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Determination of Failure Criteria for Electric Cables Exposed to Fire for Use in a Nuclear Power Plant Risk Analysis

by

Jill E. Murphy

A Thesis

Submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Master of Science

in Fire Protection Engineering

by

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on 14 January 2004.

APPROVED:

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Professor David A. Lucht, P.E., Head of Department

Abstract

The vulnerability of electrical cables exposed to a fire environment is of particular concern to the nuclear power plant community. The community is interested in data that could be used for predicting cable failures during a fire situation. For this reason, a cable test program was conducted using two different types of cable insulation. Several different exposure heat fluxes were tested, as well as different test arrangements such as cable trays and conduits. The program revealed that a single failure temperature for all cable types is not recommended, but if it is necessary a reasonable temperature could be chosen for the thermosets tested in this project.

Acknowledgements

I would like to thank the following people for their help and support for this thesis project. Without their help, this thesis project would not have been completed.

Louis Gritzo, Ph.D., manager, Sandia National Laboratories
Jonathan Barnett, Ph.D., advisor, Worcester Polytechnic Institute
Tom Blanchat, Ph.D., technical advisor, Sandia National Laboratories
Tom Lalk, Ph.D., technical advisor, Sandia National Laboratories
Steve Nowlen, Sandia National Laboratories
Frank Wyant, Sandia National Laboratories
Erin Hall, intern, Sandia National Laboratories
Radiant Heat Staff, Bldg 6536, Sandia National Laboratories

This work was performed at Sandia National Laboratories in Albuquerque, NM. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy under contract DE-AC04-94AL85000.

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Nomenclature

Material Abbreviations

PE	Polyethylene
PVC	Polyvinylchloride
XLPE	Cross-linked Polyethylene
PP	Polypropylene
PTFE	Polytetraflouroethylene (Teflon)
EPR	Ethylene-Propylene Rubber
XLPO	Cross-linked Polyolefin
EPDM	Ethylene-Propylene Diene Monomer
CSPE	Chlorosulfonated Polyethylene

IRMS	Insulation Resistance Measurement System
NPP	Nuclear Power Plant
$\dot{q}''$	Exposure Heat Flux [kW/m^2]
t_f	Time to Failure [seconds]
T_{cable}	Cable Failure Temperature [°C]
$T_{exposure}$	Exposure Temperature [°C]
ε	Emissivity
σ	Stefan-Boltzman constant [5.67E-8 W/m^{2}K^4]
V	Voltage [Volts]
I	Current [Amperes]
R	Resistance [Ohms]

Executive Summary

A fire situation is a major concern for the nuclear power plant (NPP) community. Safe shutdown of the plant following a fire is the primary focus of the NPP fire safety regulations. Electrical cables are extremely important to the endurance of the nuclear power plant and its systems because they provide power, instrumentation, and/or control to most components necessary to plant safety systems. The purpose of this experimental program is to examine the fragility of two types of electrical cables used in NPPs.

Many other tests have been conducted in an attempt to understand the fragility of electrical cables exposed to a fire environment. The information from these tests has been surveyed and collated (Nicolette, 2003). Comparing these results proved extremely difficult because of a wide variety of testing methods, failure criteria, test cables, test arrangements, etc. A threshold failure temperature for electrical cables could not be determined.

To address this issue a series of cable experiments was conducted using a consistent set of test conditions and procedures. The purpose of the program was to establish a failure threshold for electrical cables; this threshold would be used in fire simulation computer codes as a guide for determining if and when failure will occur for electrical cables.

The cable tests were conducted in a radiant heat facility, PENLIGHT, a cylindrical shroud lined with radiant heating lamps. The diameter of the interior surface of the shroud is 0.52 meters (20.4 inches). The right and left end caps of the apparatus are thermally insulated and can be assumed to be adiabatic. The lamps can be controlled to maintain a fixed shroud temperature and can be held at temperatures up to 1000°C for extended periods of time.

During the experiments, an insulation resistance measurement system (IRMS) was used to monitor the insulation resistance of the test cable and indicate electrical failure. The system was connected to the test cables using wiring harnesses. A minimum of two and a maximum of ten conductors can be connected to the IRMS, and the insulation resistance is found using the basic theory behind Ohm's Law: Voltage (V) = Current (I)* Resistance (R).

For each test, the temperatures of cables and the test shroud were monitored using thermocouples. Because current running through the cables could cause problems between the two systems, the thermocouples could not be inserted directly into the electrically monitored cables. Surrogate cables were used; three thermocouples were inserted into each cable, one in the center and the others ten inches on each side of center. The thermocouples used in the shroud were located every 90° beginning at the top.

Forty-three tests were conducted in the program using ethylene propylene rubber (EPR) and cross-linked polyethylene cables (XLPE), both common in nuclear power plants (DuCharme, 1988). There were two sizes of cable used, 3-conductor (8AWG) and 7-conductor (12 AWG). These tests include single and multiple cable tests as well as cable tray and conduit tests and the exposure heat fluxes for the experiments were 14, 18, 30, 56, and 97 kW/m^2. The lack of high heat flux data in the literature made it particularly important for this project. The recorded data from each test consisted of cable temperature, shroud temperature, average conductor to conductor resistance, and average conductor to ground resistance, all as a function of time. The failure criterion for the test was determined to be when the insulation resistance dropped one order of magnitude below its initial value. Plots were created to determine the time to failure and the cable temperature at the failure time for each test.

Most of the experiments tested cable trays. This method is the most common in transporting cables from one location to another in a nuclear power plant. In general, the EPR cables were tougher than the XLPE cables. The times to failure for the EPR cables were longer than for the XLPE cables, and the cable failure temperatures were higher for the EPR cables. The rate of decrease of the time to failure as a function of exposure to heat flux for both cable insulations was relatively the same. The number of conductors did not seem to make a difference in either time to failure or cable temperature for either insulation. At some exposure fluxes (to be discussed), the 3-conductor was more robust and at the other fluxes the 7-conductor was better.

Six cable tests were conducted using conduits at two different fluxes, 30 kW/m^2 and 97 kW/m^2. There were two tests each for the 7-conductor EPR, 3-conductor XLPE, and 7-conductor XLPE cables. The results of these tests concluded that the times to failure at both fluxes were highest for the 7-conductor EPR and lowest for the 7-conductor XLPE.

Seven multiple-cable tests were conducted. Each cable was used at least once in the multiple-cable setup. It was assumed that the cables in the "middle" row would last significantly longer than the cables on the top and bottom rows. However, the middle cables were still exposed to some direct heat flux, so the results of the tests were not as expected.

Comparing the literature results to the cable test results determined that the failure times for the EPR and the XLPE cables in this test program were higher than previous experimentally determined times. The trend of the data, however, was very much the same.

In conclusion, it is not recommended that a single failure threshold temperature be used for all cables when using fire simulation codes. The failure temperatures for the two types of insulations in this program were not drastically different, however, it is not a single failure threshold temperature should not be used for all types of cable insulations.

Introduction

The nuclear community is concerned with the risks and consequences associated with a fire in a nuclear power plant (NPP). A large unsuppressed fire in a critical plant location could result in sufficient damage to various safety systems such that the ability to achieve and maintain a safe shutdown could be severely challenged. (Siu email, 2004) This could potentially result in severe consequences such as the release of radioactive materials inside the facility or outside into the environment.

Necessary to a nuclear power plant risk analysis is information about the effect of a fire environment on the functionality of various safety-related equipment and sub-systems; that is, on their vulnerability to fire. This information is necessary in order to translate the results of a fire analysis to the survivability of equipment and sub-systems, and subsequently to an assessment of the risk and consequences at the system level. The information considered most important to a fire risk analysis is that related to the fragility of electrical cables because of their vital importance in providing power, instrumentation, and/or control to most components necessary to plant safety systems and, ultimately, to the capability for safe plant shutdown.

Many tests have been conducted to determine the fire fragility of electrical cables and this information has been surveyed and collated (Nicolette, 2003). However, these tests were not all conducted with consistent testing methods, criteria for failure, test procedures, cable sizes, test configurations, etc. Therefore, it was difficult to compare the results of the various test programs and determine a threshold failure temperature to use for cable fragility in a risk analysis. It was also found that relatively little cable failure information was available for high intensity exposure conditions (high heat fluxes) such as one might experience in a large hydrocarbon fire. (Nowlen email, 2004)

To address this limitation a series of cable tests was conducted using a consistent set of test conditions and procedures, with the objective of determining failure thresholds for electrical cables of various types, configurations, and insulation, in particular, under high heat flux conditions. These results are used in conjunction with the results of other cable fire tests to determine a general failure temperature threshold for electrical cables that can be used as a criterion in fire simulation computer codes to identify if and when electric cables will fail for various fire scenarios.

The cable tests were conducted in a cylindrical radiant heat facility, PENLIGHT. The cables were installed in the temperature-controlled cylindrical cavity of the facility and the temperatures of the cavity surface (hence, the radiant heating conditions) and a surrogate cable were monitored as functions of time. An insulation resistance (IR) device was used to monitor the test cable insulation resistance and indicate electrical failure.

1 Cable Cross-Sectional Diagram

This section discusses the elements in an electrical cable. There are four major elements, one of which is not present in all electrical cables. They can be seen in Figure 1-1.

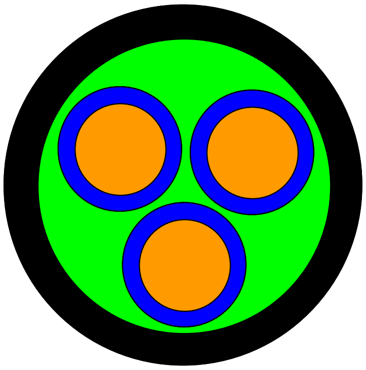

Figure 1-1 Cross Sectional Diagram of Electrical Cable

The first element is the jacketing, seen here in black. The jacketing holds together the cable and also protects the inside from the environment. The filler material, seen here in green, is not included in all electrical cables. It is used to hold the conductors tightly inside the jacketing, and it typically made of a nylon-like material. The third element is the insulation, seen here in blue. The insulation surrounds the conductors and provides additional protection against the outer environment. In the event that a current is running through the cable, the insulation also holds in any heat from that current. The fourth element is the conductors. For this program, the conductors were made of copper. The above diagram shows three conductors, but cables can have any number of conductors depending on its use.

2 Literature Review

This section discusses the information currently available in the literature.

2.1 *Introduction*

There are several purposes for this literature review. The first reason was to collect information regarding the methods in which electrical cables are tested. These test methods are used to simulate fire environments. The second purpose was to collect the data from previous experiments so comparisons and conclusions could be made. Finally, the voids in the tabulated data were identified to determine what cables would be tested in the subsequent experiments.

As the results of the literature review affirmed, “the loss of functionality in electrical cables is a complex phenomenon that depends on the materials and dimensions, the electric and mechanical loads on the cables, as well as on the magnitude of the heat flux and its time of exposure, among other factors”. (Bertrand, *et al.*)

2.2 *Cable Properties*

This section describes the available cable sizes, types, and insulation varieties.

2.2.1 Cable Sizes

Cables can range in size from very small (0.05 mm^2) to large (500 mm^2). Most often in the United States, the cables are not classified by the actual cross-sectional area but rather by a gauge number, noted as AWG. Typically, the higher the gauge number, the smaller the area. Table 2-1 gives the associated AWG number for the cross-sectional area of commonly used electric cables. (http://www.iewc.com/Tech10a.htm)

Table 2-1 Cable Sizes (AWG to mm^2)

AWG	mm^2	AWG	mm^2	AWG	mm^2	AWG	mm^2
30	0.05	18	0.75	6	16	4/0	120
28	0.08	17	1.0	4	25	300MCM	150
26	0.14	16	1.5	2	35	350MCM	185
24	0.25	14	2.5	1	50	500MCM	240
22	0.34	12	4.0	1/0	55	600MCM	300
21	0.38	10	6.0	2/0	70	750MCM	400
20	0.50	8	10	3/0	95	1000MCM	500

2.2.2 Types

The cables can also be separated by their usage: power, instrumentation, or indication/control. Power cables tend to be larger compared to control cables, but this does not have to be the case. The sizes of some of the power cables tested were 6 and 10 AWG. Some of the control cables that were tested were as small as 6 and 20 AWG, while another cables was 2 AWG.

The cables also differ by their voltage rating. Some cables tested had voltage ratings between 24 and 1000 Volts. In the set of experiments run by Bertrand, et al, the power cables could carry an alternating current of 6.6 kV or 380 V and a direct current of 125 V or 48 V with high intensity, the control cables used low voltage 48 V, and the instrumentation cables also had a low voltage of 30 V and 24 V. (Bertrand, *et al.*) In other experiments, where the cables had much higher voltages, the type of cable was not identified.

2.2.3 Thermosetting Plastics vs. Thermoplastics

Electrical cable insulation materials can be separated into two major categories, thermosetting plastics and thermoplastics. For simplicity, thermosetting plastics will be referred to as thermosets throughout this report. These two groups behave very differently when exposed to a fire environment; thermosets become rigid and form a char when heated, while thermoplastics become soft, deform, and melt. Both of the cable products tested in this effort are thermosets.

Examples of thermoset materials are cross-linked polyethylene (XLPE), ethylene propylene rubber (EPR), and silicon rubber. Examples of thermoplastic materials are polyethylene (PE), polyvinylchloride (PVC), Teflon (PTFE), and polypropylene (PP). Table 2-2 provides the decomposition temperatures for the thermoplastic material examples (Hilado).

Table 2-2 Decomposition Temperature for Some Thermoplastic Materials

Material	Decomposition Temperature (°C)
Polypropylene	328 - 410
Polyethylene	335 - 450
Teflon	508 - 538
Polyvinylchloride	200 - 300

2.3 Standardized Testing Procedures

This section discusses various standard testing procedures for cables, with a main focus on flammability.

2.3.1 UL 910: Horizontal Tray Test for Plenum Cables

The UL 910 horizontal tray test has the most severe requirements for cables. If they pass the test, they are considered plenum cables, which need adequate fire-resistant and low-smoke-producing characteristics. This test takes place in a horizontal tunnel 7.58 meters (25 feet) long by 0.61 meters (2 feet) wide (often called a Steiner tunnel), which is filled with electrical cables. The tunnel is exposed to a gas flame of 87.9 kW (300,000 BTU/hr) for twenty minutes with an air flow rate of 1.22 m/s (240 ft/min). The cables pass the test when the following requirements are met: the flame spread distance is less than five feet beyond the gas flame itself, the peak smoke optical density does not exceed 0.5, and the average optical density does not exceed 0.15. The latter two properties are measured in the exhaust duct (UL Standard 910-1998).

2.3.2 UL 1581: Vertical Tray Test for Fire Resistant Cables

The UL 1581 test is a vertical tray test that determines whether a cable is resistant to fire spread. The cable tray, 2.42 meters (8 ft) high by 0.303 meters (1 ft) wide, is loaded with cables and exposed to a 20.3 kW (70,000 BTU/hr) gas flame for twenty minutes. The burner is set horizontally at a height of 0.45 meters (18 in) above the bottom of the tray. The cables pass the test if the length of char runs all the way to the top of the cable tray. (UL Standard 1581-2001) This test is essentially identical to the flammability test included in IEEE-383 (see discussion below).

2.3.3 UL 1666: Vertical Tray Test for Riser Cables

The UL 1666 test is another vertical cable tray test that determines whether or not a cable can be classified as a riser cable. A riser cable is one having fire-resistant characteristics capable of preventing the carrying of fire from floor to floor. The cables are exposed in a 5.75-meter (19 ft) high concrete shaft. The shaft is divided into two compartments at the 3.66-meter (12 ft) level with a 0.30 by 0.61 meter (1 ft by 2 ft) opening. The exposure is a gas flame that releases 145 kW (495,000 BTU/hr) for 30 minutes. The cables pass if no "flame" appears at the top of the bottom compartment during the test. (UL Standard 1666-2000)

2.3.4 IEC 332-3: International Cable Tray Test

The IEC 332-3 cable test also uses a vertical tray configuration. The tray is 3.5 meters high and is placed directly against a wall. A gas burner, with a 20.5 kW (70,000 BTU/hr) intensity is applied to the cable tray for twenty minutes. The properties measured during the test are the damage length and the after-flame time. The cable passes the test if the char length is less than or equal to 2.5 meters from the bottom of the cable tray. (IEC Standard 332-3)

2.3.5 IEEE-383: Standard for Type Test of Class 1E Electrical Cables

The IEEE-383 standard is one of the most commonly used test procedures for electrical cables. It was originally intended for cables essential to emergency operation in nuclear power plants, but has been expanded to include non-nuclear systems.

A one-foot wide, eight-foot high vertical rack supports the test cables for this standard. The cables are placed only in the center six inches of the rack, and are spaced one-half cable diameter apart. The ignition source is a ten-inch ribbon burner with an air-propane mixture, placed two feet off the floor. The flame releases 21 kW (7,000 BTU/hr). Approximately 9 to 12 inches of cables are exposed to the direct flame for twenty minutes. If any cable propagates a flame that extends above the top of the eight-foot rack, the cable fails the test (IEEE Standard 383-1974).

2.4 Experimental Procedures

Many different procedures, often variations of the standardized test procedures, have been used by laboratories to test the integrity of electrical cables.

1. Steady State and Temperature-Controlled

2. Thermal Radiation at Constant Fluxes
3. Flammable Liquid Fires
4. Direct Flame Impingement
5. Fire Plume and Hot Gas Layer Environments

2.4.1 Steady State and Temperature-Controlled

Steady state and temperature-controlled environments are created in oven-type chambers. The cable is inserted either before or after the preheating of the chamber, depending on test specifications. For a steady-state environment, the chamber is raised to a target temperature and is held there until the cable fails. For a temperature-controlled environment, the chamber temperature is raised to a target temperature and held there for a specified period of time. If by this time the cable has not failed, the temperature is raised again, and held for that same length of time. This procedure continues until the cable has failed.

The constant-temperature oven procedure was used in thirty experiments conducted by Lukens at Sandia National Laboratories in 1982. The oven was heated to a steady temperature in the range 130 to 450°C. The cable was then inserted into the chamber. Most of the exposures lasted for sixty minutes; however, some tests lasted a shorter period of time because of cable failure. (Lukens, 1982) More recent examples include testing by Nowlen in 1991. (Nowlen, 1991)

This type of exposure environment is similar to the procedure that was used in the experiments for this project in that the environment was held at a steady-state value. The temperature was set at a particular value that yielded a desired heat flux for each test. Thermocouples were placed at a variety of locations within the apparatus and along the cable to determine the temperatures at certain times during the experiments, especially at time of failure.

2.4.2 Thermal Radiation at Constant Fluxes

Another possible test procedure is to use thermal radiation at constant heat fluxes. This method subjects a particular length of cable (this length varies depending on the size of the test chamber) to constant heat fluxes of varying magnitudes. The heat flux does not have to have an extremely high magnitude. A test with low heat flux levels "could be usable for discriminating some cables with relatively good ignition properties from those that produce stable burning behavior". (Nakagawa, 1998) The heat flux is applied until cable failure occurs. The failure time is then recorded.

Along with the oven tests in 1982, Lukens conducted ten tests that used thermal radiation as a means of creating a fire environment. The target heat fluxes for the tests ranged from 5 kW/m^2 to 40 kW/m^2. The cables were exposed for thirty minutes or until ignition (failure) occurred (Lukens, 1982).

Not just medium- or large-scale tests are used for electric cables. Small-scale tests are often used because of the reduced cost. Nakagawa conducted over thirty different tests on eight different types of cables in a cone calorimeter. The cone was held a constant heat flux (20, 30, 40, or 50 kW/m^2) until the cable ignited. Ignition did not occur at all heat fluxes for all cables. In fact, Nakagawa recommends that the heat flux be greater than 40 kW/m^2 if ignition is desired. (Nakagawa, 1998)

Determining how well small-scale tests correlate with large-scale tests is an issue. Many people would assume that higher heat fluxes would more accurately represent larger tests. However, Nakagawa showed in his cone tests that those tests using heat fluxes of 20 kW/m^2 showed good correlations to the large-scale tests. (Nakagawa, 1998) The problems in this regard appear to be more pronounced when attempting to represent the threshold heat flux conditions based on higher flux data. (Nowlen, 1988)

The constant thermal radiation procedure more accurately represents the method that was used in our study. The test apparatus is a cylindrical shroud lined with radiant heating lamps. The lamps will raise the temperature of the shroud to a chosen value that corresponded to a specific heat flux, and that heat flux was applied until the cable failed. The difference between the experiments in this study and previous tests is the magnitude of the heat flux. For our tests, the heat fluxes were brought to significantly higher values, similar to those found in an actual fire situation.

2.4.3 Flammable Liquid Fires

Flammable liquid fires are another way that laboratories have tested electrical cables. A common liquid used in cable flammability tests is heptane. It is ignited and the cable is placed in or around the flame. The fire heat release can be either controlled by the flow of the liquid or allowed to burn freely.

Flammable liquid fires have been performed at many sites. Factory Mutual Research Corporation (FMRC) conducted a set of tests on behalf of the Electric Power Research Institute (EPRI) between 1979 and 1980. The primary purpose of these tests was to provide guidance for water extinguishment of cable tray fires, but it also allowed for a better understanding of the response of electrical cables grouped in cable trays to a fire environment. The experiments used fires in 2-gallon and 4-gallon heptane pools to expose the cables to a fire environment. The cable trays were located approximately 6 inches above the ignition source. The typical 2-gallon fire burned for six minutes and released about 23,000 BTU/min. A total of seventeen tests was conducted in a very large chamber; seven free burn tests and ten tests where water was applied. (Sumitra, 1982)

This type of fire exposure was not considered for the experiments because our purpose is to determine the failure threshold of cables at steady state heat fluxes. It is more difficult to control the output of a flammable liquid fire when compared to radiant heat lamps. Another issue is the amount of fuel needed. Radiant lamps can be used repeatedly without any extra costs.

2.4.4 Direct Flame Impingement

Direct flames are also used for the testing of electrical cables because they can be the most severe type of fire exposure. When a direct flame is applied, the time to ignition is greatly reduced; cable failure occurs more rapidly. Burners are the most common method of applying a flame because they can be kept at a relatively constant temperature for the duration of the experiments.

The Boeing Commercial Airplane Company conducted flammability tests in the late 1970's. These experiments tested the cables' insulation characteristics more than the cables' electrical aspects. The circuit integrity, however, was tested and recorded. Two different types of burners were used, Fisher and Bunsen. The Fisher burner was held at 982 ± 28°C, while the Bunsen burner was kept at a slightly lower temperature of 954 ± 28°C. The burners were applied for 30 minutes or until the first failure occurred, whichever came first (Meyer, Taylor, & York, 1978).

FMRC carried out another set of fire tests for EPRI in the early 1980's. The purpose of the study was to evaluate the performance of cables in four categories, insulation/jacket degradation, ignition, electrical integrity failure, and hydrogen chloride generation. The set of experiments conducted to test the electrical integrity of the cables were performed with a pilot flame under a variety of thermal environments. A total of fourteen cables was used, with different numbers of conductors, different insulation types, and some with additives and plasticizers. All of the conductors in the cable samples were also energized to 70 Volts. (Lee, 1981)

The use of direct flame was also not considered as a means of creating a fire environment for our experiments. This type of flame tends to have short damage times due to extremely high temperatures. Another issue is that the flame can only cover a small area of cable, which does not simulate a true fire environment. In order to create an accurate environment, the fire must be big enough to expose a "non-trivial" length of cable to the flame zone.

2.4.5 Fire Plume and Hot Gas Layer Environments

Not all the cables are subjected directly to flame. Some laboratories think a more realistic approach is to put the cables within the fire plume or the hot gas layer. The fire source is placed in the vicinity of the cables and/or cable trays to create a hot, smoky environment. The test is allowed to run for a specified amount of time or it is stopped when cable failure occurs.

One particular series of tests was conducted at the Laboratory of Research and Modeling of Fires in France in 1997 ["Probability Study Program on Fire Safety"]. These experiments used five different cable bundles were placed in cable trays, each located at a different height above the fuel source, some directly above the flame level and some close to the ceiling. The initiating fire was created using 1 m^2 of Mobil DTE medium oil. The failure times of the different cable runs were recorded (Such, 1997).

The Nuclear Energy Institute and Electric Power Research Institute conducted another set of tests at Omega Point Laboratory in cooperation with Sandia National Laboratories from January to May of 2001. Eighteen cables configurations were tested using single cables and cable bundles. The exposure fire was created using a propane gas diffusion burner and the strength of the fire was controlled by the flow rate of the propane gas. The heat release rate ranged from 70 to 350 kW. The cables were placed in a cable tray and the type of fire exposure (plume or hot gas layer) determined the location of the burner. The exposure time lasted from forty minutes to two hours, depending on whether the cable failed. (Wyant and Nowlen, 2002 and EPRI, 2002)

Nakagawa performed experiments in 1997, which also used a fire plume/hot gas layer exposure as a means of testing cables. The test procedure was adapted from a draft of DIN 22 118, first developed for conveyor belt fire testing. The experiments were conducted in a horizontally ventilated duct 3.5 meters by 3.5 meters in size. The initial airflow speed for the vent was about 0.5 m/s. A propane gas burner with a gas flow rate of 2.5 liters/min created a heat release rate of approximately 3.9 kW. The fire was held for fifteen minutes. (Nakagawa, 1998)

Plume exposure was not specifically considered for our study because it is difficult to control the temperatures in a fire plume. The temperatures range from very hot near-flame to gas layer temperatures. The positive thing about using this type of exposure is that it is possible to reach the damage thresholds while the times to failure will be longer than direct flame impingement. However, this study focuses on damage heat fluxes and temperatures, which cannot be accurately controlled in a plume environment.

The tests generally run for the hot layer type of exposure use a relatively small fire (approximately 1 MW) in a large room made of concrete. The hot gas layer temperatures produced from this fire rarely reach flashover, which means that little or no cable damage is predicted. The hot layer also differs from the plume because the air is not as turbulent in the hot layer so the convective heat transfer is decreased. (Nowlen email, 18 Sep 2002)

2.5 Data Comparison

2.5.1 Issues with Direct Comparison

The tests described above have yielded data relevant to this project. A problem exists, however, in trying to directly compare the data from different tests. Each set of experiments has a particular set of failure characteristics or failure modes. Some failure modes used previously are ignition of the cable jacketing or insulation, short-circuiting, and a reduction in insulation resistance. This means that for a particular fire exposure, the failure times can vary greatly. The tables in the following two sections give the failure times for certain insulation materials and the failure mode for each time.

2.5.2 Tabulated Data

2.5.2.1 Thermoplastics

As previously stated, thermoplastics become soft and deformed when heated. Table 2-3 presents the failure times for thermoplastics subjected to a steady state environment. Two different failure modes are used for these tests. The failure times range from 13 seconds to slightly over 11 minutes and the temperatures reached 450°C. The heat fluxes, however, are kept at higher levels, around 50 kW/m^2.

Table 2-3 Thermoplastics at Steady State

Insulation Material	Exposure Time	Exposure Temperature (°C)	Exposure Flux (kW/m^2)	Failure Time (seconds)	Failure Mode	Reference
PE/PVC		250		412 +/- 264	Conductor to Conductor Short	[Chavez, 1984]
PE/PVC		350		250 +/- 85	Conductor to Conductor Short	[Chavez, 1984]
PE/PVC		450		121 +/- 23	Conductor to Conductor Short	[Chavez, 1984]
PE/PVC	60 mins	130				[Lukens, 1982]
PE/PVC	30 mins		8			[Lukens, 1982]
PVC			20	61	Cable Ignition	[Nakagawa, 1998]
PVC			30	34	Cable Ignition	[Nakagawa, 1998]
PVC			40	17 - 26	Cable Ignition	[Nakagawa, 1998]
PVC			50	13 - 22	Cable Ignition	[Nakagawa, 1998]
PE			20	395	Cable Ignition	[Nakagawa, 1998]
PE			30	142	Cable Ignition	[Nakagawa, 1998]
PE			40	54	Cable Ignition	[Nakagawa, 1998]
PE			50	35	Cable Ignition	[Nakagawa, 1998]

Table 2-4 provides the failure times for cables exposed to a plume or transient environment. The failure mode for all of these tests was some type of an electrical short. The times to failure for this type of environment are much longer, which was expected. They range from 4.9 minutes to 49.5 minutes.

The difference between insulation materials is much more apparent in the transient case. For example, the failure times for polyethylene (PE) range from 5.3 minutes to 14.2 minutes. However, the times for polyvinylchloride (PVC) vary from 12.2 minutes to 49.5 minutes. The difference in this case is most likely due to the test procedure. The PVC cables are subjected to much lower heat fluxes than the PE cables, which would decrease the time to failure.

The failure temperatures given in the literature for the thermoplastic materials are approximately 138 to 460°C. 460°C is a high failure temperature for a thermoplastic material, which generally fails at temperatures as low as 250°C.

Table 2-4 Thermoplastic at Plume/Transient Exposure

Insulation Material	Exposure Time	Exposure HRR (kW)	Failure Temp. (°C)	Failure Flux (kW/m^2)	Failure Time (seconds)	Failure Mode	Reference
PE/PVC			138 - 152		291	Cond. to Cond. Short	[Wheelis, 1986]
PE					614 - 735	Short	[Chavez, 1982]
PE	30 mins	145			850	Short	[Wyant, 2002]
PE	60 mins	200			315	Short	[Wyant, 2002]
Tefzel	40 mins	145			1032	Cond. to Cond. Short	[Wyant, 2002]
Tefzel	45 mins	200			1700	Cond. to Cond. Short	[Wyant, 2002]
PVC			370 - 460		732 – 1314 (Avg = 924)	Short	[Such, 1997]
PVC			230 - 250	5.4	1668 – 2898 (Avg = 2454)	Short	[Such, 1997]
PVC			215 - 235	5 - 5.4	2010 – 2970 (Avg = 2532)	Short	[Such, 1997]

The results of tests that subject thermoplastic-insulated cables to a direct flame environment are given in Table 2-5. As expected, the failure times are much shorter for direct flame exposure. The failure times start as soon as 6 seconds and reach as long as 16.5 minutes.

Some of the times for the polyethylene cables may be questionable, however. First of all, it is unlikely that for one particular cable the times to failure would range from 1.3 minutes to almost 16.5 minutes, especially for such a repeatable exposure. Secondly, a failure time of 16.5 minutes seems quite long for a severe exposure like a direct flame. More information should be determined for these tests if the results are going to be used for other purposes.

Table 2-5 Thermoplastics under Direct Flame Environment

Insulation Material	Flame Temperature (°C)	Failure Flux (kW/m^2)	Failure Time (seconds)	Failure Mode	Reference
PE	954 +/- 28		3	Short	[Meyer, 1978]
PE	982 +/- 28		80 - 987	Short	[Meyer, 1978]
PE		24		Cond. to Cond. Short	[Meyer, 1978]
Teflon	954 +/- 28		22 - 29	Short	[Meyer, 1978]
Polypropylene	982 +/- 28		684	Short	[Meyer, 1978]
Tefzel	954 +/- 28		6-14	Short	[Meyer, 1978]
Tefzel	982 +/- 28		39	Short	[Meyer, 1978]
PVC	954 +/- 28		4-41	Short	[Meyer, 1978]

2.5.2.2 Thermosets

Thermoset materials become rigid and form a char when they are heated. Table 2-6 gives the failure times for cross-linked polyethylene (XLPE) in steady-state environments. The failure times for this material ranged from a mere 13 seconds to approximately 20 minutes. Like the thermoplastic materials, two failure modes were used in these steady-state tests. The heat fluxes are again kept below 50 kW/m^2, similar to the thermoplastics.

Table 2-6 Thermosets under Steady State

Insulation Material	Exposure Time	Exposure Temperature (°C)	Exposure Flux (kW/m^2)	Failure Time (seconds)	Failure Mode	Reference
XLPE		350		794 +/- 415	Cond. to Cond. Short	[Chavez, 1984]
XLPE		450		241 +/- 68	Cond. to Cond. Short	[Chavez, 1984]
XLPE		500		196 +/- 59	Cond. to Cond. Short	[Chavez, 1984]
XLPO	60 mins	250				[Lukens, 1982]
XLPO	30 mins		18			[Lukens, 1982]
XLPE			20	85 - 553	Cable Ignition	[Nakagawa, 1998]
XLPE			30	35 -167	Cable Ignition	[Nakagawa, 1998]
XLPE			40	18 - 54	Cable Ignition	[Nakagawa, 1998]
XLPE			50	13 - 31	Cable Ignition	[Nakagawa, 1998]

The results of tests where thermoset materials were subjected to plume or transient environments are given in Table 2-7. The failure times for these materials range from 8.2 minutes to 52.2 minutes. The higher failure times are associated with heat release rates that vary between 145 and 450 kW. Cables insulated with ethylene propylene rubber (EPR) have the highest average failure time compared to other thermoset materials. The failure temperatures for the tested thermoset materials begin at 249°C and reach 395°C.

Table 2-7 Thermosets under Plume/Transient

Insulation Material	Exposure Time	Exposure HRR (kW)	Failure Temp. (°C)	Failure Time (seconds)	Failure Mode	Reference
XLPE	80 mins		325 - 330		Cond. to Cond. Short	[Nowlen, 1991]
XLPE	75 mins	145		2751	Cond. to Cond. Short	[Wyant, 2002]
XLPE	60 mins	145		1000	Cond. to Ground Short	[Wyant, 2002]
XLPE	50 mins	Variable (350/200/450)		2020	Short	[Wyant, 2002]
XLPE			249 - 277	491	Cond. to Cond. Short	[Wheelis, 1986]
XLPE			374 - 378		Insulation Resistance ? 1kΩ	[Jacobus, 1991]
EPR			366 - 395		IR ? 1kΩ	[Jacobus, 1991]
EPR	80 mins		365 - 370		Cond. to Cond. Short	[Jacobus, 1991]
EPR	75 mins	145		2751	Cond. to Cond. Short	[Wyant, 2002]
EPR	66 mins	350		3134	Cond. to Cond. Short	[Wyant, 2002]
EPR	60 mins	145		1000-1753	Short	[Wyant, 2002]
EPR	50 mins	Variable (350/200/450)		2020	Short	[Wyant, 2002]
SR			396		IR ? 1kΩ	[Nowlen, 1991]
XLPO			254 - 267		IR ? 1kΩ	[Nowlen, 1991]
EPDM			370 - 372		IR ? 1kΩ	[Nowlen, 1991]

As previously noted, with the thermoplastic materials, the shortest failure times are generally given with direct flame impingement. According to Table 2-8, the times to failure range from 1.75 to 21.2 minutes, with an average failure time of 14.7 minutes.

Table 2-8 Thermosets under Direct Flame

Insulation Material	Flame Temperature (°C)	Failure Flux (kW/m^2)	Failure Time (seconds)	Failure Mode	Reference
XLPE		19		Conductor to Conductor Short	[Lee, 1981]
EPR		9-17		Conductor to Conductor Short	[Lee, 1981]
EPR	954 +/- 28		105	Short	[Meyer, 1978]
EPR	982 +/- 28		1259	Short	[Meyer, 1978]
SR	954 +/- 28		1270	Short	[Meyer, 1978]
Asbestos	954 +/- 28		896	Short	[Meyer, 1978]

2.6 Data Evaluation

According to the above data, the thermoset materials seem more resistant to fire environments. For each type of exposure - steady state, plume/transient, and direct flame - the thermosets had higher average times to failure. Damage thresholds for thermoplastics also appear substantially lower than those of most thermosets.

2.7 Conclusions

As previously stated, the purpose of this literature review was to determine what information is not covered by the previous electrical cable tests. By tabulating the data it has been determined that several areas could be covered by the upcoming experiments. Previous tests have only reached temperatures of up to 500°C except the direct flame impingement. Although these temperatures are often indicative of flashover, they are not representative of actual fire temperatures. The apparatus for the experiments in this project can reach temperatures of up to 1200°C, and can be held for longer periods of time at levels up to 1000°C.

Another area not covered well by previous tests is exposure to heat flux. While some tests have exposed cables to heat fluxes up to 50 kW/m^2, these fluxes are not as severe as the fluxes that might be given off in a fire environment. The effect of higher fluxes will also be examined in subsequent tests.

Thermosetting plastics were not examined as often as the thermoplastic insulation materials. This project is going to focus on the thermoset insulations.

2.8 Works Cited in Literature Review

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3 Methodology

The methodology for this set of experiments consists of the test plan, the operating procedure, and the failure criteria during the testing as well as the criteria during data reduction.

3.1 Test Plan

After the literature review was completed, a test plan was constructed that filled in as well as extended the current literature data.

3.1.1 Number of Tests

Forty-three tests were completed. Typically, two tests were run per day at the beginning; towards the end of the program, up to three to four experiments were performed daily. At approximately halfway through testing, the collected data was reviewed to prioritize the remaining tests so the greatest amount of useful data could be collected.

3.1.2 Cable Insulation Materials

It was evident from the literature review that the previous test experiments favored thermoplastic insulation materials, such as polyethylene (PE) and polyvinylchloride (PVC). For this reason, three thermoset materials were chosen for the test program, ethylene-propylene rubber (EPR), cross-linked polyethylene (XLPE), and silicone rubber. These three materials are often used in a typical nuclear power plant. (DuCharme, 1988) However, because of lead time and delivery issues, the silicone rubber cables were not tested. The same type of jacketing was used for all of the cables, chlorosulfonated polyethylene (CSPE), also common to nuclear power plants.

3.1.3 Exposure Temperatures/Fluxes

In the initial stages of the testing program, the shroud exposure heat fluxes (temperatures) were 8 kW/m^2 (350°C), 14 kW/m^2 (450°C), 23 kW/m^2 (550°C), and 97 kW/m^2 (900°C). These exposure heat fluxes were sufficient to fill in some of the missing low flux data, but also to extend into the higher flux area. After several tests it was evident that the fluxes were not causing enough cable failures to produce a statistically significant sample for the determination of possible failure criteria. (Nicolette email, 2004) Therefore, the heat fluxes (temperatures) were changed to 14 kW/m^2 (450°C), 18 kW/m^2 (500°C), 30 kW/m^2 (600°C), 56 kW/m^2 (750°C), and 97 kW/m^2 (900°C). These values provided more original data and covered a wider spectrum of exposure. Note that the exposure heat flux is measured at the surface of the shroud and not at the surface of the electrical cable.

3.1.4 Cable Function

In previous experimental programs the focus has been on control and light power cables. For this reason, this program concentrated on power cables as well as control cables for comparison. The power cables were 3-conductor, 8 AWG cables, which would typically be used for light duty applications such as motor operated valves, small fan motors, or small fan pumps (<15 HP, 480 Volt). (Wyant email, 2004) The control cables were 7-

conductor, 12AWG cables. For a more in-depth description of gauge sizes, see Section 2.2.1.

3.1.5 Routing Configuration

The configurations used for this cable program were a combination of single cable, multiple cable, open ladder cable tray, and conduit. The cable trays were six-inches wide with six-inch rung spacing. The conduit was a 2” diameter, galvanized steel conduit. Only straight cable runs were used for both the tray and conduit configurations, so no mechanical stress points (bends) were present to affect the failure times.

3.1.5.1 Single Cables

The first section of the program consisted of single cables in cable trays. Tests labeled “single cable” actually used two cables of the same size and insulation material. One cable was instrumented with thermocouples to measure the temperature under the jacketing. The other cable was connected to the insulation resistance (IR) measurement system to monitor the leakage current of the cable. Figure 3-1 shows the arrangement of the single cable test in the cable tray. The cable on the left was instrumented with thermocouples and the cable on the right was connected to the IR system. While the cables were not placed in any particular location in the tray, they were not touching one another. Although highly unlikely, it is possible that voltage from the IR system could affect the other cable.

Figure 3-1 Single Cable Experiment in Cable Tray

Figure 3-2 and Figure 3-3 show the cable tray placed inside the PENLIGHT apparatus. The tray is located in the center, both vertically and horizontally, and affixed to stands at each end to keep it immobile during test preparation and the test itself. Insulation board (Figure 3-4 and Figure 3-5) was placed at the end of the apparatus so hot air could not exit.

Figure 3-2 Single Cable Experiment in PENLIGHT, front view

Figure 3-3 Single Cable Experiment in PENLIGHT, side view

Next, single cables were tested in conduits. The cables were both placed into the conduit. Though they could not be kept separate because of the curvature of the conduit, no problems were encountered with the insulation resistance system. Figure 3-4 shows one piece of insulation board and its location inside PENLIGHT. Because the board needed to be secure, it could not be placed at the end. It was held in place with small metal clips. Figure 3-5 is a picture of the two pieces of board put together. The conduit was also placed on stands and secured.

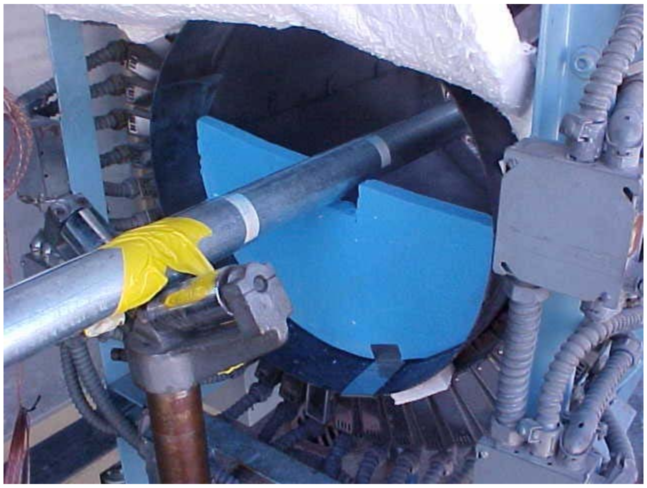

Figure 3-4 One Piece of Insulation Board in PENLIGHT

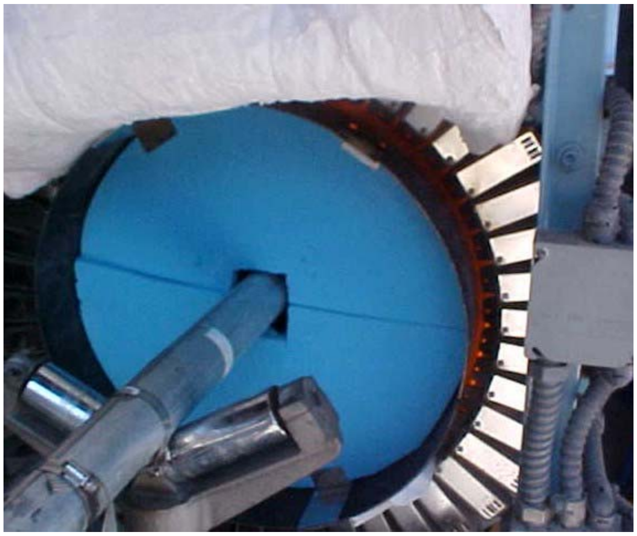

Figure 3-5 Insulation Board in PENLIGHT

3.1.5.2 Multiple Cables

After the single cable tests, the next step was to conduct multiple cable tests. The only configuration possible for these tests was the cable tray; the conduit was too small to contain a bundle of cables, especially the 8AWG cables. In an actual nuclear power plant, cables are piled into a tray with no particular order, and hundreds of cables might be in one tray. For this program, the cables were arranged in a 2-cable by 3-cable matrix. Figure 3-6 illustrates the matrix. The blue circles indicate the cables connected to the insulation resistance system. The red circles signify cables instrumented with thermocouples. The two cables at the bottom of the arrangement were surrogate cables to shield the center cables from direct heat flux.

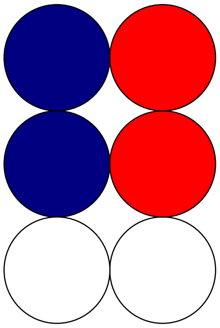

Figure 3-6 Multiple Cable Experimental Setup

To hold the cable bundle together, small metal plates were used at two locations equidistant from the center of the cable, where the hottest location was assumed to be. Insulation blanket was wrapped around the bundle to keep the plates from heating the cable prematurely. The plates and blanket were both secured with thin metal wire. Figure 3-7 and Figure 3-8 show the multiple cable bundles.

Figure 3-7 Multiple Cable Bundle, Side View

Figure 3-8 Multiple Cable Bundle, Top View

The center of each piece of insulation blanket was ten inches from the center of the cables, as shown in Figure 3-9. Pieces of fiberglass tape were placed at other locations to hold the bundle together without changing the surface area open to heat flux. While the metal plates and tape held together the cables outside the apparatus, it was impossible to predict how the cables would act once a heat flux was applied.

Figure 3-9 Multiple Cable Bundle, Overhead View

3.1.6 Diagnostic Monitoring

The cables were connected to an insulation resistance system as well as instrumented with thermocouples, to monitor progress.

3.1.6.1 Insulation Resistance Monitoring System

This section will discuss the way in which the cables were connected to the insulation resistance system. A separate section of the report will examine the actual method by which the system works from an electrical point of view. Previous experiments by Wyant and Nowlen have used this system to monitor the insulation resistance. (Wyant and Nowlen, 2002)

Wiring harnesses connected the instrumentation cabinet to the cable. The harnesses can be attached to a minimum of 2 maximum of 10 conductors. The conductors on each of the wiring harnesses were numbered from one to ten, each conductor of the cable was given a number, and one harness was connected to each end using a wire nut as shown in Figure 3-10. The other end of the wiring harness was plugged into a coordinating location at the back of the instrumentation cabinet.

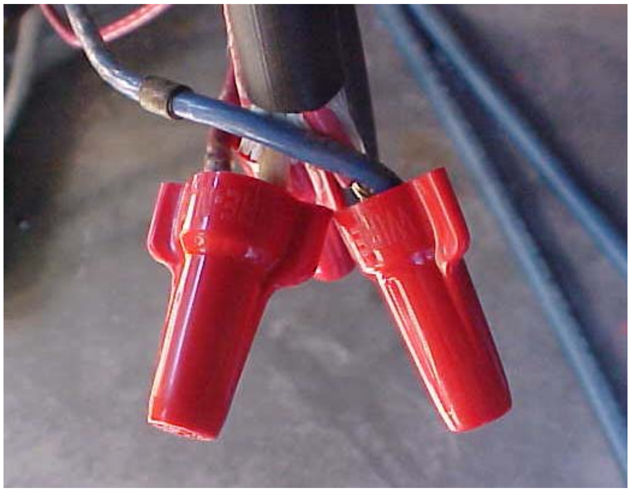

Figure 3-10 Wire Nut Connections

3.1.6.2 Thermocouple Insertion

The thermocouples are used to measure the temperature of the cable under the jacketing. Type K thermocouples, made of a positive Chromel wire and a negative Alumel wire, were used for this program. These thermocouples are widely available because they are the most popular type, have a wide range of measurement, and good temperature precision. The insertion process is outlined in this section.

One of the thermocouples was placed in the center of the cable, and two locations ten inches from either side of center were marked. The remaining two thermocouples were placed at these marks. To place them accurately, a slice was cut through the jacketing to the inside of the cable.

Figure 3-11 is a picture of a slice in a representative cable, not one of the actual program cables. The blue material is nylon filler; the black strip inside the cable is one of the conductors. It is important to put all of the slices on the same side of the marks. All of the thermocouple wires should run in the same direction so they can be hooked into the data acquisition system easily.

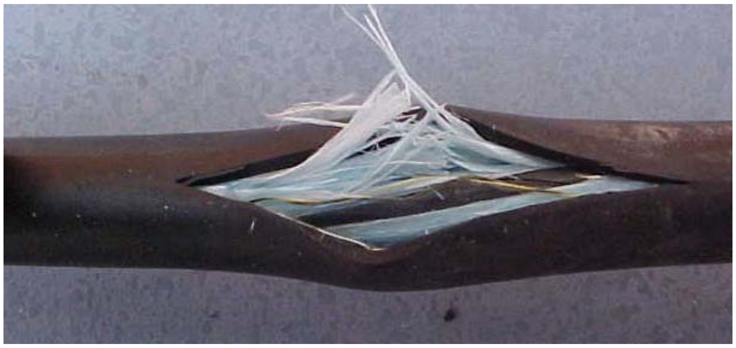

Figure 3-11 Slice in Jacketing

Once the slices are made, the tips of the thermocouples were slid under the jacketing, in the area of the filler material. If no filler material exists, the thermocouple should be placed between the jacketing and the conductor insulation. If the cable is extremely tight, it is easiest to slide the thermocouple in the area between conductors. The most important part of the insertion is that the tip of the thermocouple rests underneath the mark. The distance between thermocouple tips was ten inches.

Figure 3-12 shows the thermocouple being inserted into the cable. The filler material is pulled back for a better view.

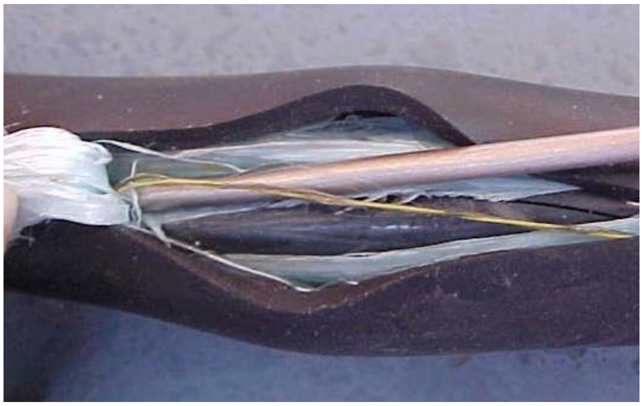

Figure 3-12 Thermocouple Insertion

Once the thermocouple was inserted, it was secured with fiberglass tape. The tape was wrapped around the cable to close the slit and hold the thermocouple in place. An example of the fiberglass tape wrapping is shown in Figure 3-13. The thermocouple is exiting the tape on the right side of the picture.

Figure 3-13 Fiberglass Tape

Figure 3-14 shows the cable with three thermocouples inserted. The outer thermocouples rested close to the insulation board and the center thermocouple was in the middle of the shroud. Extra tape was used to hold the thermocouples in place.

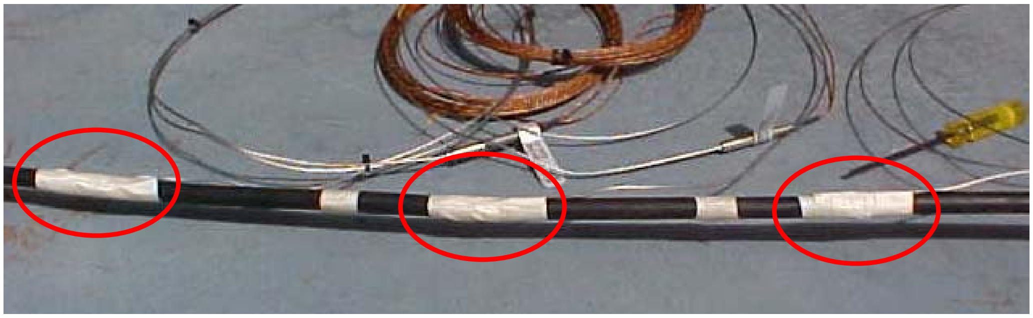

Figure 3-14 Thermocouples in Cable

3.1.7 Failure Modes

There are three primary modes of failure for electrical cables: conductor-to-conductor, conductor-to-ground, and cable-to-cable. For most of the tests in this program, only the first two modes could be observed. The cable-to-cable mode could only be seen in the multiple cable experiments.

Conductor-to-conductor failure occurred when the insulation between conductors deteriorated, allowing contact between the metals. Conductor-to-ground failure occurred when the insulation on a conductor and the jacketing material wore off, allowing contact between the conductor metal and the ground. The ground differs for each test program. For this test program, the ground was either the cable tray or the conduit. The cable-to-cable failure mode could only happen in the multiple cable tests. It occurred when conductors in two different cables came in contact. The insulation on both conductors and the jacketing on the cables had to deteriorate before this could happen.

It was possible for more than one of these modes to occur in a single test. Generally, conductors in a single cable will short together before they short to ground or to conductors in another cable.

3.2 Operating Procedure

For all the tests, a general procedure was followed to ensure repeatability. The procedure was separated into three distinct segments: pre-test, test, and post-test.

The pre-test tasks included cable instrumentation, conduit/tray instrumentation and insertion, and data acquisition setup. During the test, the single task is monitoring all data acquisition to ensure proper operation and to observe the data being collected. The post-test tasks were data collection and storage, and instrumentation and apparatus cleanup.

A complete list of tasks can be found in the checklist in Appendix A: Cable Test Procedure Checklist.

3.3 Failure Criteria

During the experiments, criteria were followed to determine when the tests should be stopped. A different set of criteria was used during data reduction to determine the time to cable failure.

3.3.1 Criteria During Experiments

Two criteria were used during testing to determine when the test should be stopped. The first was a time limit and the second was a specific value on the insulation resistance.

The time limit for the test was one hour; if the cable had not failed before this time, the test would be terminated. If obvious degradation began close to the time limit, the test would be allowed to continue until failure occurred or until ninety minutes. This was not an issue during this test program, however. Failure was either rapid or it did not occur.

The other criterion was based on the values read off the insulation resistance system. Two voltmeters displayed the measurement readings and a 120VAC source energized the conductors. If both voltmeters read ~60 Volts, then the conductors had shorted together. If one of the meters read ~120 Volts while the other was ~0 Volts, then the conductor had shorted to ground. Once the cable had shorted to ground, the test was terminated.

3.3.2 Determination of Post-Test Criteria

In previous electrical cable experimental programs, there had not been one consistent failure criterion. Each program defined failure in a different way. The various criteria include cable ignition, flame propagation, reduction in insulation resistance, etc. Based on the available literature data, the goal of the particular program determined the criteria used, and it was not evident if any of the criteria was “better” than others.

For this cable program, insulation resistance was used to determine the time to failure. However, whether the criteria would be a particular value of resistance, a drop in resistance, or something else, was unknown. To determine which criterion would be the “best”, three different criteria were examined; when the insulation resistance dropped below 1000 Ohms, when the insulation resistance dropped one order of magnitude from the initial value, and when the insulation resistance dropped two orders of magnitude.

Figure 3-15 shows the results for the EPR insulation, 7-conductor cable at 900°C. This graph illustrates that the decision for a failure criterion is somewhat arbitrary, because the insulation resistance initially drops quite rapidly and then begins to level off. The initial value for resistance and the rate of resistance decrease varies from cable to cable. If a low value is chosen, it may take a while for the failure time to be reached, especially if the resistance begins to level off and the rate of resistance decrease approaches zero.

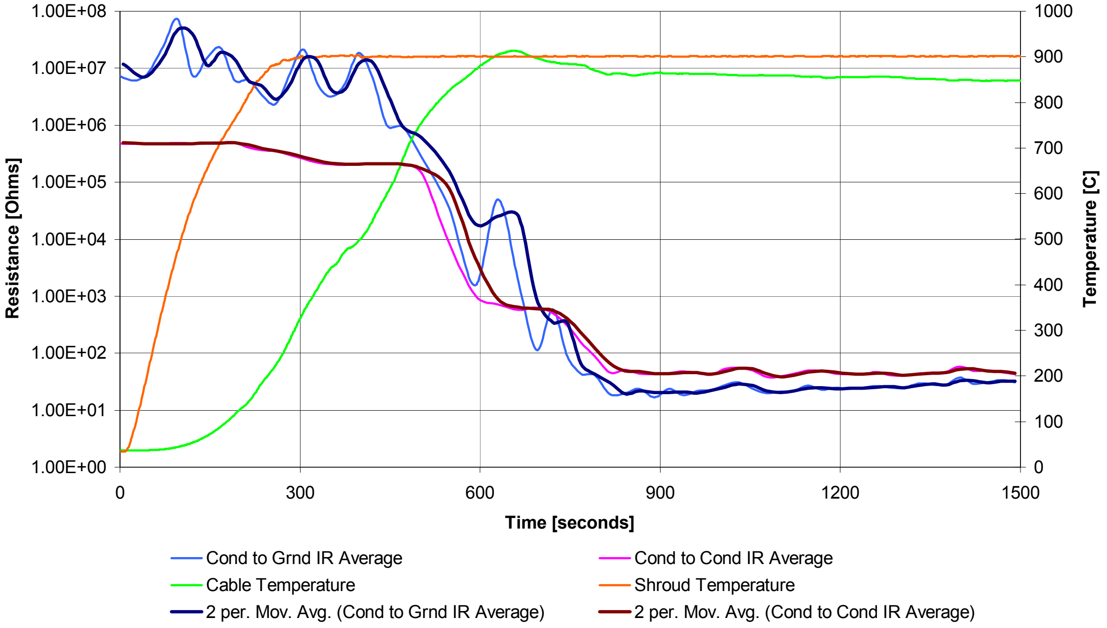

Figure 3-15 Cable Test Results for EPR 7-conductor at 900°C

Forty-three total experiments were run, some cables with cross-linked polyethylene (XLPE) insulation and some with ethylene propylene rubber (EPR) insulation. The time to failure for each test for each of the above criteria was determined using the insulation resistance results. For the analyses, the insulation materials were kept separate. The times to failure were plotted on a logarithmic scale versus the exposure heat flux for each of the criteria. This particular fit may not have been the best for each individual graph; however, it was the best overall fit, which kept the resulting graphs consistent, making comparison rather straightforward.

Figure 3-16, depicts the cable failure temperature versus the heat flux for the XLPE insulation.

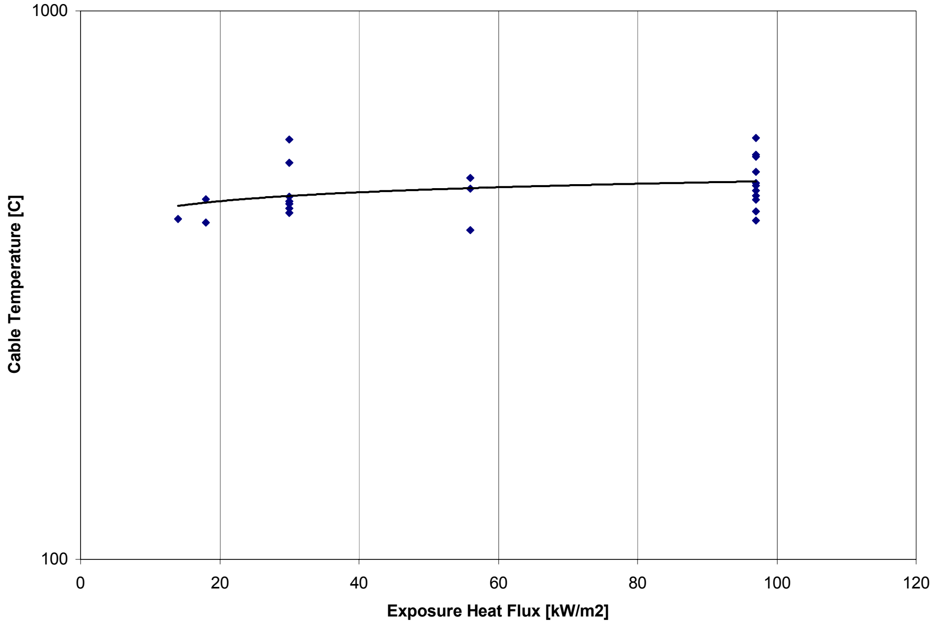

Figure 3-16 Cable Failure Temperature versus Exposure Heat Flux for XLPE insulation

The superimposed line is a logarithmic trend line that fits the data. The equation of the trend line is given as

$$T_{cable} = 30.478 * \ln(\dot{q}'') + 358.21,$$

Equation 3-1 Equation for Cable Failure Temperature versus Exposure Heat Flux Trendline Data

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where $\dot{q}''$ is the exposure heat flux [kW/m^2] and t_f is the time to failure [seconds]. This is just one example of why this criterion was the best choice. The XLPE time to failure and the EPR results are presented in a later section.

3.3.3 Post-Test Criteria

During the data reduction phase, the temperature data and the insulation resistance data were combined to determine the time to failure and the cable temperature at failure. The time to failure occurred when the insulation resistance dropped one order of magnitude from its original value, which was determined to be the best criterion for this experimental project. This time to failure was used to determine the cable failure temperature.

4 PENLIGHT Apparatus

This section describes the operation of the PENLIGHT apparatus used for the cable test program.

4.1 Apparatus Dimensions and Views

Known as the PENLIGHT Facility, the apparatus is a cylindrical shroud lined with radiant heating lamps that run length-wise. Figure 4-1 shows the dimensions of the end caps of PENLIGHT; 0.52 meters (20.4 inches) is the diameter of the interior surface of the shroud. The right and left end caps are thermally insulated and can be assumed to be adiabatic.

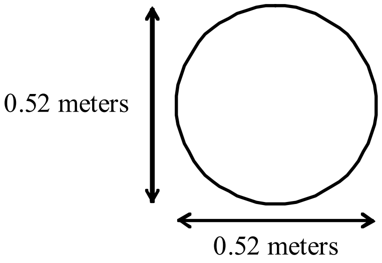

Figure 4-1 End Dimensions of the PENLIGHT Apparatus

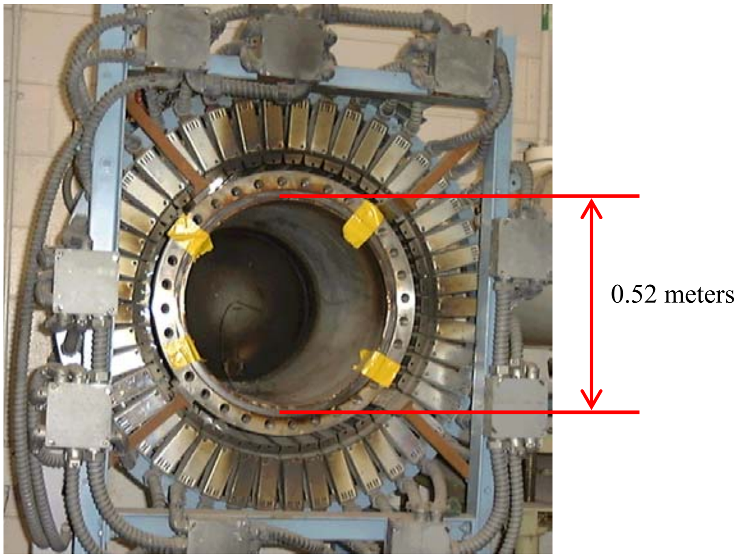

Figure 4-2 End View of PENLIGHT

Figure 4-2 shows an end view of PENLIGHT.

Figure 4-3 shows the dimension of the apparatus from end to end. The red lines represent the orientation of the radiant lamps. The shroud can hold a specimen 0.81 meters (32 inches) long. As seen in Figure 4-4, PENLIGHT is a mobile unit, but it is very heavy so movement is generally limited.

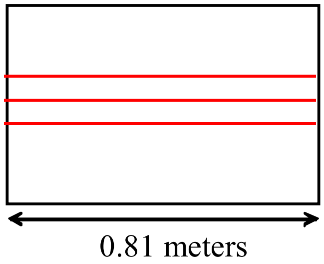

Figure 4-3 Side Dimensions of the PENLIGHT Apparatus

Figure 4-4 Side View of PENLIGHT

4.2 Apparatus Operation

The lamps in PENLIGHT can be controlled to maintain a fixed shroud temperature. If a test is going to be run for an extended period of time, the apparatus can be held at temperatures of up to 1000°C (possibly 1100°C). In previous experiments, the shroud reached temperatures of 1200°C, but was not held there for any length of time. Figure 4-5 and Figure 4-6 show the appearance of PENLIGHT during its operation.

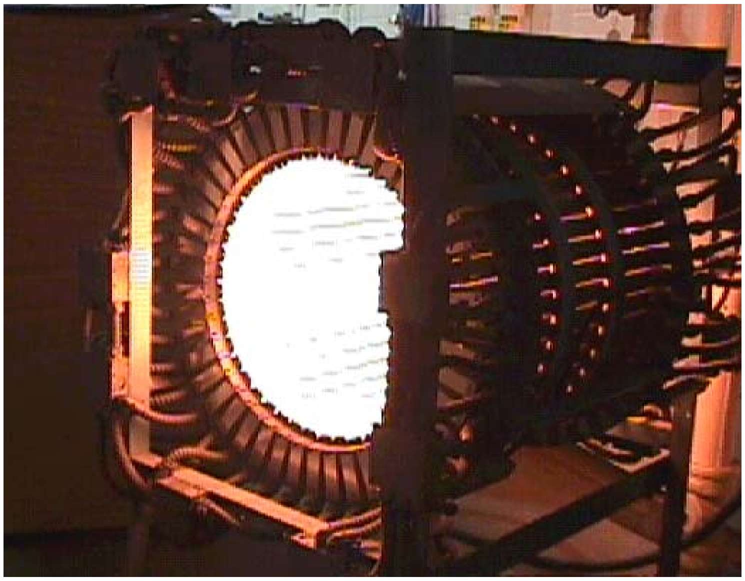

Figure 4-5 Side View of PENLIGHT during Operation

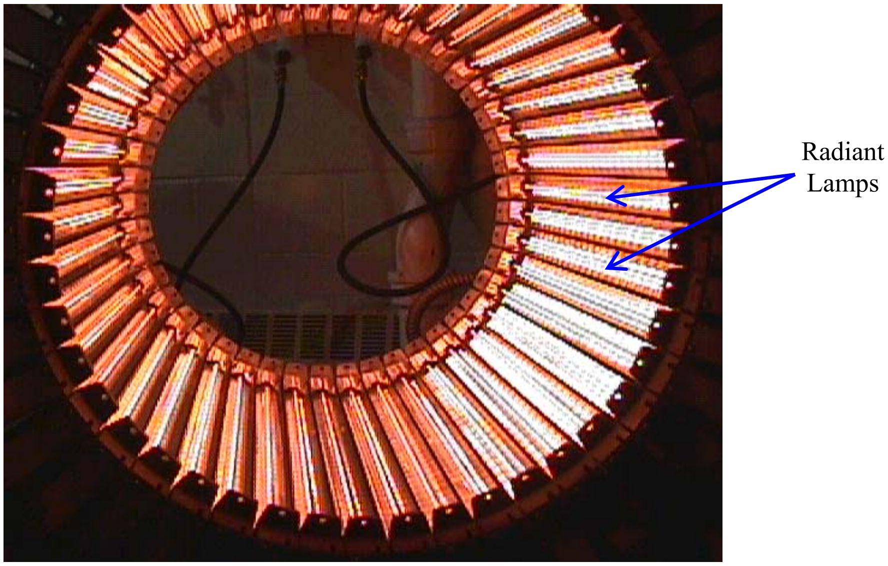

Figure 4-6 End View of PENLIGHT during Operation

4.3 Other Considerations

One important consideration for the cable testing is "end effects". The cable end is open, and if placed inside the apparatus along with the rest of the cable, the conductors and inner materials are often exposed to the high temperatures or fluxes; therefore failure may occur prematurely. To ensure accurate testing, the cable ends ran outside of the shroud.

Another issue is possible temperature gradients. Calibration experiments performed at Sandia in April of 2002 proved there are "significant temperature gradients along the surface of the PENLIGHT shroud" (Kearney, 2002). These gradients along with the lower temperature of the end caps may cause the effective radiation temperature of the

PENLIGHT cavity to be lower than the desired temperature. Figure 4-7 shows the representative temperatures along the lower surface of the shroud. The two graphs show that the actual temperature can have variations as large as a few hundred degrees Kelvin on the shroud surface. It is believed that the smaller gradient from the shroud end cap will have a greater impact than the lateral surface because there is a larger view factor associated with it (Kearney email, 2002).

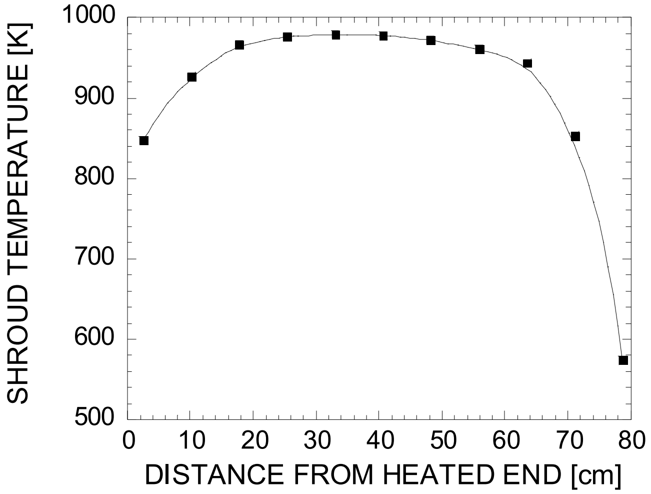

Figure 4-7 Representative Shroud Temperature Data for Lower Surface of PENLIGHT for Setpoint Temperature of 700°C

Figure 4-8 shows the representative temperatures for the end cap.

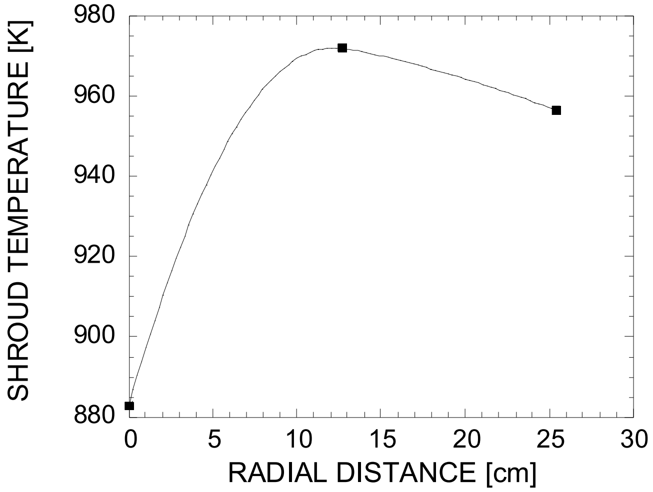

Figure 4-8 Representative Shroud Temperature Data for Heated Endcap of PENLIGHT for Setpoint Temperature of 700°C

Figure 4-7 and Figure 4-8 are Figures 4a and 4b in (Kearney email, 2002).

To determine the emissivity of the shroud, several calibration tests were run. The first test occurred on February 21, 2001. The value for the emissivity was expected to be close to

1, but the obtained value was 0.85. Because this value was so much lower than what was expected, another test was run on April 4, 2002. This test yielded a slightly higher value of 0.86, still much lower than expected. The explanation for the difference between recorded and expected is the temperature gradient along the end cap of the shroud. As a note, the emissivity of the Pyromark paint that lines the shroud is taken to be 0.95.

Another possible issue to be considered is the view factor between the shroud and the cables. In particular, this may have been a significant factor in the damage times recorded for the cable tray tests. The tray used was an off-the-shelf product, but was in fact, rather narrow in comparison to typical plant trays. The presence of the tray clearly reduced the effective rate of heat transfer from the shroud to the cables, and therefore likely delayed the onset of damage. (Nowlen email, 2004)

5 Insulation Resistance Measurement System

"The concept of the SNL IR Measurement System is based on the assumption that if one were to impress a unique signature voltage on each conductor in a cable then by systematically allowing for and monitoring known leakage current paths it should be possible to determine if leakage from one conductor to another, or to ground, is in fact occurring." (Wyant, 2003) This is the basic principle of operation for the measurement system. The method of instrumentation for the cables was presented in the Methodology, Section 3. This section will discuss, in further detail, the inner operation of the IR measurement system.

Determining the insulation resistance between two conductors involves a simple calculation using Ohm's Law,

$$I_{1-2} = \frac{V_2}{R},$$

Equation 5-1 Ohm's Law

where I is the current, V is the voltage, and R is the resistance.

Figure 5-1 (Figure 1 of Wyant, 2003) shows a simple insulation resistance measuring circuit.

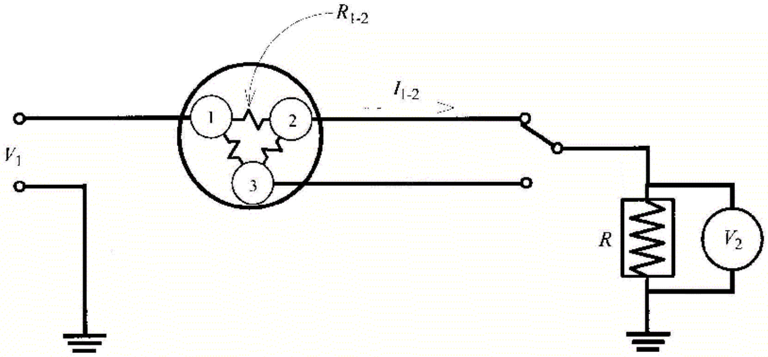

Figure 5-1 Simple Insulation Resistance Measuring Circuit

If the cable has more than two conductors, the resistance between, for example, conductors 1 and 3 can be determined by switching between the two conductors and recording the voltage drop across R as a function of time. The resistance between conductors 2 and 3 cannot be found by the above method because conductor 1 is always the energized conductor. The resistance between any two pairs of conductors can be found be "sequentially energizing each conductor and reading the impressed voltages on the remaining conductors" (Wyant, 2003).

Figure 5-2 (Figure 4 in Wyant, 2003) shows conductor 2 connected to the input side and conductor 3 connected to the measurement side.

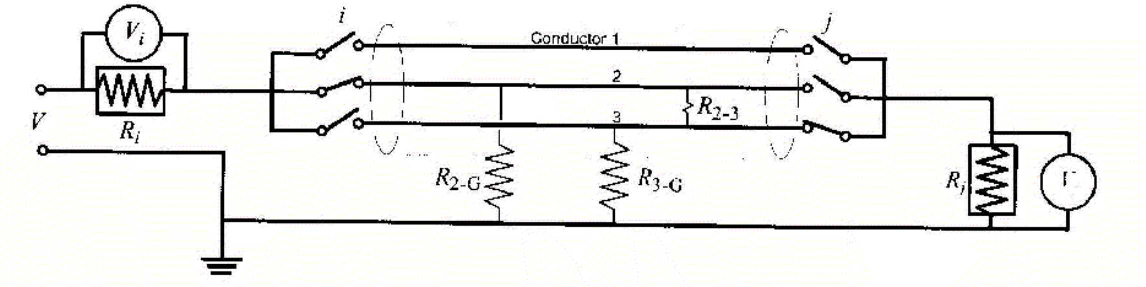

Figure 5-2 Insulation Resistance Measuring Circuit with Ground Paths

Figure 5-3 (Figure 5 in Wyant, 2003) illustrates the opposite case where conductor 3 is on the input side and conductor 2 is on the measurement side.

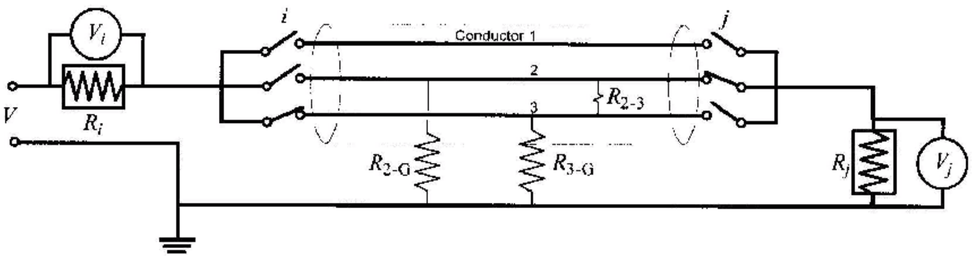

Figure 5-3 Complementary IR Measuring Circuit with Respect to the Circuit shown in

For each pair of conductors, four voltage readings are used to determine three separate resistances, $R_{2\text{-}3}$, $R_{2\text{-Ground}}$, $R_{3\text{-Ground}}$. The subscript *i* indicates the input side and subscript *j* is the measurement side. The following three equations are used to determine the three resistances (Wyant, 2003).

$$R_{2-G} = \frac{\left[V_{j2}V_{j3} - (V - V_{i2})(V - V_{i3})\right]}{\left[\left(\frac{V_{i3}}{R_i} - \frac{V_{j2}}{R_j}\right)V_{j3} - \left(\frac{V_{i2}}{R_i} - \frac{V_{j3}}{R_j}\right)(V - V_{i3})\right]}$$

Equation 5-2 Resistance between Conductor A and Ground

$$R_{3-G} = \frac{V_{j3}}{\left[\left(\frac{V_{i2}}{R_i} - \frac{V_{j3}}{R_j}\right) - \frac{(V - V_{i2})}{R_{2-G}}\right]}$$

Equation 5-3 Resistance between Conductor B and Ground

$$R_{2-3} = \frac{\left\lfloor \left(V - V_{i2}\right) - V_{j3} \right\rfloor}{\left[\left(\frac{V_{j3}}{R_{3-G}} \right) + \left[\frac{V_{j3}}{R_j} \right] \right]}$$

Equation 5-4 Resistance between Conductors A and B

The IR measurement system used by Sandia National Laboratories can examine the insulation resistance of a maximum of ten conductors. The system has the ability to test with either an AC or DC power source. Only the AC source was used for this cable test program.

5.1 Components of IRMS

There are eight major components of the system: power input panel; switching relay panels; interface patch panel; wiring harnesses; IR cable bundle; voltmeters; computer; and relay controller. Figure 5-4 is the schematic diagram (Figure 6 in Wyant, 2003).

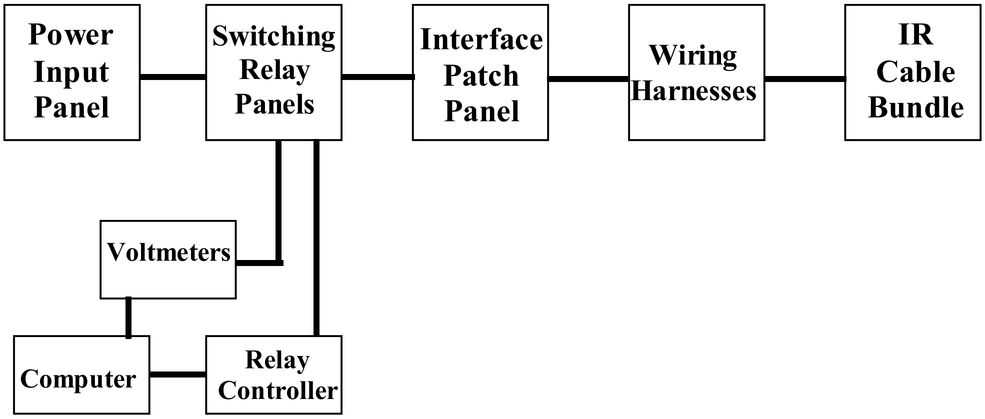

Figure 5-4 Schematic Diagram of IRMS

5.1.1 Power Input Panel

There are four elements of the power input panel: a small terminal block for connecting the input power cables; a master disconnect switch; a 5-amp fuse; and a power indicating light. If the system is changed from AC to DC operations, manual modifications are required.

5.1.2 Switching Relay Panels

There are two switching relay panels, each consisting of a 125-ohm ballast resistor.

5.1.3 Voltmeters

The system has two HP 34401A digital multimeters. Each voltmeter is connected across one of the relay panels. The voltage drop is measured across the two ballast resistors.

These meters were closely watched during tests to determine when the cables had failed. Because a standard single-phase “wall” source was used, the maximum value that a voltmeter would read is ~120 Volts. When this happens, the other voltmeter will read ~0 Volts. (Wyant email, 2004)

5.1.4 Relay Controller

An HP 3497A Data Acquisition/Control Unit connects specific conductors to the voltage source by controlling the closing and opening of the relays.

5.1.5 Computer

The controlling mechanism and data logger for the system is a standard personal computer utilizing Microsoft Windows NT™. The software program LabView™ was used for control and the collected data was saved directly into a file on the computer’s hard drive.

5.1.6 Interface Patch Panel

The interface patch panel is where the wiring harnesses are connected to the instrumentation cabinet. The wiring harness is equipped with banana plugs that can be easily connected to the jacks of the patch panel.

5.1.7 Wiring Harnesses

Two ten-conductor cables connect the IR measurement system and the test cable(s).

5.1.8 Test Cables

As previously stated, the maximum number of conductors that can be monitored is ten. This can be either in a single cable or in multiple cables. The minimum number of conductors that must be tested is two.

5.2 System Operation

The IRMS system uses LabView™ for control and data acquisition. The program first reads the date and time from the computer’s internal clock and saves this information into a data file while the program starts the voltmeters and relay controller. Then the sequential closing of relays begins. There are two voltmeter readings for each switch configuration; these readings are saved into the aforementioned data file. This process continues until the user stops the program from scanning.

In summary, while the system seems uncomplicated to use, a great deal of switching occurs in the instrumentation cabinet during an experiment. It is important for the conductors to be connected correctly or the readings will not be accurate. This can be assured by doing continuity checks with an ohmmeter during the connection process.

6 Cable Experimental Program Results

This section describes the results of this experimental test program, which utilized EPR and XLPE insulations.

6.1 Test Observations

For most of the cable tray and some of the conduit experiments, the cables caught fire and then burned for some period of time. This situation may have caused an increase in the cable temperature during the initial test stages. The jacketing material was the cause of the fire and once the combustibles in that material had burned off, there was still a char surrounding the conductors, so the thermocouple beads were still protected from the direct flux. The flames may have increased the initial thermocouple readings, but once the fire burned out, the thermocouples read more accurate inner cable temperatures.

There seems to be little effect of the results of the tests, because the fire occurs in the initial stages and subsequently burns out and also because the results of tests that did not burn were essentially the same as those that did burn; there was only a slight deviation in the times to failure and cable failure temperatures.

6.2 Typical Cable Test Results

This section describes the information gathered from a typical single cable test. During each test, the cable temperature and shroud (control) temperature were recorded as a function of time; a typical set of results is shown in Figure 6-1. The left vertical axis is the resistance in Ohms and the right vertical axis is the temperature in degrees Celsius.

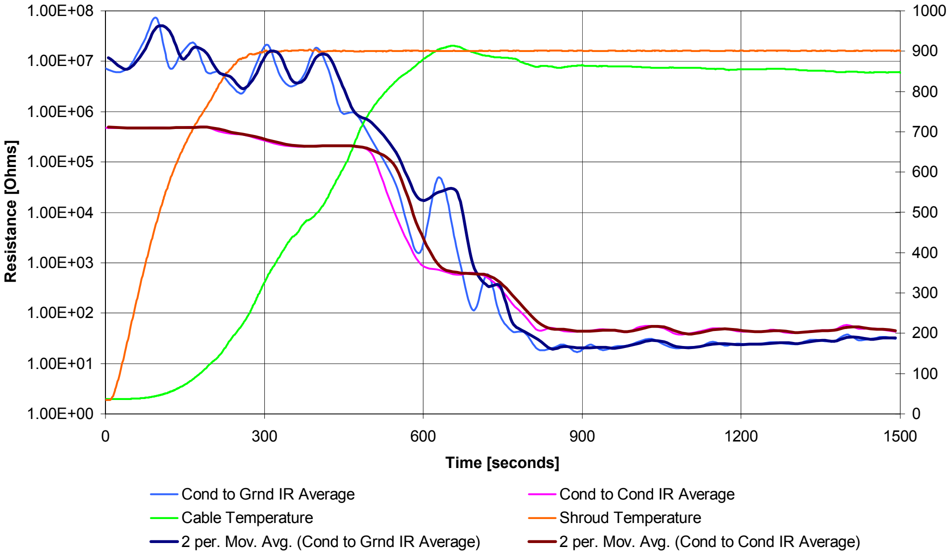

Figure 6-1 Single Cable Test Results for EPR, 7/C cable at 900°C

The orange line represents the shroud temperature. It begins at room temperature and gradually increases to the target temperature of 900°C. The green line represents the internal cable temperature. This rises slowly, along with the shroud's, close to the target temperature. The red and blue lines represent the conductor-to-conductor insulation resistance average and the conductor-to-ground insulation resistance average, respectively. The lighter lines are the actual test data, and the darker lines are the smoothed averages. The insulation resistance system does not record data points at a specific time interval, so the smoothed data provides a more accurate representation of what the cable is experiencing. The time between data points varies depending on the number of conductors being monitored.

The time to failure was determined by locating the point where the conductor-to-ground average dropped one order of magnitude. For the above test, the time to failure is 464 seconds. At this time, the cable failure temperature was 650°C. The cable did not reach the target shroud temperature of 900°C before it failed. Tabular Data for all cable tests can be found in Appendix B: Resultant Tabular Data for Cable Experiments.

6.3 Cable Tray Test Results

Two types of insulations were tested this project, ethylene propylene rubber (EPR) and cross-linked polyethylene (XLPE). Both insulations are thermoset materials that form a char when heated.

6.3.1 Ethylene Propylene Rubber

The data for thirteen cable tray tests of EPR cables is presented in this section.

6.3.1.1 Exposure Heat Flux versus Time to Failure

The time to failure of the electrical cables is important because it helps predict when the system may cease to operate. The cables provide power and control to the systems, and if they fail, the system will likely fail or be in some way inoperable.

Figure 6-2 shows the time to failure for each test for the EPR cables. The triangles represent the 7-conductor cables and the orange stars represent the 3-conductor cables. Both 7- and 3-conductor cables behaved similar when exposed to the same heat fluxes.

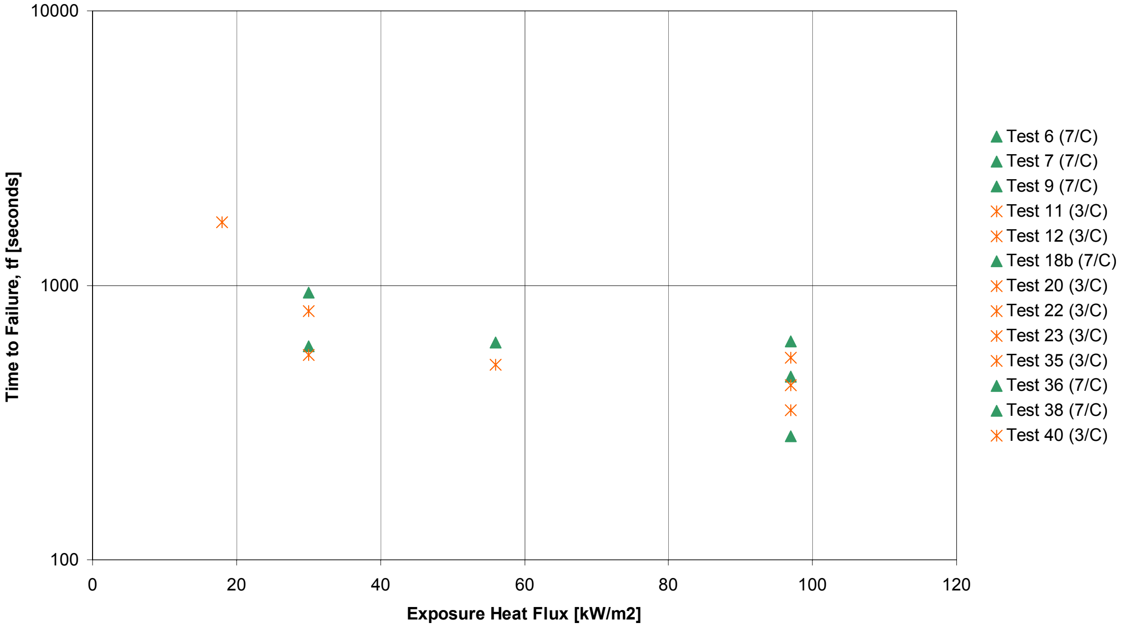

Figure 6-2 Exposure Heat Flux vs. Time to Failure Test Data for EPR

Figure 6-3 is a plot of the same data shown in Figure 6-2 except a trendline has been added.

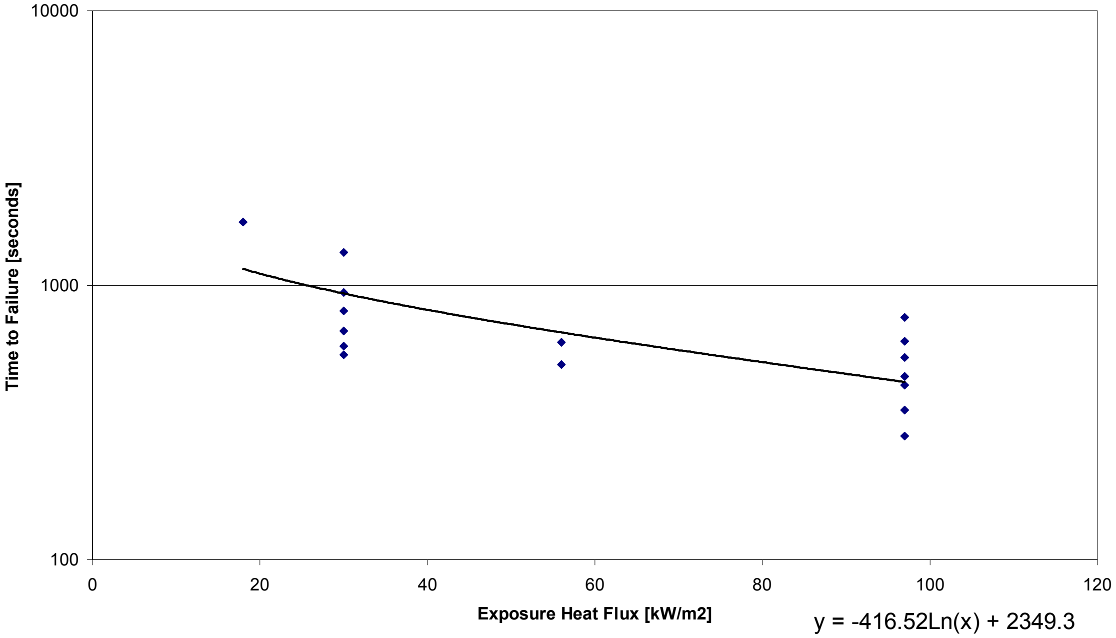

Figure 6-3 Exposure Heat Flux vs. Time to Failure Trendline for EPR

The equation for the best-fit line is given as

$$t_f = -416.52 * \ln(\dot{q}'') + 2349.3\,,$$

Equation 6-1 Trendline for Time to Failure as a Function of Exposure Heat Flux for EPR

where t_f is the time to failure and $\dot{q}''$ is the exposure heat flux. If an exposure heat flux is substituted into the equation, the result will be an approximate time to failure for an EPR cable.

6.3.1.2 Exposure Heat Flux versus Cable Failure Temperature

The cable failure temperature data for the EPR cables are presented in Figure 6-4. The data points are extremely close for each heat flux, and relatively no difference exists between the 3-conductor and the 7-conductor cables. The maximum standard deviation for any given heat flux is 14.1%.

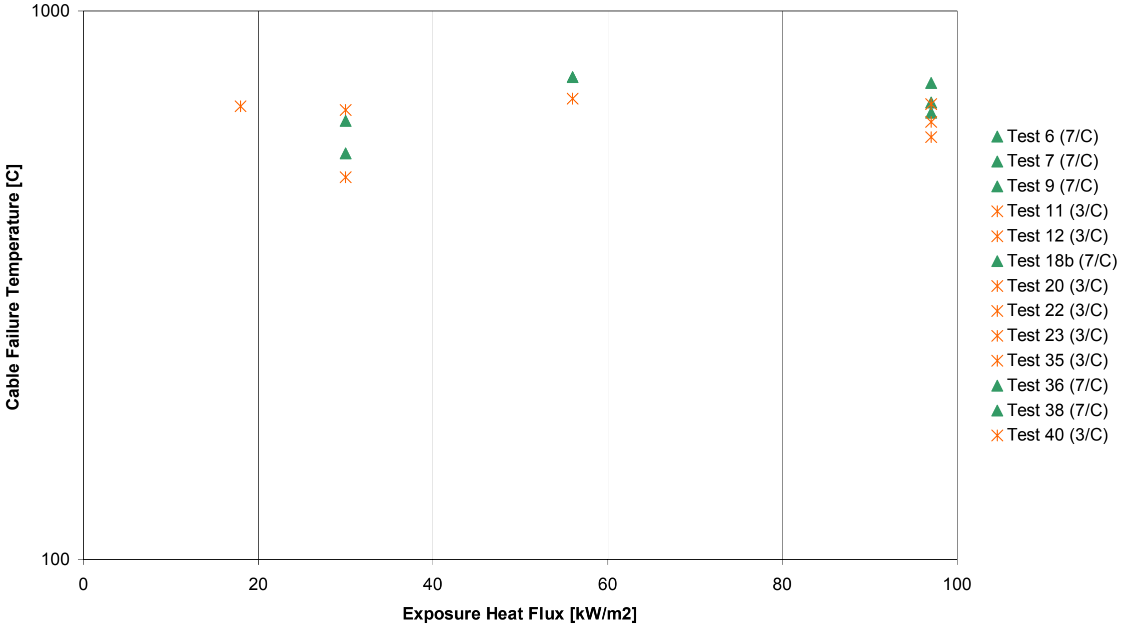

Figure 6-4 Exposure Heat Flux vs. Cable Failure Temperature Test Data for EPR

Because the deviation in the cable temperature is small, the best-fit line is nearly linear on the semi-log paper. The equation for the line is given as

$$T_{cable} = 53.687 * \ln(\dot{q}'') + 393.89\,,$$

Equation 6-2 Trendline for Cable Failure Temperature as a Function of Exposure Heat Flux for EPR

where T_{cable} is the cable failure temperature and $\dot{q}''$ is the exposure heat flux.

Figure 6-5 shows the cable failure temperature data for the EPR cables, with a trendline.

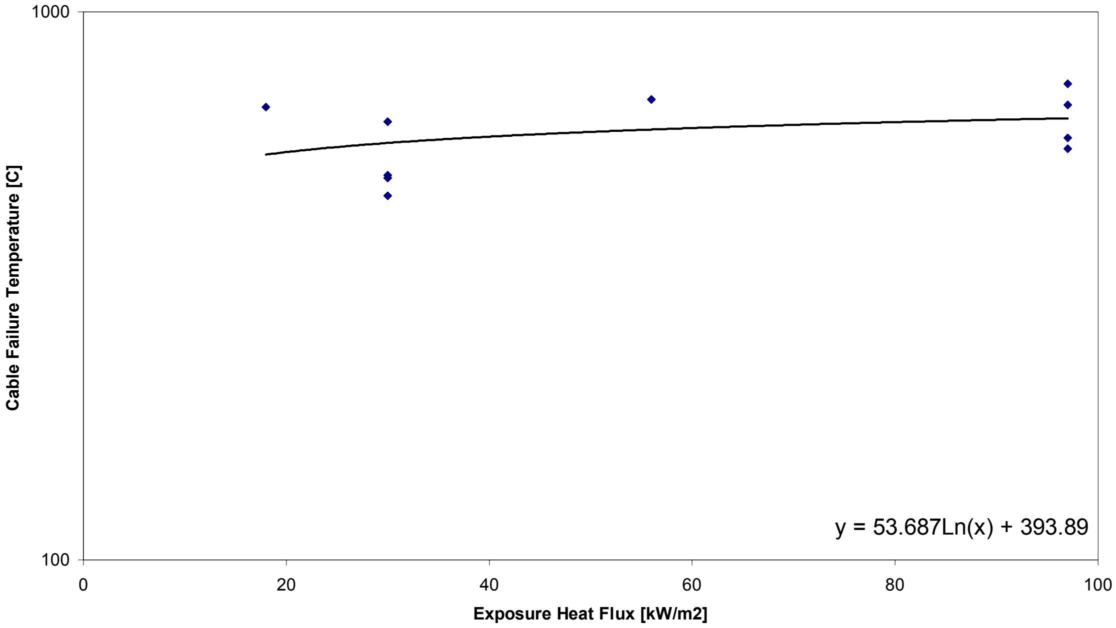

Figure 6-5 Exposure Heat Flux vs. Cable Failure Temperature Trendline for EPR

6.3.1.3 Comparison of 3-Conductor and 7-Conductor EPR cables

The average failure times for the 3-conductor and 7-conductor cables are provided in Table 6-1. One purpose of the test program was to determine if conductor size affected the time to failure at each exposure flux. According to the times listed in the table, there is no evident difference in failure times for the EPR cables. At one flux, the failure time for the 3-conductor cable was higher and for the other two test fluxes, the times for the 7-conductor were higher.

Table 6-1 Average Failure Times for 3-Conductor and 7-Conductor EPR Cables at each Exposure Flux

Exposure Heat Flux [kW/m2]	3-Conductor	7-Conductor
14	DNF	DNF
30	682	600
56	514	620
97	442	580

6.3.2 Cross-linked Polyethylene

The data for seventeen tests that utilized cross-linked polyethylene cables (XLPE) is presented in this section.

6.3.2.1 Exposure Heat Flux versus Time to Failure

Figure 6-6 shows the test data for the exposure heat flux versus the time to failure for the XLPE cables. The blue circles represent the 7-conductor cables, the magenta squares represent the 3-conductor cables, and the one green dash represents a 61-conductor “trunk line” cable. The XLPE cables behaved like the EPR cables, in the sense that the 3-conductor and 7-conductor cables had similar failure times for each heat flux.

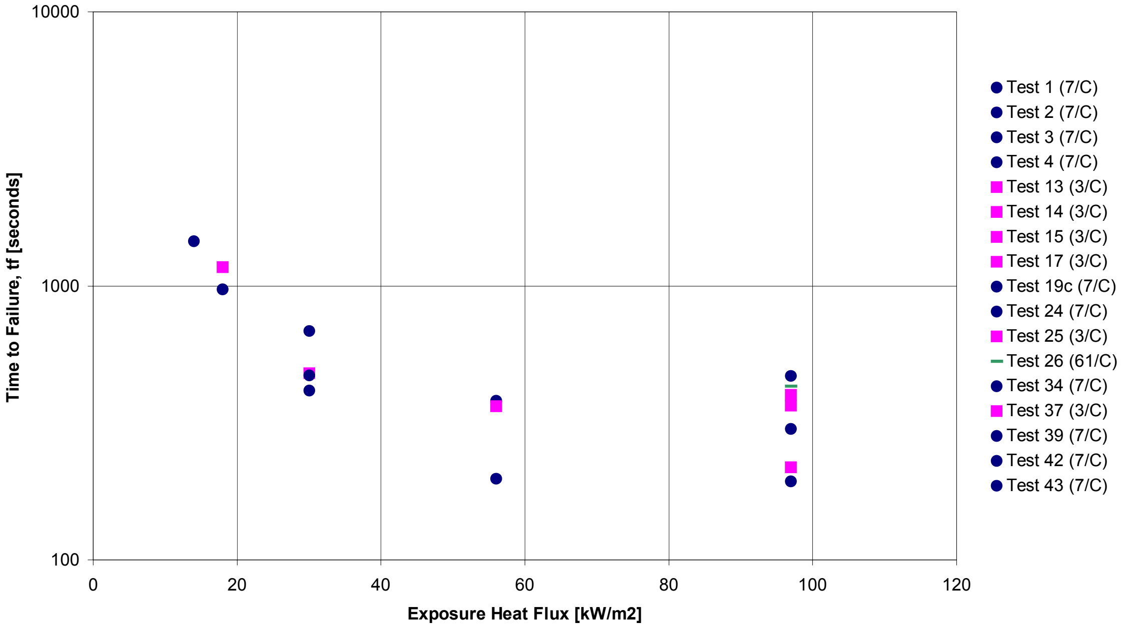

Figure 6-6 Exposure Heat Flux vs. Time to Failure Test Data for XLPE

Figure 6-7 plots the test data along with the best-fit equation for the data.

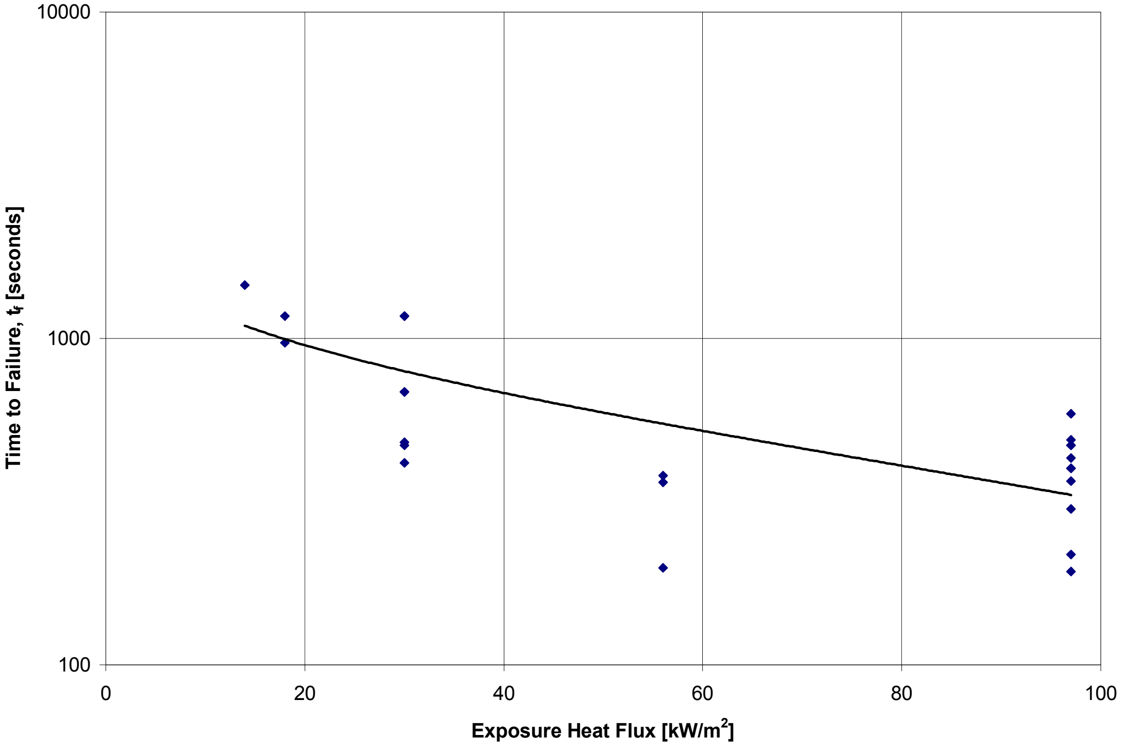

Figure 6-7 Exposure Heat Flux vs. Time to Failure Trendline for XLPE

The equation for the line is given as

$$t_f = -414.95 * \ln(\dot{q}'') + 2211.6$$

Equation 6-3 Trendline for Time to Failure as a Function of Exposure Heat Flux for XLPE

This line seems to fit agreeably with most of the heat fluxes, except 56 kW/m^2. If this equation is used, it appears to over-predict the time to failure for a cable exposed to that flux. While this may be the case, the predicted value should only be used as an approximate failure value and not as a specific or definite value.

6.3.2.2 Exposure Heat Flux versus Cable Failure Temperature

Figure 6-8 shows the exposure heat flux versus the cable failure temperature data for the XLPE cable tests. Similar to Figure 6-4, little variation exists in the cable failure temperature data. The standard deviation of the failure temperature for the XLPE cables is 12.5%.

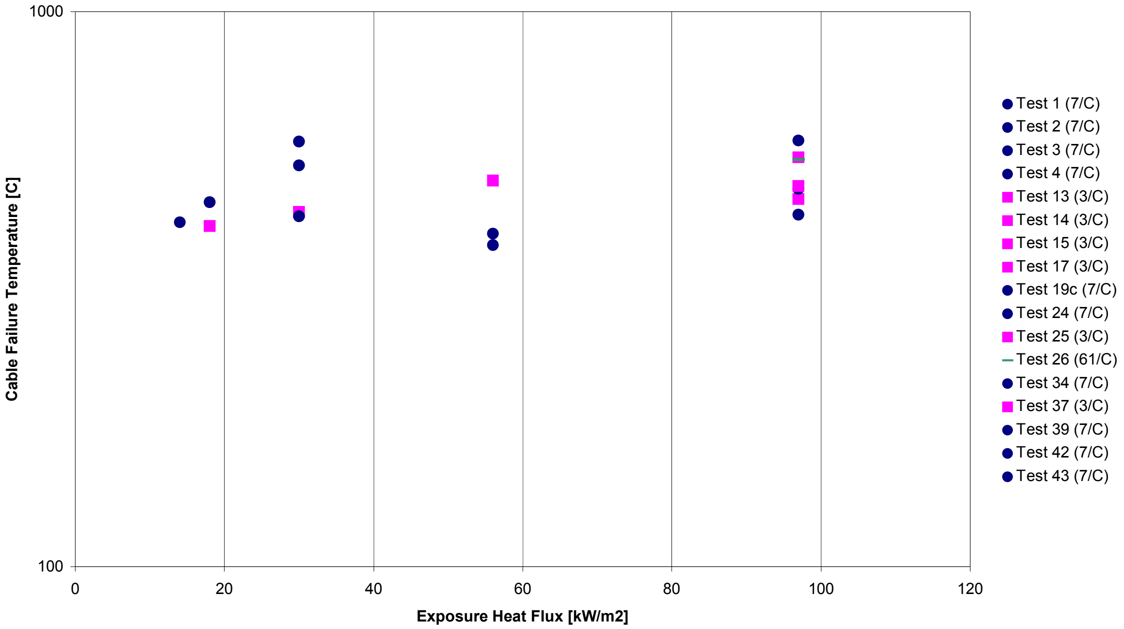

Figure 6-8 Exposure Heat Flux vs. Cable Failure Temperature Test Data for XLPE

Figure 6-9 plots the test data and the trendline for the cable failure temperature for the XLPE tests.

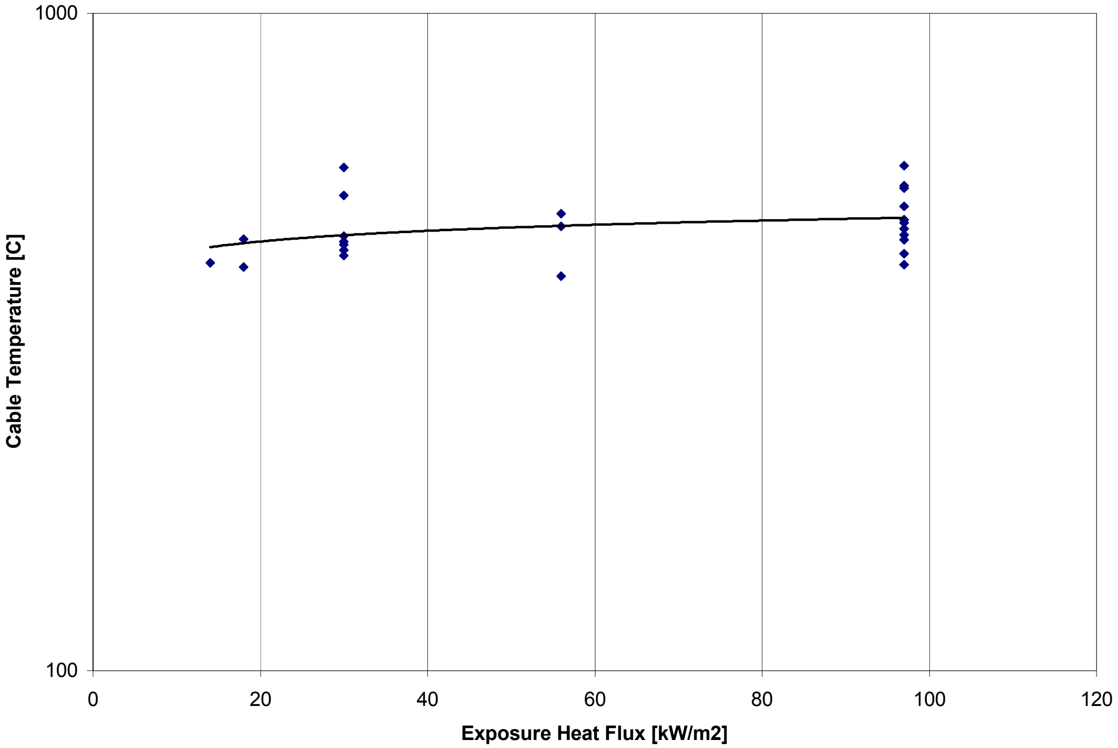

Figure 6-9 Exposure Heat Flux vs. Cable Failure Temperature Trendline for XLPE

The equation for this line is given as

$$T_{cable} = 30.478 * \ln(\dot{q}") + 358.21$$

Equation 6-4 Trendline for Cable Failure Temperature as a Function of Exposure Heat Flux for XLPE

6.3.2.3 Comparison of 3-Conductor and 7-Conductor XLPE cables

The failure times for the different number of conductors in the XLPE cables are given in Table 6-2. Similar to the EPR cables, none of the cables has higher failure times at all exposure fluxes. At three of the fluxes, the 3-conductor cables have higher failure times, while the 7-conductor cables have higher failure times are the other two fluxes.

Table 6-2 Average Failure Times for 3-Conductor and 7-Conductor XLPE Cables at each Exposure Flux

Exposure Heat Flux [kW/m2]	3-Conductor	7-Conductor
14	DNF	1458
18	1170	970
30	480	550
56	363	380
97	383	321

6.3.3 Comparison of Cable Insulations

Figure 6-10 is a comparison of the trendlines for both insulations for the time to failure versus exposure heat flux test data. The equations for the trendlines were given in previous sections, and are stated again here for easy comparison.

EPR (Equation 6-1): $t_f = -416.52 * \ln(\dot{q}") + 2349.3$

XLPE (Equation 6-3): $t_f = -414.95 * \ln(\dot{q}") + 2211.6$

The slopes of the lines are -416.52 and -414.95, almost identical. This means that as the heat flux increased, the time to failure decreased at virtually the same rate. The time difference between the two lines was approximately 130 seconds and stayed relatively the same over the test heat flux values. Some possibilities for the higher EPR times are that the insulation was thicker so it took longer for the heat to get to the conductors, or that the thermal conductivity was higher than that of XLPE.

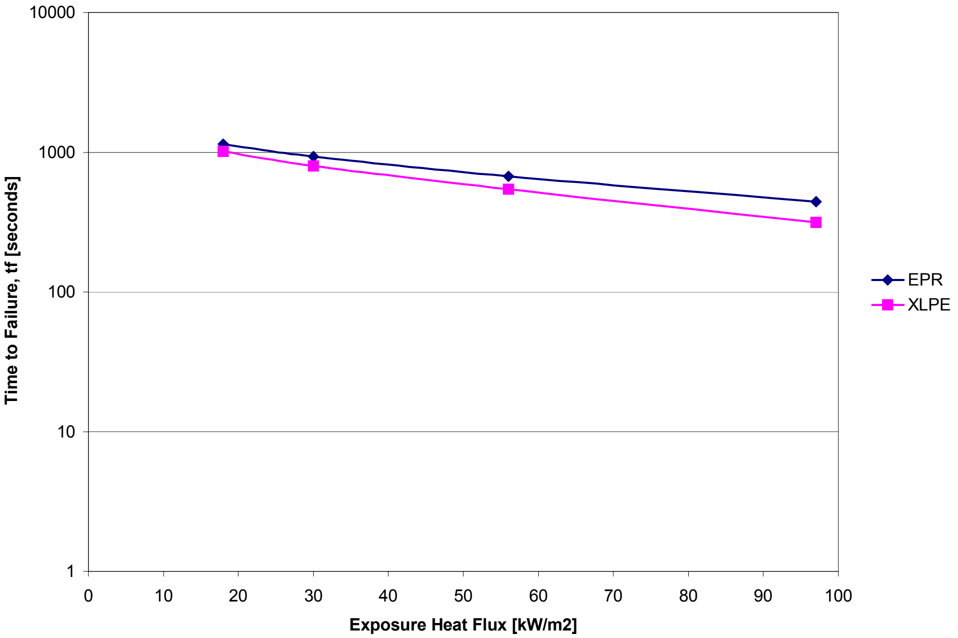

Figure 6-10 Comparison of Trendlines for Time to Failure

Figure 6-11 is another comparison of the two insulations, EPR and XLPE. The trendline equations for the cable failure temperature versus heat flux data are restated below for both insulations.

EPR (Equation 6-2): $T_{cable} = 53.687 * \ln(\dot{q}") + 393.89$

XLPE (Equation 6-4): $T_{cable} = 30.478 * \ln(\dot{q}") + 358.21$

Similar to the time to failure data, the EPR cable temperature values were higher than the XLPE. However, there was a much greater difference in slopes. The EPR values increased at a rate 1.8 times faster than the XLPE values. At the first test heat flux, the difference was approximately 100°C. At the last test heat flux (97 kW/m^2), the difference in temperature was 140°C. Again, it appears as though the thermal conductivity for the EPR is higher since the cable was able to withstand the higher fluxes for longer periods of time. The temperature was measured between the jacketing and the insulation. The heat had a harder time getting from this space to the conductor through the EPR insulation than it did through the XLPE insulation.

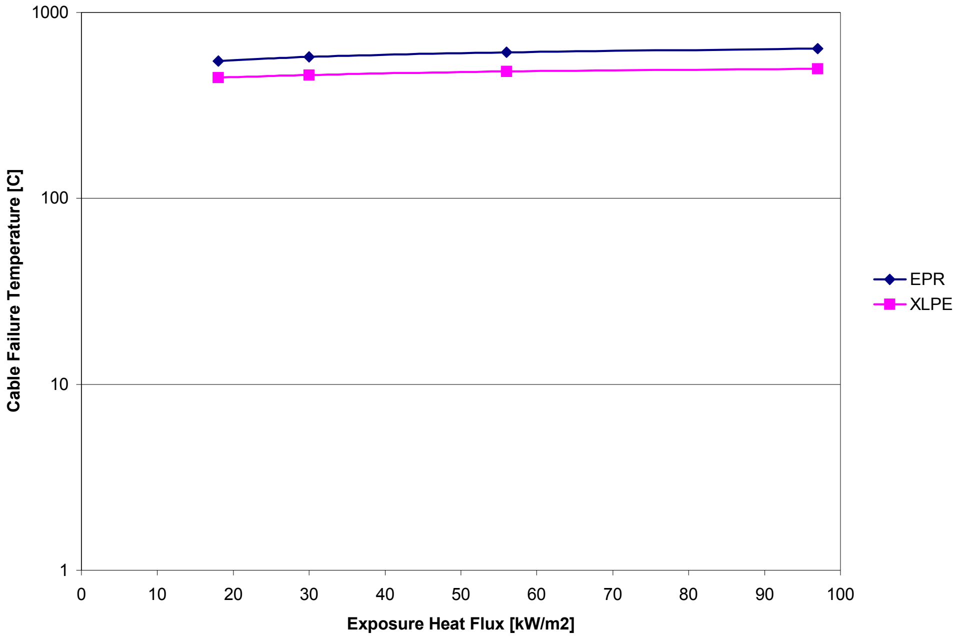

Figure 6-11 Comparison of Trendlines for Cable Failure Temperature

6.4 Conduit Test Results

Part of the cable test program was to determine the difference between cable trays and conduits. Both of these methods are used in nuclear power plants as a way of transporting cables from one location to another. Typically the conduits are used to transfer an important cable from a tray to a piece of equipment. Generally, the conduits provide better protection against fire.

Table 6-3 presents the time to failure for each of the cable tests. Six cable experiments were conducted using conduits at two fluxes, 30 kW/m^2 and 97 kW/m^2.

Table 6-3 Time to Failure for Conduit Test Data

Exposure Heat Flux [kW/m2]	Times to Failure for each Cable Type			
	EPR		XLPE	
	3-Conductor	7-Conductor	3-Conductor	7-Conductor
30	N/A	1314	1171	1170
97	N/A	763	588	490

Figure 6-12 is a plot of the above data. The standard deviation at the lower heat flux is 83 seconds, while the deviation at 97 kW/m^2 is 138 seconds.

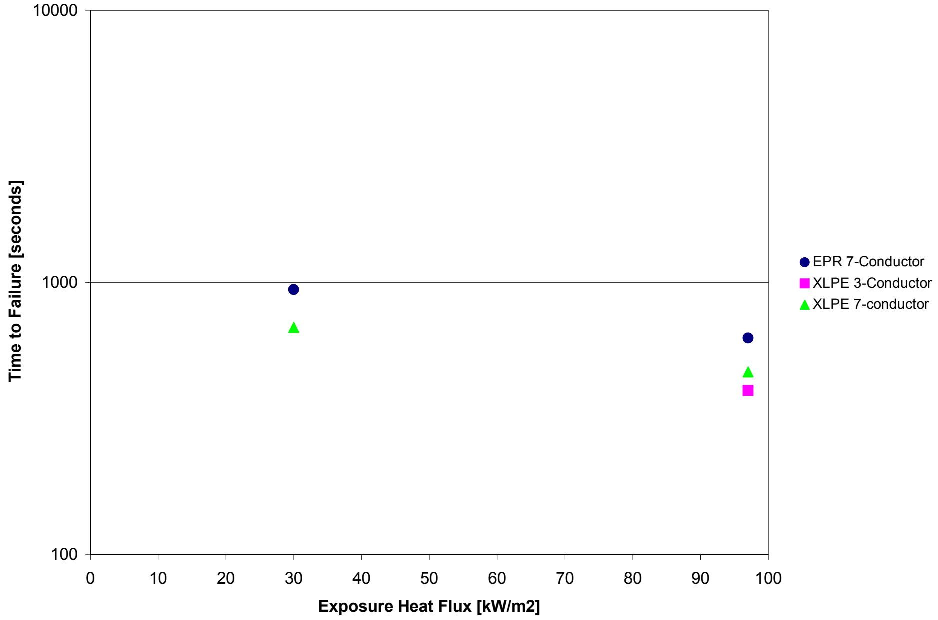

Figure 6-12 Time to Failure versus Exposure Heat Flux Data for all Cables in Conduit

Based on the data presented in Figure 6-12 and Table 6-3, the 7-conductor EPR cables appear to be the most robust, followed by the 3-conductor and the 7-conductor XLPE cables, respectively. However, only six tests were conducted so this must be examined further.

6.5 Multiple Cable Test Results

Multiple cable tests were another part of the cable program. In a nuclear power plant, cables are typically piled on top of one another with no pattern or logic. The times to failure for the multiple cable tests are presented in Table 6-4.

Table 6-4 Times to Failure for Multiple Cable Test Data

Exposure Heat Flux [kW/m2]	Times to Failure for each Cable Type			
	EPR		XLPE	
	3-Conductor	7-Conductor	3-Conductor	7-Conductor
18	1700	N/A	N/A	N/A
30	N/A	942	N/A	685
97	544	625	400	470

The graphical results of the multiple cable tests are given in Figure 6-13. The standard deviation at 30 kW/m^2 is 182 seconds, while the deviation at 97 kW/m^2 is 97 seconds.

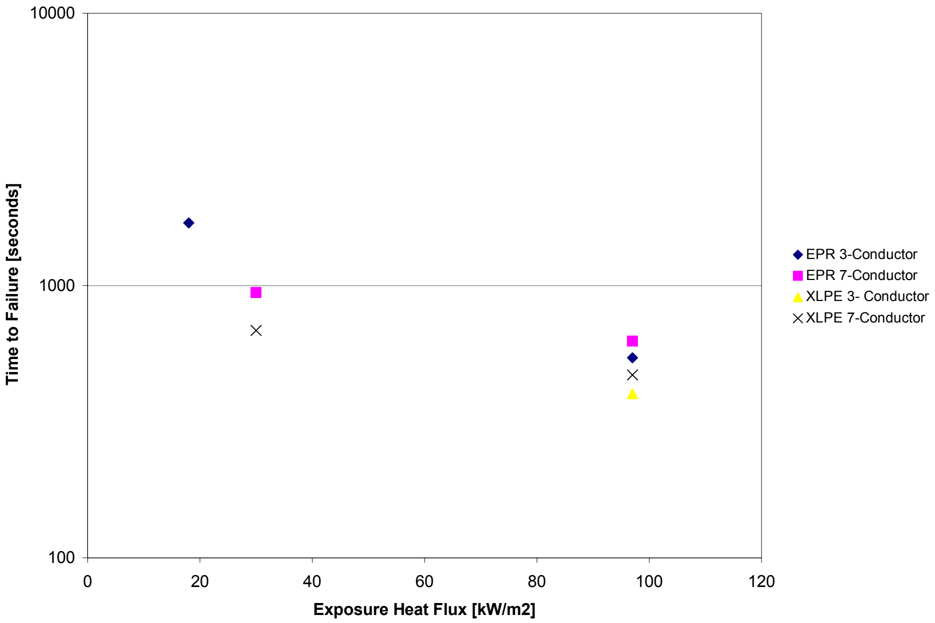

Figure 6-13 Time to Failure versus Exposure Heat Flux Data for all Multiple Cable Tests

The results of the multiple cable tests are somewhat inconclusive. It is difficult to compare these numbers to a situation in the real world because only six cables were tested. The "middle" cables are still getting some direct radiation from the shroud. If the trays were fully loaded, the results would probably be much different, however a fully loaded tray would have created a dangerous fire situation in the test facility and was therefore infeasible.

7 Comparison of Program Results and Literature Review Findings

This section compares the results of the cable test program with the findings of the literature search. The data used from the literature search was the information presented as cable failure time as a function of exposure temperature.

7.1 Literature Review Data

There was an abundance of information collected during the literature search regarding thermoset-insulated electrical cables. All data that included time to failure and exposure temperature was averaged and fit to a function. The form of the function is $1/t_f = aT - b$ because it exhibits a threshold behavior. The given function is

$$\frac{1}{t_f} = 2.90E-5 * T_{\exp osure} - 9.33E-3\,,$$

Equation 7-1 Literature Data Predicted Model Equation, f(T)

where t_f is the failure time in seconds and T_{exposure} is the exposure temperature in Celsius. The threshold value for this function is 322°C, which means that the thermoset cable will never fail below this temperature. (Wilson, 2003)

This information, however, cannot be directly compared because the program results involve exposure to heat flux rather than exposure to temperature. To convert the equation to heat flux, the following equation should be substituted in.

$$\dot{q}'' = \sigma\varepsilon T^4_{\exp osure}\,,$$

Equation 7-2 Radiant Heat Transfer

where σ is the Stefan-Boltzman constant and has a value of 5.67E-8 $\text{W/m}^2\text{K}^4$ and ε is the emissivity of the surface. In the case of the PENLIGHT shroud, the emissivity is 0.9. This is the equation for basic radiant heat transfer. The exposure temperature in the radiation equation is in Kelvin. This difference will be accounted for during substitution.

When Equation 7-2 is substituted into Equation 7-1 for the heat flux the resulting equation is

$$\frac{1}{t_f} = 2.90E-5 * \left(\sqrt[4]{\frac{\dot{q}''}{\sigma\varepsilon}} - 273 \right) - 9.33E-3$$

Equation 7-3 Literature Data Predicted Model Equation, f(q)

.

The subtraction of 273 changes the temperature from Kelvin to Celsius. Figure 7-1 illustrates the trend of the graph. The heat flux values substituted into the equation correspond to the threshold value (6.4 kW/m^2) as well as the four heat fluxes used in the cable program (14, 30, 56, and 97 kW/m^2).

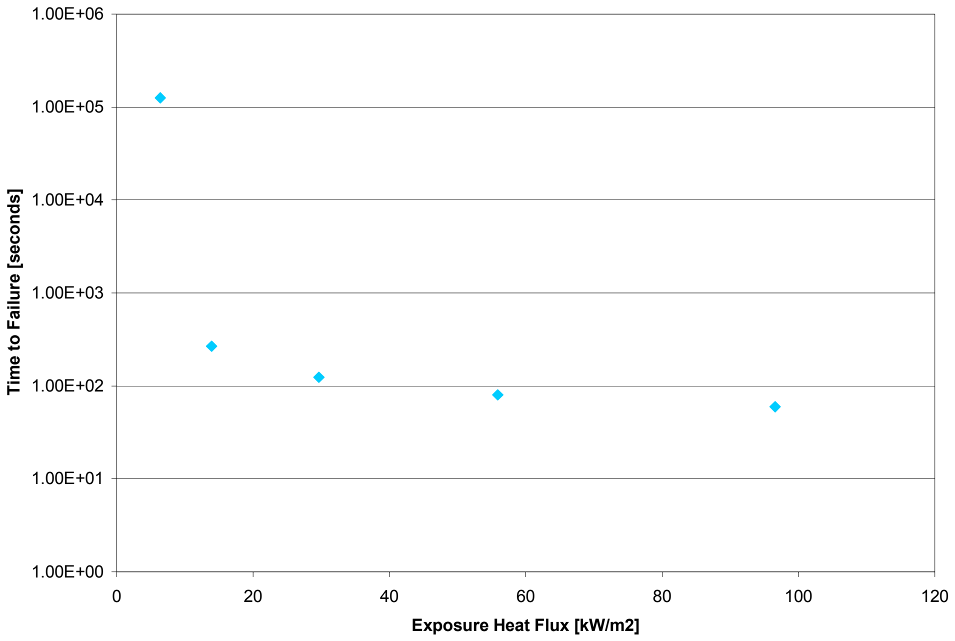

Figure 7-1 Literature Data Graph

7.2 Cable Test Program Data

As was stated in the previous section, the following two equations were acquired from the cable test data for the EPR and the XLPE cables, respectively.

EPR: $t_f = -416.52 * \ln(\dot{q}") + 2349.3$

XLPE: $t_f = -414.95 * \ln(\dot{q}") + 2211.6$

7.3 Comparison

In order to directly compare the data from the two sources, the literature data equation must be changed into a best-fit logarithmic equation. To do this, the threshold value should be disregarded. The remainder of the data points more closely represents the trend of the cable program results. Also, a threshold was not reached during the cable testing. All of the exposure heat fluxes caused cable failure to occur at least once. The initial heat flux of 14 kW/m^2 will be used.

When the threshold point is removed, the resulting logarithmic best-fit line is

$$t_f = -106.77 * \ln(\dot{q}") + 523.41$$

Equation 7-4 Logarithmic Best-Fit Time to Failure Line for Literature Data

The best-fit equations for EPR and XLPE cables and the literature data are plotted for the four program exposure heat fluxes in Figure 7-2.

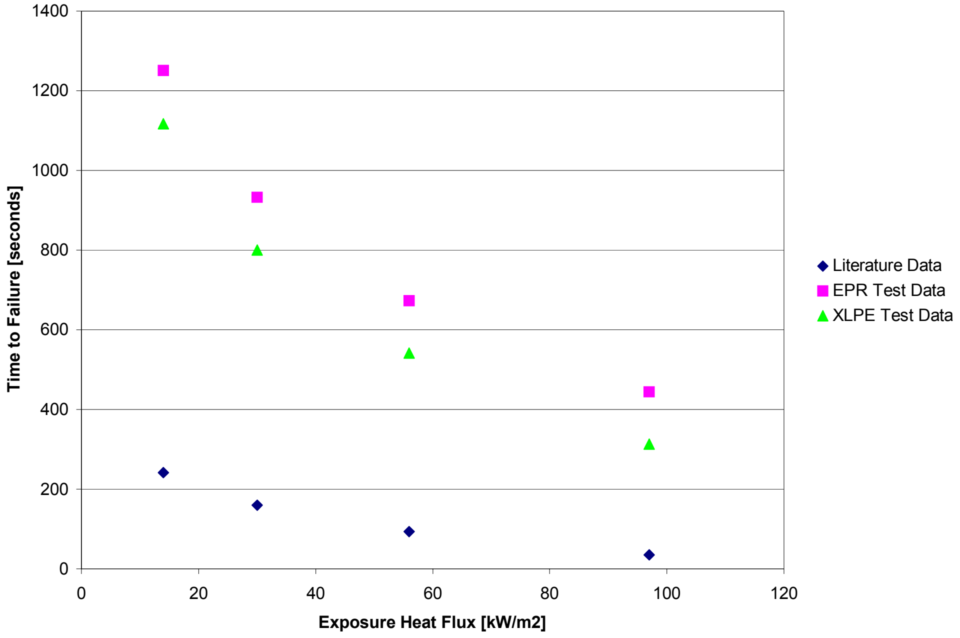

Figure 7-2 Comparison of Cable Test and Literature Data

Figure 7-2 illustrates that the information gathered during the test program is different from the data collected during the literature review. There are several possible reasons for this inconsistency. One reason could be the uncertainty of the exposure conditions for the literature data. In many of the reports the term "temperature" is used to mean a variety of things; it is difficult to determine if the author means surface temperature, air temperature, cable temperature, etc. Good engineering judgment must be used to verify which data should be used for an analysis or comparison.

Another reason for the difference could be the numerous types of exposure used. Some of these exposures were described in the literature review section. While the data may be reported as heat flux or temperature versus time to failure, it is important to also know the basics of the experimental setup. For example, direct thermal radiation is very different from a convective plume exposure, even though they may be reported at the same exposure flux.

A third reason for the differences may be the radiant heating geometry. In earlier tests, a single strand of cable was typically exposed to a full 360-degree radiant heater so the view factor was essentially 1.0. In the current tests, the view factor for the cable tray exposures in particular was substantially lower and this undoubtedly impacted the heating rates and damage times. This will be a configuration specific factor in actual applications as well. (Nowlen email, 2004) Approximate calculations for a 15-mm cable in a 150-mm wide cable tray with 100-mm sidewalls indicated the range of view factors around 0.3 to 0.6. (Wyant email, 2004)

A fourth reason for the difference in failure temperatures is the variety of failure criteria that was used. The criterion for this project was discussed in Section 3.3 and failure was described as the time when the insulation resistance dropped below one order of magnitude from its initial value. Other criteria could be when the cable starts on fire, reduction of resistance to a specific value, etc. None of these criteria is “better” than the others; the chosen criteria should be the most suitable for a particular experiment.

Based on the information presented in this section, the data found in literature can be used to predict possible trends for electrical cables. The exact values of the data should only be used if the corresponding test conditions are the same as the tests to which they are being compared, and even in that case, the data should be used with caution.

8 Conclusions

This section presents conclusions of the results presented in this report, regarding cable trays, conduits, cable insulations, and cable sizes.

Based on the results presented in previous sections, the ethylene propylene (EPR) cables seem more robust than the cross-linked polyethylene (XLPE) cables. The times to failure at all the exposure heat fluxes are higher for the EPR cables, although the rate of decrease is relatively the same for both insulations. The cable temperatures at failure are also higher for the EPR cables at all of the fluxes.

The number of conductors does not seem to affect the failure times for either of the cable insulations. At certain exposure heat fluxes (different for each insulation), the 3-conductor cables have higher failure times, while at the other fluxes the 7-conductor cables have higher failure times.

The conduit provides better protection against a fire environment than the cable tray. The few failure times presented for the conduits are longer than the average cable tray failure times for the corresponding cables. The small amount of data for the conduit experiments, however, makes it difficult to make specific comparisons. It was difficult to draw conclusions from the results of the multiple cable tests because of the small number of tests and the test arrangement.

Overall, it is not recommended that a single cable failure temperature be used for all cable types. Even small variations in failure temperature may cause large inconsistencies in a fire simulation code. However, if a failure temperature must be chosen, a temperature between 400 and 450°C would seem to be accurate for the EPR and XLPE cables because some did not fail at the 450°C exposure temperature. This threshold should only be used for these two thermoset materials since there may be less robust materials available.

9 Recommendations

Many recommendations for future research surfaced during the cable test program. The first recommendation would be to test thermoplastic materials using the same method as this test program. Thermoplastic materials have been extensively tested in other programs, however, because the outcome of this test program was drastically different than what was expected for thermoset materials, it would be interesting to verify if the same situation would occur for the thermoplastics.

Another recommendation would be to test the thermoset and thermoplastic materials together. Both have been tested individually to determine how they react under fire conditions, but the interaction between the materials has never been studied.

It appears as though the jacketing material would have a significant effect on the behavior of the cable in a fire situation. In this test program, only one jacketing (chlorosulfonated polyethylene) was used. To test the resistance of the jacketing material, a test program could be conducted using the same types of cable (number of conductors, size of conductors, insulation, etc.), with different jacketing materials. Using a specified experimental condition, such as temperature or heat flux, the properties of the jacketing materials could be determined and compared.

Additional cable tests should be conducted using the conduit arrangement. Conduits provide an important function in a nuclear power plant, so their behavior should be studied thoroughly.

The multiple cable experimental arrangement should also be studied more comprehensively. A typical nuclear power plant has trays loaded with electrical cables in no particular pattern. If this arrangement were recreated and its fire properties tested, the data would provide a more accurate representation of what would happen in the event of a nuclear power plant fire.

Another recommendation would be to test at some lower temperatures/fluxes to determine the actual failure threshold for different types of cables. The literature failure temperature was approximately 320°C, yet some of the cables in this program didn't fail at 450°C. Therefore, tests should be run at small intervals between these temperatures to determine if a failure threshold for thermosetting plastics can be determined.

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11 Appendices

11.1 Appendix A: Cable Test Procedure Checklist

Day/Date: ________________ Time: _________a.m./p.m.

Cable Test #: ___________ File Name: ______________________

Cable:
Gage: ________AWG Conductors: ___________ Insulation: ___________

Jacketing: ___________

Test Conditions:
Conduit/Tray: ___________ Test Set-point Temp [C]: ___________ Nom. Inc. Heat Flux [kW/m^2]: ___________

Length of Test: ___________

PRETEST

Pre-Test Preparations

1. ☐ Check for Personal Protective Equipment
    a. Coveralls (preferably Tyvek)
    b. Gloves
    c. Masks/Respirators
2. ☐ Cutting cables
    a. Measure 10 foot lengths
    b. Cut length
    c. Strip cable jacket and conductors that will be monitored
3. Testing thermocouples
    a. ☐ Use ohm meter to measure resistance (>3 MΩ)
    b. ☐ Use thermocouple tester to read temperature
4. ☐ Pieces of Duraboard must be cut to fit around cable tray/conduit after it has been inserted into PENLIGHT
5. ☐ Make sure exhaust fans in 6538 are turned on. Switch is located just outside the west door.

Thermocouple Insertion into Cables

6. ☐ Make small (1”) incisions where thermocouples will be placed.
7. ☐ Insert thermocouple between jacketing and insulation
8. ☐ Slide thermocouple in approximately 1-2 inches
9. ☐ Wrap fiberglass tape around cable to close incision and to hold thermocouples in place

Tray/Conduit Insertion

10. ☐ With assistance, place one end of the tray/conduit onto a stand at one end of the apparatus

11. ☐ Slowly slide the tray/conduit through PENLIGHT. DO NOT TOUCH any of the surfaces on the inside of the shroud
12. ☐ Rest the cable tray/conduit on the stand at the other end of the apparatus
13. ☐ Ensure that the length of tray/conduit that is outside the shroud on either end is the same
14. ☐ Ensure that tray is horizontally level and centered in conduit
15. ☐ Secure tray/conduit to stand
16. ☐ Place previously-cut pieces of Duraboard around the cable tray/conduit at both ends of the shroud

Placement of Cables in Tray or Conduit

17. Cable tray
    a. ☐ Lay instrumented cables into tray
    b. ☐ Arrange cables in tray so placement is correct
        1. Single cable tests, spacing = 1 inch between cables
        2. Multiple cable tests, two rows of cables
        3. Secure cables in tray, if necessary
18. ☐ Conduit Testing
    a. Bundle cables together without moving instrumentation
    b. Gently push/pull cables through conduit until desired length is inside the piping
19. ☐ Fill in any holes in Duraboard with Kaowool insulation
20. ☐ Plug ends of the conduit with Kaowool insulation

Instrumentation Setup

21. ☐ Plug connectors on the ends of the thermocouples (for cables, tray/conduit, and air) into PENLIGHT DAQ system
22. ☐ Record which conductor is connected to each thermocouple and also what channel that thermocouple is plugged in to
23. ☐ Ground the tray/conduit by attaching a grounding clamp

IRMS Setup

24. ☐ Review the Hazards and Cautions section in User's Guide
25. ☐ Conduct the following visual inspections
    a. No frayed wires or cords
    b. Front, back, and side panels are installed and secured in place
    c. Voltmeters, data acquisition/controller, computer and monitor, power supplies are intact and operable condition
26. ☐ Connect the wiring harnesses to the test cable conductors with wire nuts and insulate any unused harnesses from each other and the ground
27. ☐ Plug the wiring harnesses into the top row of the patch panel located on the back of the instrument rack while checking for proper continuity (using ohm meter) (1-1, 2-2, etc.)
28. ☐ Plug the instrument rack cord into a convenient 110-volt outlet
29. ☐ Turn on the 5 VDC power supply (HP 6128B) located at the back of the instrument rack and check that the meter reads between 5-6 Volts

30. ☐ Turn on the two HP 34401 digital multimeters (“V1” & “V2”) located at the top front of the instrument rack
31. ☐ Turn on the HP 3497A data acquisition/control unit located in the front of the instrument rack
32. ☐ Turn on the control computer and let it boot up to the desktop
33. ☐ Select the desired control program file (IRMS-AC.vi or IRMS-DC.vi) from the “IRMS Prog” folder
34. ☐ Follow the instructions on the Control Panel display screen to conduct the IRMS run

PENLIGHT Apparatus Setup

35. ☐ Bring PENLIGHT DAQ power cord from Building 6536 to 6538 and plug into the back side of the DAQ system
36. ☐ Start the 300 gpm pump, located on the west wall of the control room behind the control console, by pressing the START button
37. ☐ Completely open the cooling water return valve – Valve #1 (Open is parallel to pipe)
38. ☐ Slowly open the cooling water supply valve – Valve #1 (Open is parallel to pipe). Adjust to ~13gpm.
39. ☐ Check flow rate of water at flow meter. Flow rate = _________ gpm
40. ☐ Load the computer control program

Computer Program(s) Start-up and Operation

41. ☐ IRMS
    a. Start IRMS control program, LabView^{TM}, by clicking switch to SCAN
42. PENLIGHT
    a. ☐ Close the 480 VAC disconnect, located on the west wall of 6536, by pushing the lever up to the ON position
    b. ☐ Place the “Control Enable” switch, located on the PENLIGHT power cabinet front panel, to Enable
    c. ☐ Set test set-point temperature on program interface
    d. ☐ Start the control program, LabView^{TM}
    e. ☐ Ensure that temperature rises to target temperature and stays there

TEST

During Test

43. ☐ Monitor the PENLIGHT shroud temperature
    a. Ensure that it stays at set-point temperature
44. ☐ Monitor cable, tray/conduit, and air temperatures
45. ☐ Monitor IRMS readings for electrical failure of cables

POST-TEST

PENLIGHT Shutdown

46. ☐ Verify that both set point controllers are in manual mode
    (This is indicated by a small green light located in the lower left corner of each controller)

47. ☐ Place the “Control Enable” switch into the Disable position

Computer Program Shutdown

48. ☐ Turn PENLIGHT LabView^{TM} program into off mode
49. ☐ Turn IRMS LabView^{TM} switch to STOP and wait for program to halt
50. ☐ Record length of test

IRMS Shutdown

51. ☐ Turn off the power disconnect switch on the front of the instrument rack and check that the power indication light goes out. Click OK on pop-up box.
52. ☐ Unplug the wiring harnesses from the patch panel jacks at the back of the instrument rack
53. ☐ Disconnect the test cable conductors from the wiring harnesses
54. For extended shutdown:
    a. ☐ Turn off the two digital multimeters (both HP 34401s)
    b. ☐ Turn off the data acquisition/control unit (HP 3497A)
    c. ☐ Turn off the small 5 volt DC power supply (HP 6218B) in the back of the instrument rack
    d. ☐ Unplug the instrument rack power cord from outlet
    e. ☐ Backup data to floppy or zip disks
    f. ☐ Shutdown the control computer
    g. ☐ Turn off power to control computer and monitor (usually power strip)

PENLIGHT Shutdown continued

55. ☐ Ensure both set-point controllers indicate T < 100 °C
56. ☐ Shut down the 300-gpm pump. Make sure no other tests are using pump.
57. For extended shutdown:
    a. ☐ Close cooling water supply valve (Closed is perpendicular to pipe)
    b. ☐ Close the cooling water return valve (Closed is perpendicular to pipe)
    c. ☐ Open the 480 VAC disconnect by pushing the lever down to the OFF position
    d. ☐ Unplug the PENLIGHT DAQ and bring power cable into Bldg 6536

Cables and Instrumentation Removal, and Clean-up

58. ☐ Wait for apparatus to cool to workable temperature
59. ☐ Remove Duraboard and/or Kaowool insulation from ends of PENLIGHT
60. ☐ With assistance, remove tray/conduit from PENLIGHT. DO NOT TOUCH any of the surfaces on the inside of the apparatus.
61. ☐ Carefully remove thermocouples from cables without bending wires.
62. ☐ Remove cables from tray and dispose in recycle bin
    (Cables will be kept until end of test program)
63. ☐ Clean any residue from inside PENLIGHT cavity

PENLIGHT EMERGENCY SHUTDOWN PROCEDURE

1. ☐ Place the “Control Enable” switch in the Disable position
2. ☐ Open the 480 VAC disconnect

3. ☐ Shut down the 300 gpm pump
4. ☐ Close <u>ALL</u> cooling water valves

11.2 Appendix B: Resultant Tabular Data for Cable Experiments

Test Number	Test Date	Insulation	Cable Type	Cable Size (AWG)	Number of Test Cables	Number of Conductors	Configuration	Shroud Temp [C]	Nominal Incident Heat Flux [kW/m^2]	Cable Temp	Time to Fail
1	7/9/03	XLPE	Control	12	1	7	Tray	450	14	417	1458
2	7/9/03	XLPE	Control	12	1	7	Tray	900	97	431	300
3	7/10/03	XLPE	Control	12	1	7	Tray	600	30	528	415
4	7/10/03	XLPE	Control	12	1	7	Tray	750	56	474	380
5	7/11/03	XLPE	Control	12	1	7	Tray	900 Fireball	97	Test Unsuccessful	
6	7/14/03	EPR	Control	12	1	7	Tray	600	30	550	600
7	7/14/03	EPR	Control	12	1	7	Tray	900	97	652	464
8	7/15/03	EPR	Control	12	1	7	Tray	450	14	N/A	DNF
9	7/15/03	EPR	Control	12	1	7	Tray	750	56	757	620
10	7/15/03	EPR	Power	8	1	3	Tray	450	14	N/A	DNF
11	7/16/03	EPR	Power	8	1	3	Tray	900	97	627	350
12	7/16/03	EPR	Power	8	1	3	Tray	600	30	659	806
13	7/17/03	XLPE	Power	8	1	3	Tray	900	97	460	365
14	7/21/03	XLPE	Power	8	1	3	Tray	750	56	496	363
15	7/21/03	XLPE	Power	8	1	3	Tray	600	30	436	480
16	7/21/03	XLPE	Power	8	1	3	Tray	450	14	N/A	DNF
17	7/22/03	XLPE	Power	8	1	3	Tray	900 Fireball	97	547	218
18	7/22/03	EPR	Control	12	1	7	Tray	900 Fireball	97	Test Unsuccessful	
18b	7/23/03	EPR	Control	12	1	7	Tray	900 Fireball	97	681	282
19	7/23/03	XLPE	Control	12	1	7	Tray	900 Fireball	97	Test Unsuccessful	
19b	7/23/03	XLPE	Control	12	1	7	Tray	900 Fireball	97	Test Unsuccessful	
19c	7/29/03	XLPE	Control	12	1	7	Tray	900 Fireball	97	480	193
20 (12b)	7/29/03	EPR	Power	8	1	3	Tray	600	30	498	557
21 (6b)	7/29/03	EPR	Control	12	1	7	Tray	600	30	N/A	DNF
22	7/29/03	EPR	Power	8	1	3	Tray	750	56	692	514
23 (11b)	7/30/03	EPR	Power	8	1	3	Tray	900	97	589	433
24	7/30/03	XLPE	Control	12	1	7	Tray	500	18	453	970
25	7/30/03	XLPE	Power	8	1	3	Tray	500	18	411	1170
26	7/30/03	XLPE	Trunkline	16	1	61	Tray	900	97	542	431
27	7/31/03	XLPE	Power	8	1	3	Conduit	900	97	509	588
28	7/31/03	XLPE	Control	12	1	7	Conduit	900	97	452	490

29	7/31/03	EPR	Control	12	1	7	Conduit	900	97	563	763
30	8/4/03	EPR	Control	12	1	7	Conduit	600	30	462	1314
31	8/4/03	XLPE	Control	12	1	7	Conduit	600	30	458	1170
32	8/5/03	XLPE	Power	8	1	3	Conduit	600	30	450	1171
33	8/6/03	SR		12	1	7		750	56	N/A	DNF
34	8/7/03	XLPE	Control	12	1	7	Tray multiple	900	97	586	470
35	8/7/03	EPR	Power	8	6	3	Tray multiple	900	97	676	544
36	8/7/03	EPR	Control	12	6	7	Tray multiple	900	97	739	625
37	8/8/03	XLPE	Power	8	6	3	Tray multiple	900	97	485	400
38	8/8/03	EPR	Control	12	6	7	Tray multiple	600	30	631	942
39	8/8/03	XLPE	Control	12	6	7	Tray multiple	600	30	583	685
40	8/11/03	EPR	Power	8	6	3	Tray multiple	500	18	670	1700
41	8/13/03	EPR	Control	12	1	7	Tray	600 Fireball	30	503	680
42	8/13/03	XLPE	Control	12	1	7	Tray	600 Fireball	30	428	471
43	8/13/03	XLPE	Control	12	1	7	Tray	750 Fireball	56	398	198