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Response of Nuclear Power Plant Instrumentation Cables When Exposed to Fire Conditions - Test Plan

Prepared by
Alice B. Muna, Chris B. LaFleur

Sandia National Laboratories
Risk and Reliability Analysis Dept. 6231
P.O. Box 5800, MS 0718
Albuquerque, NM 87185-0718

Prepared for:
Gabriel Taylor, NRC Contracting Officer Representative
US Nuclear Regulatory Commission
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EXECUTIVE SUMMARY

Background

A fire at a nuclear power plant (NPP) has the potential to damage structures, systems, and components important to safety, if not promptly detected and suppressed. At Browns Ferry Nuclear Power Plant on March 22, 1975, a fire in the cable spreading room (CSR) and reactor building damaged electrical power instrument and control systems. Damage to instrumentation cables impeded the function of both normal and standby reactor coolant systems, and degraded the operators' plant monitoring capability. This event resulted in additional NRC involvement with utilities to ensure that NPPs are properly protected from fire as intended by the NRC principle design criteria (i.e., general design criteria 3, Fire Protection). Current guidance and methods for both deterministic and performance based approaches typically make conservative (bounding) assumptions regarding the fire-induced failure modes of instrumentation cables and those failure modes effects on component and system response.

Numerous fire testing programs have been conducted in the past to evaluate the failure modes and effects of electrical cables exposed to severe thermal conditions. However, that testing has primarily focused on control circuits with only a limited number of tests performed on instrumentation circuits. In 2001, the Nuclear Energy Institute (NEI) and the Electric Power Research Institute (EPRI) conducted a series of cable fire tests designed to address specific aspects of the cable failure and circuit fault issues of concern[1]. The NRC was invited to observe and participate in that program. The NRC sponsored Sandia National Laboratories to support this participation, whom among other things, added a 4-20 mA instrumentation circuit and instrumentation cabling to six of the tests. Although limited, one insight drawn from those instrumentation circuits tests was that the failure characteristics appeared to depend on the cable insulation material. The results showed that for thermoset insulated cables, the instrument reading tended to drift and fluctuate, while the thermoplastic insulated cables, the instrument reading fell off-scale rapidly. From an operational point of view, the latter failure characteristics would likely be identified as a failure from the effects of fire, while the former may result in inaccurate readings and subsequent erroneous operation actions.

Overview of Test Plan

This test plan covers a series of small-scale instrumentation cable fire tests sponsored by the NRC Office of Nuclear Regulatory Research (RES) and performed at Sandia National Laboratories (SNL). These tests are designed to better understand the fire-induced failure modes of instrumentation cable and evaluate the potential effect those failure modes could have on plant instrumentation circuits (i.e., circuit, component, and/or system response).

[1] "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."

ACKNOWLEDGEMENTS

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ACRONYMS AND ABBREVIATIONS

7/C	seven conductor
ac	alternating current
AWG	American wire gage
CAROLFIRE	the Cable Response to Live Fire project
CFR	Code of Federal Regulation
CPT	control power transformer
CSPE	chlorosulfanated polyethylene
dc	direct current
DESIREE-Fire	the Direct Current Electrical Shorting in Response to Exposure Fire project
EPDM	Ethylene Propylene Diene Monomer
EPR	ethylene propylene rubber
EPRI	Electric Power Research Institute
EQ	equipment qualification
IEEE	Institute of Electrical and Electronics Engineers
IR	insulation resistance
IRMS	insulation resistance measurement system
NA	not applicable
NEI	Nuclear Energy Institute
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
PE	polyethylene
PRA	probabilistic risk assessment
PVC	polyvinyl chloride
RES	NRC Office of Nuclear Regulatory Research
SCDU	surrogate circuit diagnostic units
SNL	Sandia National Laboratories
TC	thermocouple
TP	thermoplastic
TS	thermoset
XLPE	cross-linked polyethylene
XLPO	cross-linked polyolefin

1 OBJECTIVES, TECHNICAL BACKGROUND AND APPROACH

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.

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[2]. The NRC was invited to observe and participate in the industry 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 and thermoset cables. Thermoplastic cables generally displayed no characteristics of signal degradation prior to complete loss of signal. Thermoset cables displayed a substantial amount of signal degradation for approximately ten minutes prior to the total loss of

[2] "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."

the signal, shown in Figure 1. If a fire affected a thermoset 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 drift). In contrast, a fire affecting a thermoplastic 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.

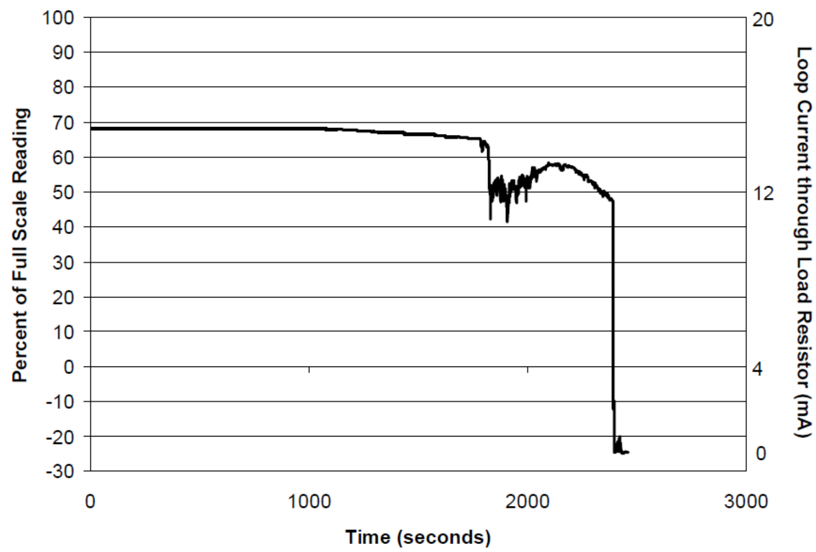

Figure 1. Degradation of Signal Data from Thermoset Test

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.

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 previous industry 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).

2 CABLE SELECTION

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 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.

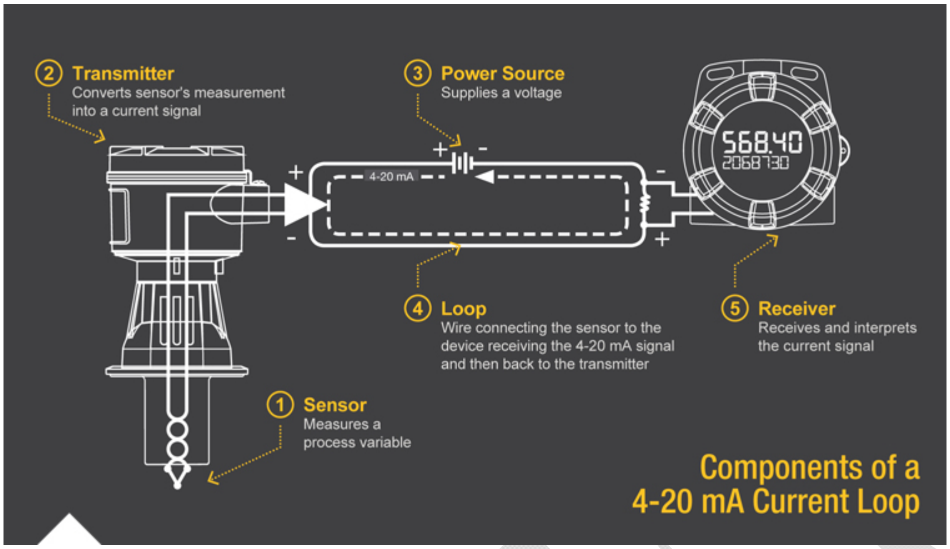

Figure 2. 4-20 mA Current Loop Example[1]

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.

2.3 Cable Failures and Circuit Faults

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

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

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 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.

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: 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-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.

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 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.
- 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.

2.5 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.[2] 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

[2] 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.

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 thermoset- (TS) and thermoplastic- (TP) insulated cables behaved differently; however the various thermoset cable types behaved similarly, as did the various thermoplastic 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. See Appendix A for more details on CAROLFIRE.

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 NEI/EPRI industry 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 thermoset and thermoplastic 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.

3 TEST APPARATUS AND EXPERIMENTAL SETUPS

3.1 Heating Apparatus

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 penligiht, 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 1. The heater will have a high emissivity coating which provides it the constant emissivity, shown in Figure 3.

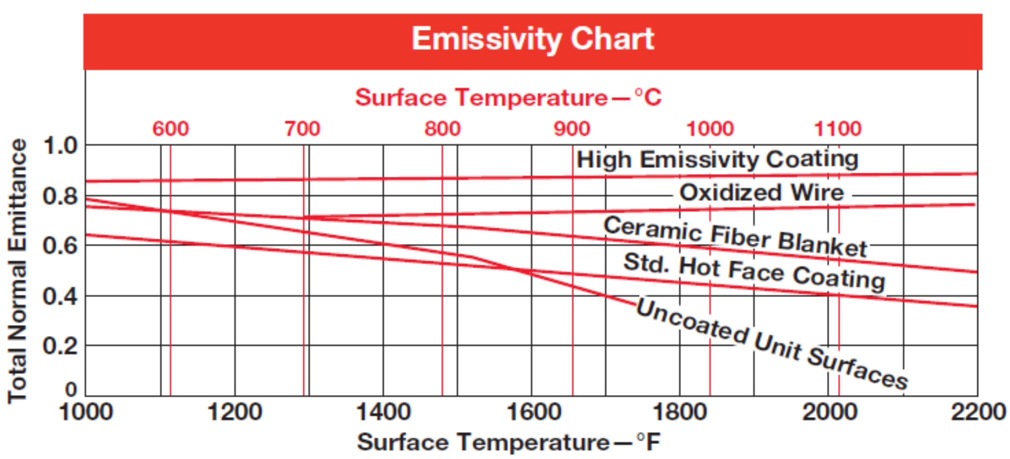

Figure 3. Emissivity of Heat Surface for Watlow Ceramic Fiber Heater[5]

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

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).

Table 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
500	17.22
525	19.56

3.1.2 Temperature Heating Profiles

For comparison purposes, the heat profile information for the industry tests is included here because this objective of this test plan is to confirm the circuit behavior demonstrated in the industry tests. The industry 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 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. As discussed in Appendix A, the TP cables failed at around 205-225°C. The thermal response cable for the TS cables ignited prior to electrical failure.

Table 2. Heat fluxes and temperatures from previous instrumentation cable testing

Test	Cable Description	Radiant Heat Flux Tested (kW/m^2)	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 Thermoplastic	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
CAROLFIRE_65	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.

Thermoplastic 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 thermoplastic 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). 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 was initiated.

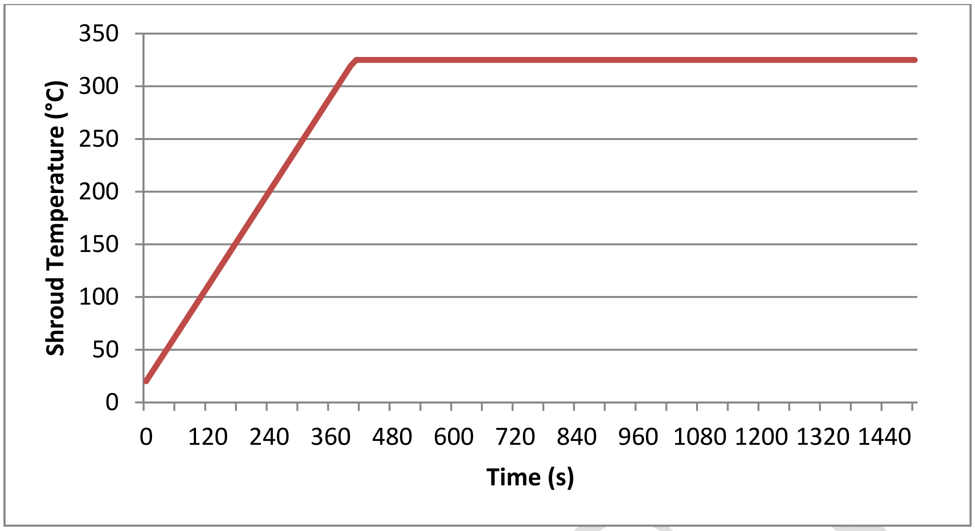

Figure 4. Thermoplastic Cable Heating Profile- 325°C

To test the thermoset 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 thermoplastic failure times. Thermoset cables will fail earlier than the desired time at a heat flux of 26.9 kW/m^2 (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 being 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.

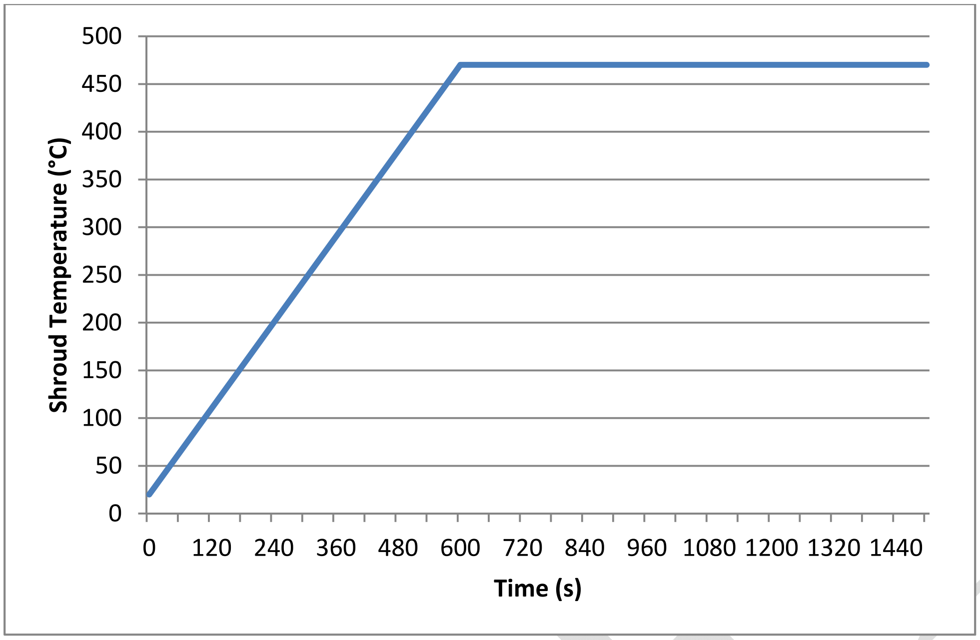

Figure 5. Thermoset Cable Heating Profile- 470°C

Although the temperatures for the majority of the tests will based on damage thresholds, additional tests will also 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 show in Figure 6 and Figure 7.

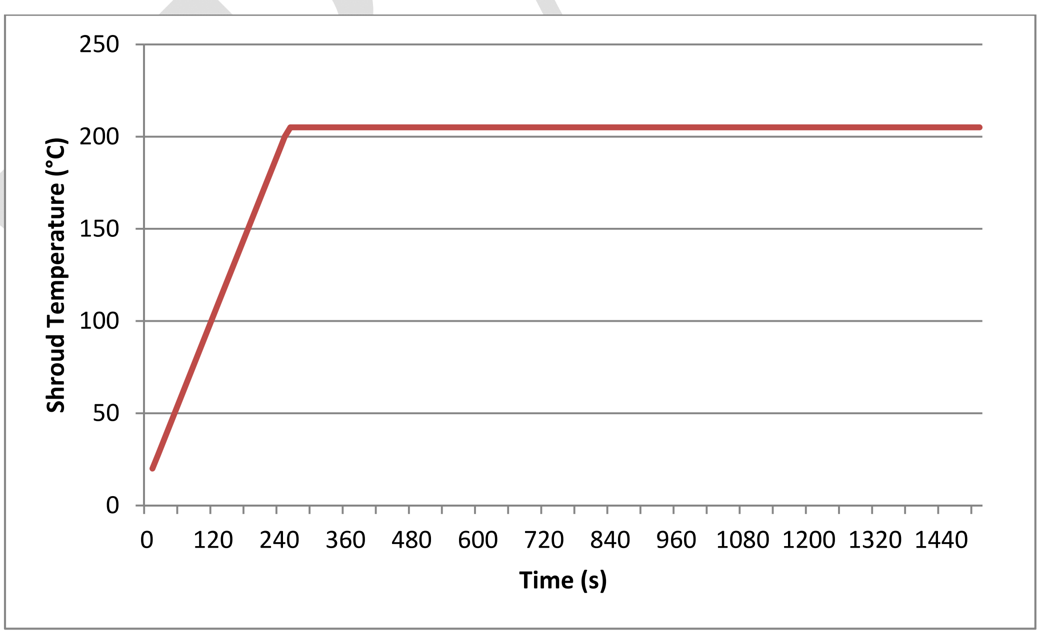

Figure 6. Thermoplastic Cable Heating Profile- 205°C

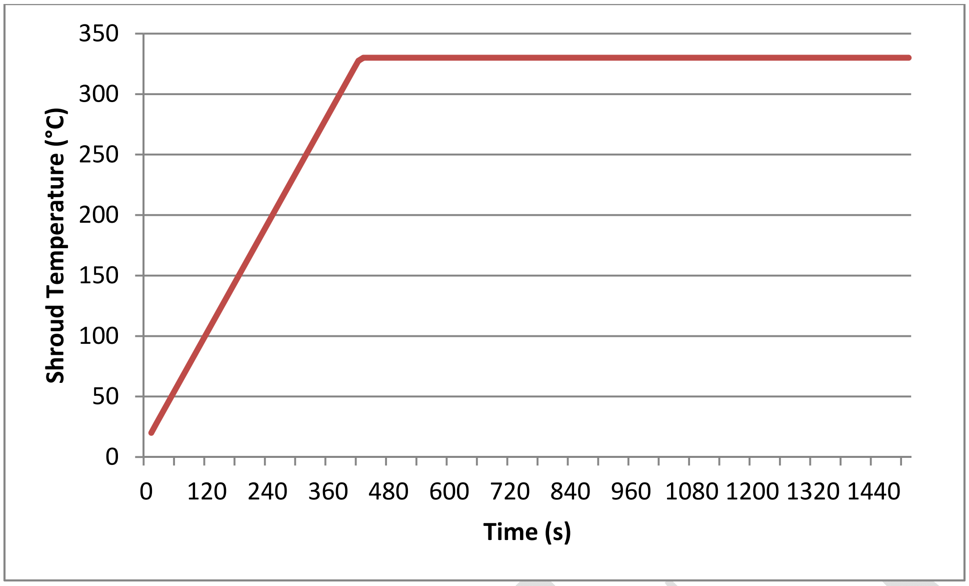

Figure 7. Thermoset Cable Heating Profile- 330°C

The maximum temperature values remain subject to peer review input and can be easily modified to suit program needs.

3.2 Experimental Setups

3.2.1 Instrumentation Circuits

3.2.1.1 Instrument Loop: 4 – 20 mA grounded and ungrounded

A schematic representation that simulates a typical 4-20 mA current loop is shown in Figure 8. Figure 9. 4-20 mA Instrumentation Circuit for Fire Test, UngroundedFigure 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 ohms 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 not be grounded. This was discussed with the industry working group for the project and it was determined that not grounding the twisted pairs shield is 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% process variable scale to ease the interpretation of the results. That is, an output reading of 1 V corresponds to 0% on the process variable scale, and an output reading of 5 V corresponds to 100% on the process variable scale. Given the 15 mA constant input current, a reading of about 68% 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.

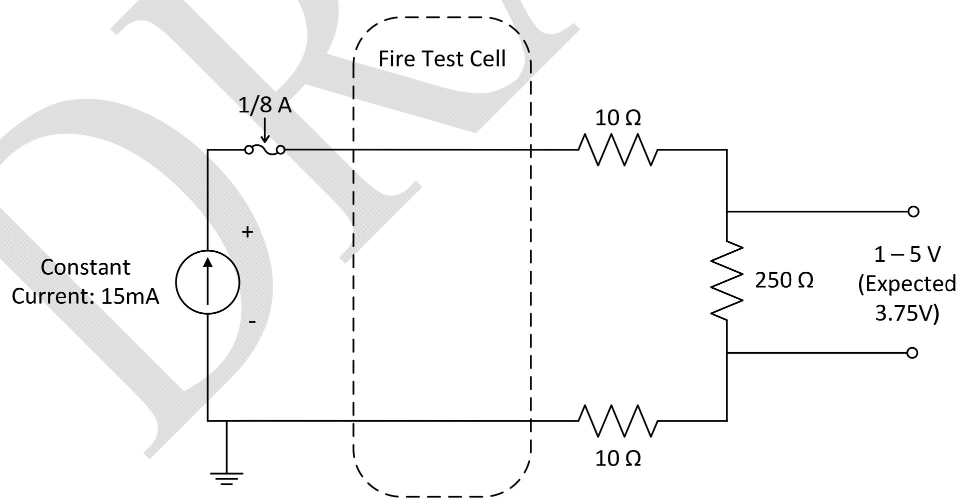

Figure 8. 4-20 mA Instrumentation Circuit for Fire Test, Grounded

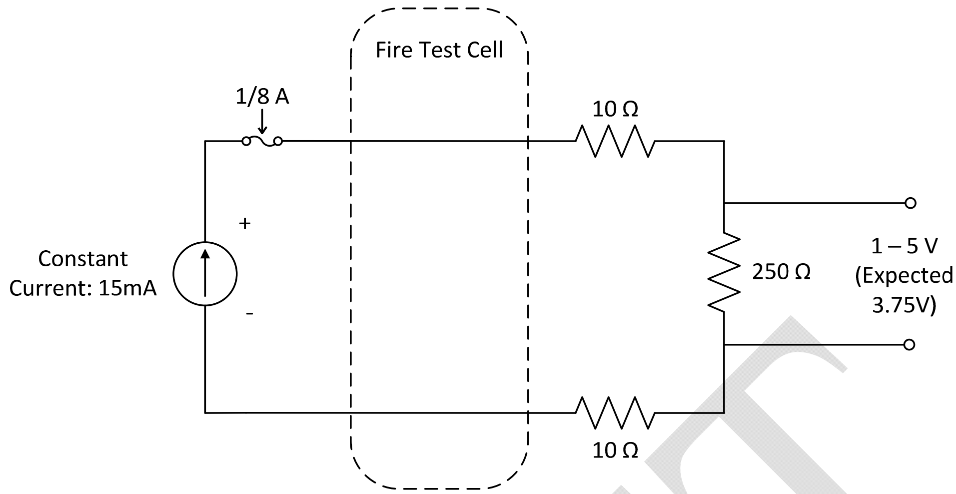

Figure 9. 4-20 mA Instrumentation Circuit for Fire Test, Ungrounded

3.2.1.2 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 10 for the 10-50 mA current loop test setup.

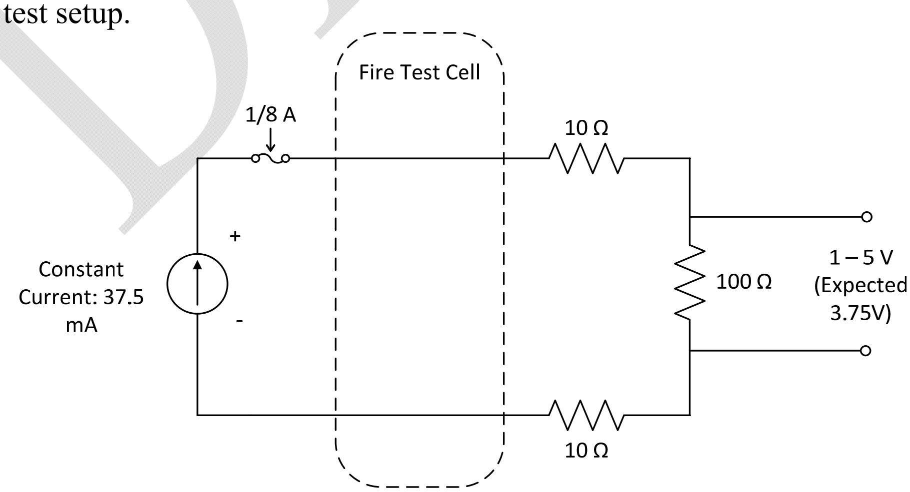

Figure 10. 10-50 mA Instrumentation Circuit for Fire Test

3.2.1.3 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 24V DC 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.

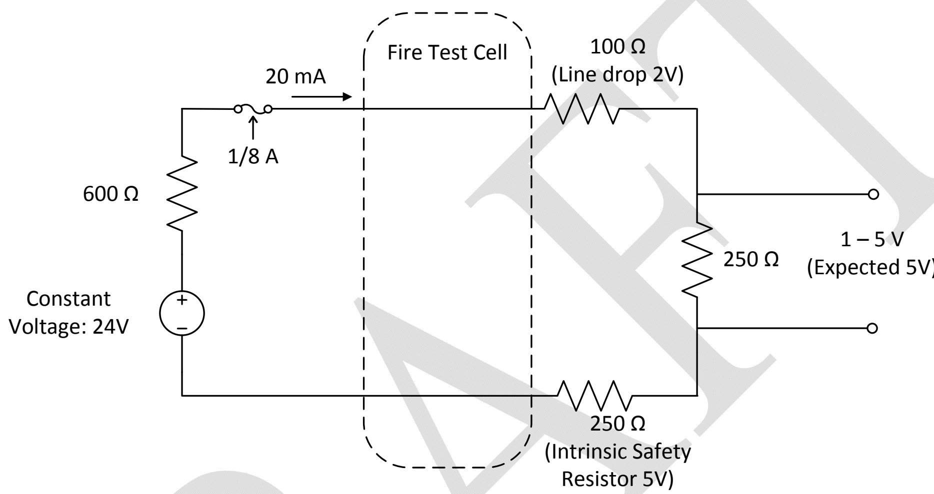

Figure 11. 1-5 VDC Instrumentation Circuit for Fire Test

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.

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 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.

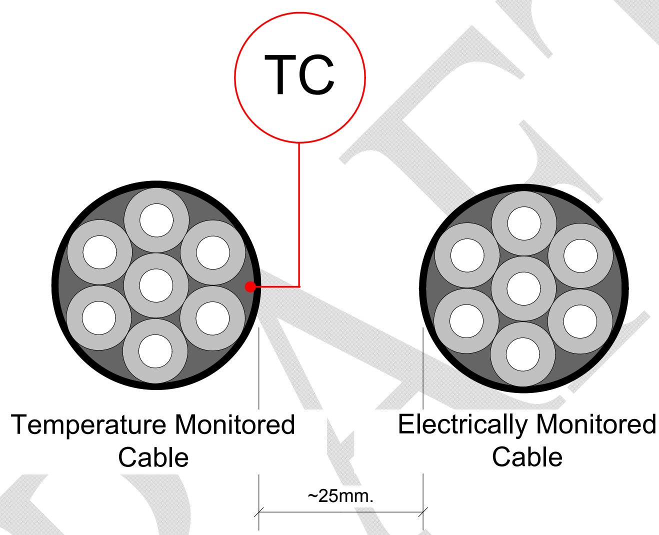

Figure 12. Example thermocouple arrangement for monitoring of 7-conductor cable located near the electrically monitored cable in tray.

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 industry 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 13 shows the planned test setup.

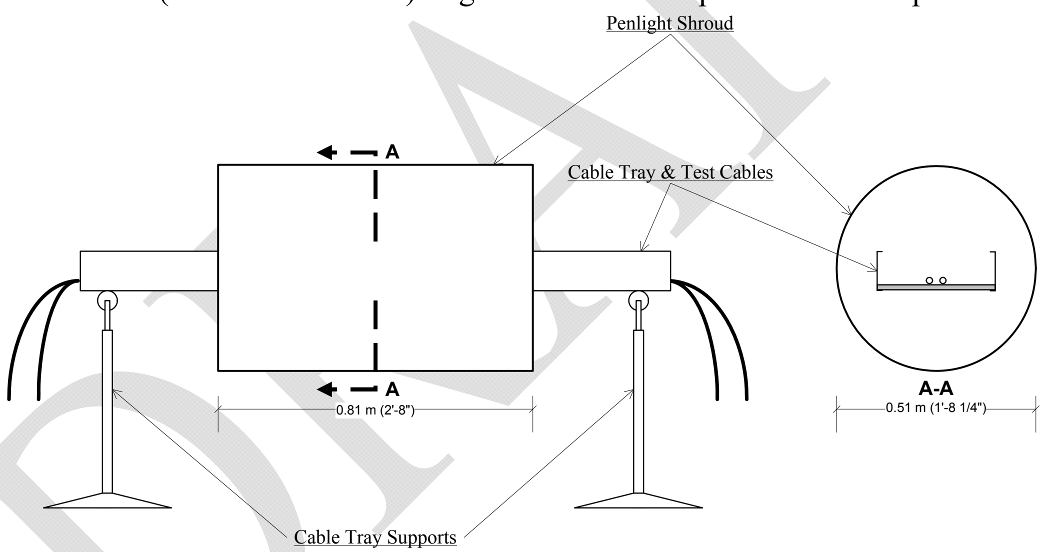

Figure 13. Ceramic Fiber Heater Testing Apparatus (shown with cable tray)

DRAFT

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 thermoplastic and thermoset instrumentation cables. Our goals are to confirm previous tests indicating that a fire affecting a thermoplastic cable would likely cause an abrupt failure and to better characterize the failure of a thermoset 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 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 thermoplastic or thermoset, as described in Section 2.5.
- 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 325 ºC or 470 ºC (617 ºF or 878 ºF), 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 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	
Houston Wire	PVC/PVC-Nylon		x	2	16	x	
Houston Wire	PVC/PVC Nylon		x	8	16	x	
Houston Wire	FR-EP/CPE	x		2	16	x	x
Houston Wire	FR-EP/CPE	x		8	16	x	x
Houston Wire	XLP/LSZH	x		1	16	x	x
Houston Wire	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.

5 REFERENCES

NUREG-1805: Stroup, D., Taylor, G., Hausman, G., *Fire Dynamics Tools (FDT^s) Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program, Volume 1, Supplement 1*, June 2013.

NUREG/CR-6776: Wyant, F.J., Nowlen, S.P., *Cable Insulation Resistance Measurements Made During Cable Fire Tests,* SAND2002-0447P, US NRC, Washington DC, June 2002.

NUREG/CR-6834: LaChance, J.L., Nowlen, S.P., Wyant, F.J., Dandini, V.J., *Circuit Analysis-Failure Mode and Likelihood Analysis,* SAND2002-1942P, US NRC, Washington DC, September 2002.

NUREG/CR-6850: *EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities, Volume 2: Detailed Methodology,* a joint publication of the US NRC, Washington DC, and the Electric Power Research Institute (EPRI), Palo Alto, CA, September 2005.

NUREG/CR-6931: Nowlen, S. P., Wyant, F. J (Vols. 1 and 2), and McGrattan, K. (Vol. 3) *Cable Response to Live Fire (CAROLFIRE) Volume 1-3*, April 2008.

NUREG/CR-7010: McGrattan, K., et al, *Cable Heat Release, Ignition, and Spread in Tray Installations During Fire* (CHRISTIFIRE) *Volumes 1 and 2,* July 2012.

NUREG/CR-7100: Nowlen, S. P., Brown, J. W., Olivier, T. J., Wyant, F. J., *Direct Current Electrical Shorting in Response to Exposure Fire* (DESIREE-Fire), April 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.

Regulatory Guide (RG) 1.189: *Fire Protection for Nuclear Power Plants,* October 2009.

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SAND 89-2369, *"Aging of Cables, Connections, and Electrical Penetration Assemblies Used in Nuclear Power Plants,"* July 1990.

SAND 96-0344, "*Aging Management Guideline for Commercial Nuclear Power Plants – Electrical Cable and Terminations,"* September 1996.

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

APPENDIX A. Literature Search on Research Related to Instrumentation Cable Fire Tests

A.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.

A.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.

<u>Conclusions</u>

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.

A.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 ohm 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.

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.

A.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 A-1. 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.

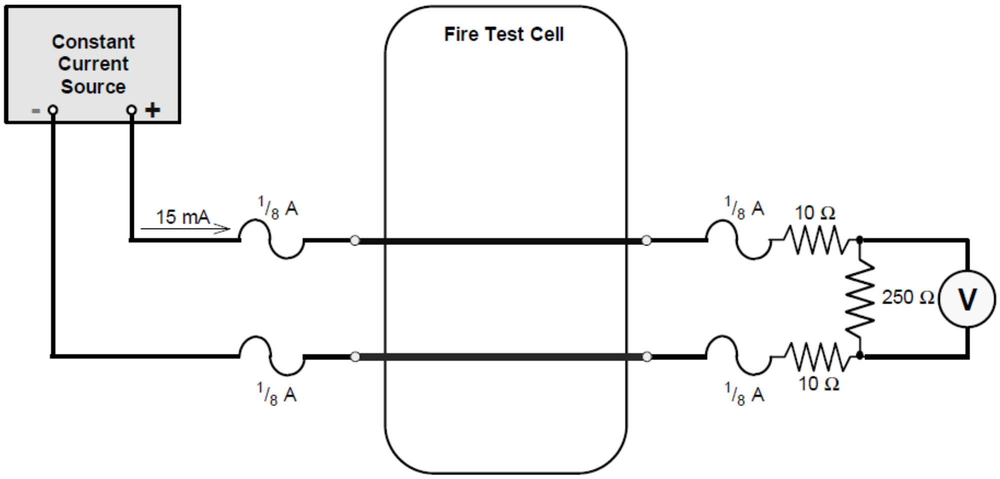

Figure A-1. Instrument Loop Circuit

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 insulation resistance (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 A-1.

Table A-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	Thermoset	Horiz. Tray	350	1100	2390

14	Thermoplastic	Conduit	145	—	2225
15	Thermoset	Horiz. Tray	Variable (350/200/450)	1100	1500
16	Thermoplastic	Horiz. Tray	145	—	100
17	Thermoset	Vert. Tray	200	930	1600
18	Thermoset	Conduit	250	1140	1325

Conclusions

This test demonstrated that there are pronounced behavior differences observed between the failure of the thermoplastic and thermoset cables. Thermoplastic cables generally displayed no characteristics of signal degradation prior to complete loss of signal. Thermoset 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 A-2. As demonstrated in the thermoset 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.

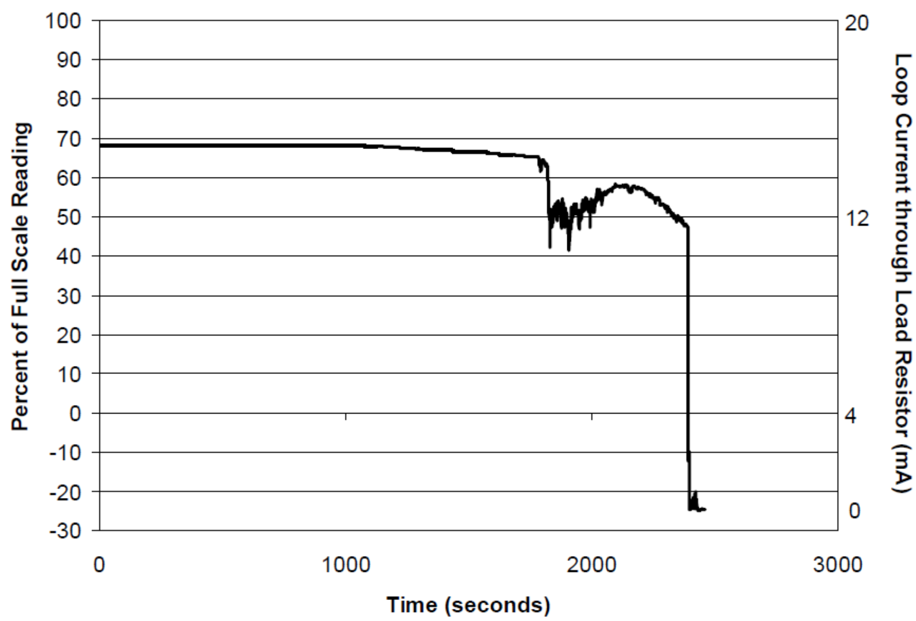

Figure A-2. Current Loop Data from Thermoset Test Number 13

A.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 A-2.

The results of the tests are found in Table A-3. For Tests 62 and 64, both thermoset 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 thermoset 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 earlier industry 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.

Conclusions

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

Table A-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 A-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)

A.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.

A.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 A-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 A-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.

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 A-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.
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.

No.	Instrumentation Control System Type	Description	Usage in Nuclear Industry	PIRT panel Recommendation
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.
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.

No.	Instrumentation Control System Type	Description	Usage in Nuclear Industry	PIRT panel Recommendation
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.

A.8 **General test conclusions**

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

A.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 postfire 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 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 designed in Section 3.2.1.1.
- 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."

A.10 **References**

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

A.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.

A.12 **Documents reviewed, but not summarized in the report.**

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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.