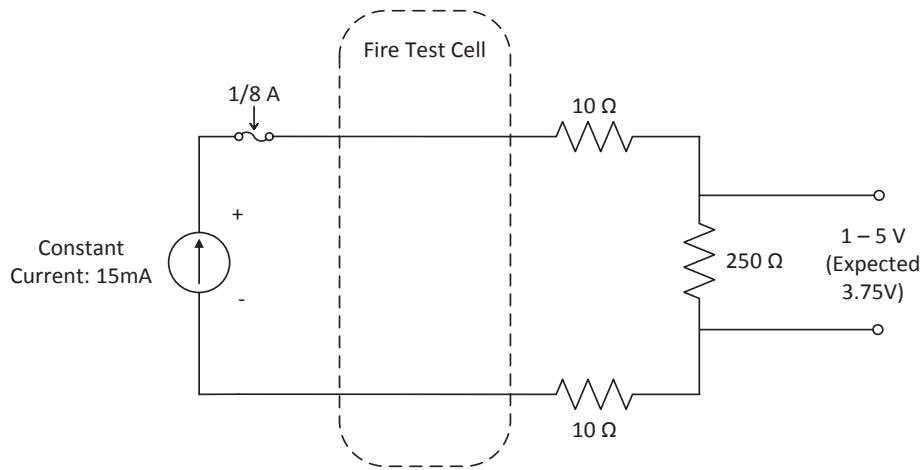**Figure C-8   4–20 mA Instrumentation Circuit for Fire Test, Grounded**

Figure C-9   4–20 mA Instrumentation Circuit for Fire Test, Ungrounded

Instrumentation Loop: 10–50 mA

The 10–50 mA control signal circuit design began back in the days of vacuum tubes where high line voltages were required to power up the circuitry. Since transistor circuits have become more widely used (and are more stable and accurate) the 10–50 mA current loop is not as prevalent in industry, however, these types of circuits may be present in older NPPs and is therefore considered in this test plan. The design is similar to the 4–20 mA in that there is no transmitter and instead a constant current source is used. Two 10 Ω resistors are used again to simulate a long run of instrument cable, and a 100 Ω load resistor will act as a shunt resistor. A voltmeter will again be used to capture the voltage across the shunt resistor in the range of a 1 to 5 V signal.

The constant current output from the current source will be 37.5 mA. The output was chosen to have the same expected output as the 4–20 mA circuit: 3.75 V. The rest of the setup will be the same as the ungrounded 4–20 mA instrumentation circuit. The fire behavior will be reflected as an inaccurate reading at the shunt resistor and voltmeter assembly. See Figure C-10 for the 10–50 mA current loop test setup.
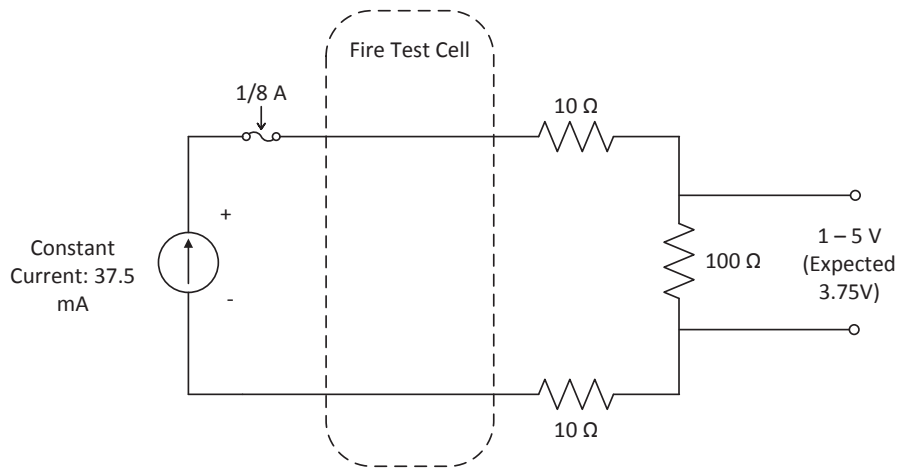

Figure C-10   10–50 mA Instrumentation Circuit for Fire Test

Instrumentation Loop: 1–5 VDC

A 1 to 5 VDC instrumentation circuit will also be tested to see how a voltage loop acts reacts in response to a fire. Instead of a current source, a 24VDC power supply will be used. Instead of a transmitter, a resistor with a 600 Ω load, along with a line drop of 100 Ω and an intrinsic safety resistor of 250 Ω are included in the instrumentation circuit. The voltage drops across these loads equals the constant voltage, 24V. The load resistor is 250 Ω, which will provide a standard output of 5V, instead of the 3.75V in the previous two instrumentation circuits. This is the maximum load for the voltage source, and in the field the transmitter load drop would be less than 600 Ω, but for the purposes of this test we decided to test the loop at its maximum operating characteristics. A voltmeter will again be used to measure the expected voltage from the shunt resistor.
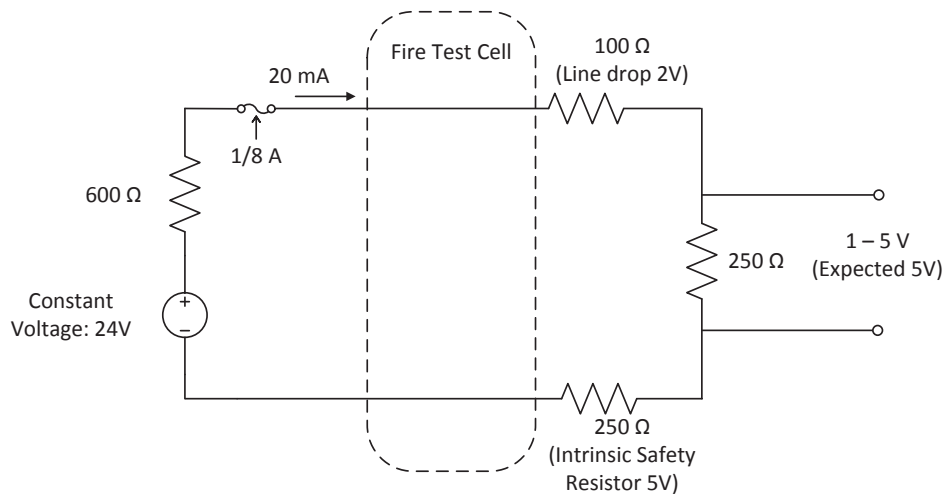
Figure C-11   1-5 VDC Instrumentation Circuit for Fire Test

C.3.2.2 Cable Electrical Performance Monitoring

Labview ® modules will be used to read current and voltage from the circuits described. These circuits are suitable for testing with typical twisted-pair instrument cables in particular. For testing, the cable shield wrap (typically present in such cables) will be connected to electrical ground as would be typical practice. As noted during the CAROLFIRE and DESIREE-Fire series of tests it is not appropriate to instrument any single cable for both thermal and electrical response since the instillation of a thermocouple on or within a cable could impact the electrical failure behavior. An additional cable will be included in the fire test cell to mirror the cable being monitored for electrical performance but will instead be monitored for thermal response.

C.3.2.3 Thermal Response Monitoring

The cable's temperature response will be measured using a thermocouple inserted below a 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. The cable used for monitoring the temperature response will be the same instrumentation cable type as the cable used for determining electrical failure.

The thermocouples will be of Type K and will be placed just below the cable jacket. A small slit in the cable jacket allows for the insertion of the thermocouple bead. The bead itself will be inserted into a distance of approximately 2.5 – 10 cm (1-4 inches) along the length of the cable placing it well away from the cut in the outer jacket. The slit will then be closed and secured with a single layer of fiberglass tape. Figure C-12 demonstrates the placement of the thermocouple under the jacket and also shows the relation of the temperature monitored cable to the electrically monitored cable. The thermocouples will be electrically isolated from the conductors.
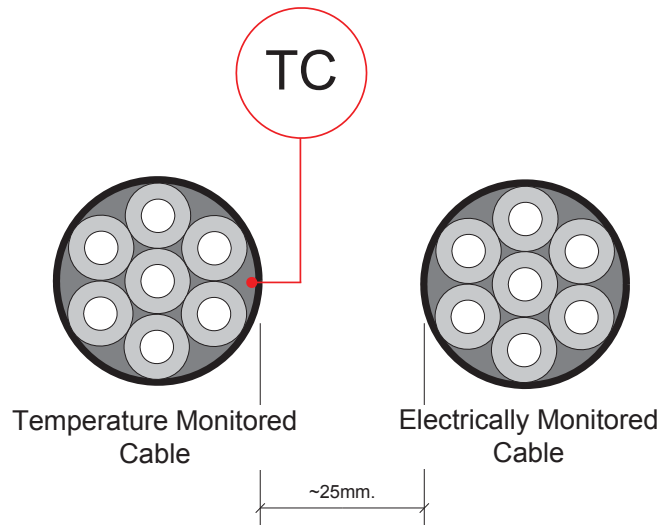

Figure C-12 Example Thermocouple Arrangement for Monitoring of 7-Conductor Cable Located Near the Electrically Monitored Cable in Tray

C.3.2.4 Placement of Cables

The two cable manufacturers chosen for this test matrix are General Cable and Rockbestos Firewall III. The instrumentation cables from these manufacturers were analyzed during the CAROLFIRE tests and are intended to have representative properties of cables across industry. There are two sizes of conductors for both manufactures: 16 and 18 AWG. The current test plan includes both sizes for testing but focuses on 16 AWG as it is understood to be the most common size cable for instrumentation circuits. For this series of testing the lowest number of twisted pairs available (1-pair for General Cable TP-insulated cable and 2-pair for Rockbestos TS-insulated cable) and a 7-pair conductor cables were selected. The plan is also to test cables with an overall shield, shielded pairs, or both shields, depending on what the manufacturer offers. An armored cable (preferably with an EPR insulation and CSPE jacket to correspond to the test in the 2001 test where signal degradation was found) has not yet been identified as available. If one is located, it will be included it in the tests. Finally, the plan is to route the cables in cable trays as individual cables and not cable bundles.

The cables will be tested in a horizontal position and run through the heating apparatus on a cable tray. The CAROLFIRE and DESIREE-Fire tested straight lengths of cable rather than cables with a radial bend section. This choice was made because a radial bend is expected to maximize the likelihood that a cable will fail, but it might also more likely that failure will lead to a fuse blow

rather than a spurious action. For example, if the failure occurs fairly abruptly, the bent section might drive all conductors together more quickly leading to more fuse blow failures and fewer spurious actuation failures. With a straight section, the cable failure would be driven primarily by the internal cable geometry and any residual internal stresses normal within a multi-conductor or twisted pair cable. This could lead to more failures that involve a subset of the conductors present and therefore more failures that involve hot shorts and spurious actuation. For this reason, the cables for this test will also be straight rather than in a radial bend.

The cable tray will be 300 mm (12-inch) wide standard ladder-back configuration, which are identical to those used in CAROLFIRE and DESIREE-Fire. For this series of tests, the open ends of the ceramic fiber heater will be closed off using a 24 mm (1 in) thick, low-density, solid refractory insulating board material. These boards will be cut around the raceways. It is not intended for the heating apparatus to be well sealed. The primary purpose of these end covers is to minimize air circulation into and out of the exposure chamber, as demonstrated in the CAROLFIRE Tests (NUREG/CR-6931). Figure C-13 shows the planned test setup.
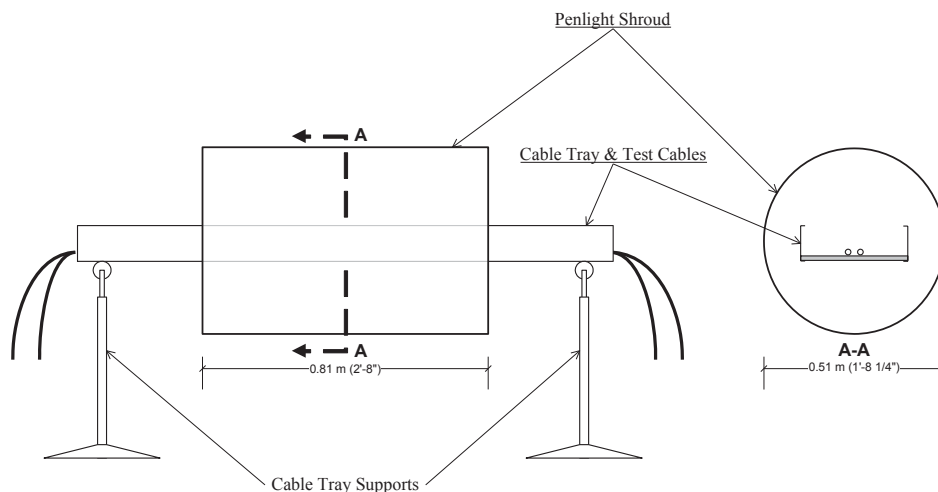

Figure C-13   Ceramic Fiber Heater Testing Apparatus (Shown with Cable Tray)

C.4 Test Matrix

This text matrix is intended to focus the test planning for instrumentation cables. The tests are designed to measure the temperature and time at failure, and electrical failure behavior, particularly focusing on the behavior differences between TP and TS instrumentation cables. Our goals are to confirm previous tests indicating that a fire affecting a TP cable would likely cause an abrupt failure and to better characterize the failure of a TS cable. This draft test matrix is based on data available during the literature search and Sandia assumptions. It can be modified based on information received during the public comment period as no direct operations experience data was made available during the test plan preparation process.

The test matrix is shown in Table C-3 . These tests are characterized by the following parameters where either a value or an "X" in a given column indicates the active choice for each experimental variable:

- Cable Manufacturer. General Cable and Rockbestos Firewall III instrumentation cables will be tested.

- Cable Type. Specifies the cable insulation and jacket material for the cables being tested. These are either TP or TS, as described in Section C.2.4 .

- Number of Twisted Pairs. Specifies the number of twisted pairs in each cable. For this series of testing the lowest number of twisted pairs available (1-pair or 2-pair) and a 7-pair conductor cables were selected.

- Conductor Size. Identifies the AWG size of the copper conductors within the cable. Typical conductor sizes range from AWG 16 – 22 for instrument circuits. The manufacturers only listed cables with 16 and 18 AWG conductor sizes. The majority of the tests will analyze 16 AWG conductors.

- Overall Shield. Specifies whether or not the cable has a shield system in-between the insulated conductors and the cable jacket.

- Shielded Pairs. Specifies whether or not the twisted pairs have a shield.

- Exposure Temperature. Defines the initial set-point temperature of the heating apparatus. The final set point is either 325ºC or 470ºC (617ºF or 878ºF), for the TP and TS samples, respectively. At least two tests will be done on a lower heating setting of 205 °C or 330 °C or (401ºF or 626ºF) for TP and TS samples to analyze the failure in a less severe, but still damaging condition.

Table C-3   Test Matrix for Instrumentation Cable Tests

Cable Type				Cable Characteristics			
Manufacturer	Insulation & Jacket Materials	TS	TP	Number of Twisted Pairs	Conductor Size (AWG)	Overall Shield	Shielded Pairs
Rockbestos Firewall III	XLPE/CSPE	x		2/c	16	x	
Rockbestos Firewall III	XLPE/CSPE	x		4/c	16	x	
Rockbestos Firewall III	XLPE/CSPE	x		2	16	x	
Rockbestos Firewall III	XLPE/CSPE	x		4	16	x	
Belden	PVC/PVC-Nylon		x	2	16	x	
Belden	PVC/PVC Nylon		x	8	16	x	
Belden	FR-EP/CPE	x		2	16	x	x
Belden	FR-EP/CPE	x		8	16	x	x
Belden	XLP/LSZH	x		1	16	x	x
Belden	XLP/LSZH	x		8	16	x	x

All of the cables in the matrix will be tested for the following three circuits:

- 4–20 mA instrumentation circuit, ungrounded
- 10–50 mA instrumentation circuit
- 1–5 VDC instrumentation circuit

A limited number of tests will be performed on the 4–20 mA grounded instrumentation circuit. The initial test will be performed on a 16 AWG, 2-twisted pair Rockbestos cable with an overall shield and shielded pairs. Depending on the outcome, more tests could be conducted on grounded circuits.

The total number of tests, not including multiple iterations of the same test, will equal 38. The equipment and physical test configurations used for these tests are similar to the CAROLFIRE and DESIREE-Fire small-scale series of tests.

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10. SUPPLEMENTARY NOTES
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11. ABSTRACT (200 words or less)

This report presents the results of instrumentation cable tests sponsored by the US Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research and performed at Sandia National Laboratories (SNL). The goal of the tests was to assess thermal and electrical response behavior under fire-exposure conditions for instrumentation cables and circuits. The test objective was to assess how severe radiant heating conditions surrounding an instrumentation cable affect current or voltage signals in an instrumentation circuit.

A total of thirty-nine small-scale tests were conducted. Ten different instrumentation cables were tested, ranging from one conductor to eight-twisted pairs. Because the focus of the tests was thermoset (TS) cables, only two of the ten cables had thermoplastic (TP) insulation and jacket material and the remaining eight cables were one of three different TS insulation and jacket material. Two instrumentation cables from previous cable fire testing were included, one TS and one TP. Three test circuits were used to simulate instrumentation circuits present in nuclear power plants: a 4–20 mA current loop, a 10–50 mA current loop and a 1–5 VDC voltage loop. A regression analysis was conducted to determine key variables affecting signal leakage time.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

Electrical cables, cables, fire, cable failure, fire risk, fire PRA, post-fire safe shutdown, spurious operation, spurious actuation, hot short, leakage current, instrumentation circuit, instrument cable

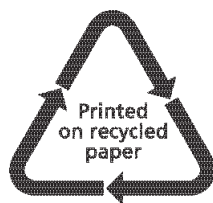| 13. AVAILABILITY STATEMENT |
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