ABSTRACT

Title of Thesis: AN EXAMINATION OF THE METHODS AND DATA USED TO DETERMINE FUNCTIONALITY OF ELECTRICAL CABLES WHEN EXPOSED TO ELEVATED TEMPERATURES AS A RESULT OF A FIRE IN A NUCLEAR POWER PLANT

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This thesis investigates the functionality of critical electrical cables when exposed to an unwanted fire in a commercial nuclear power plant (NPP). A review of electrical cable functionality concerns during fire exposure was performed. Data from previously performed testing were evaluated. The hypothesis predicts: (1) the United States Nuclear Regulatory Commission (NRC) decision to apply American Society for Testing and Materials (ASTM) E 119 acceptance criteria for non-load bearing fire walls to Electrical Raceway Fire Barrier Systems (ERFBS) is by and large conservative and therefore safe, (2) the amount of cable mass inside the ERFBS, provides additional safety margins, and (3) cable functionality at elevated temperatures will differ based on the functional role of the cable, (instrumentation, control, or power) and its construction. More precise cable functionality data could be developed and used in fire hazard and risk assessments to reduce the level of uncertainty in the analysis. Cable data developed as a part of the NPP industry's extensive environmental qualification (EQ) test programs may be used to make these approximations of cable functionality during the thermal insult resulting from a fire. A brief review of the fire potential in a NPP was performed. The results are presented in the form of plausibility arguments that could be further developed into rules or engineering judgments by future users. Suggestions for future cable testing protocol are discussed.

AN EXAMINATION OF THE METHODS AND DATA USED TO DETERMINE FUNCTIONALITY OF ELECTRICAL CABLES WHEN EXPOSED TO ELEVATED TEMPERATURES AS A RESULT OF A FIRE IN A NUCLEAR POWER PLANT

by

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And, Angela.

DEDICATION

This thesis is humbly dedicated to the two men who believed in me and influenced my career in Fire Protection. Without the guidance, wisdom, and influence of both these men, its doubtful whether I would have progressed to this level:

In memory of my Grandfather, Henry Thomas Urban (1913 - 1997). From my earliest childhood memories up through my adult life, he taught me the skills, honor, pride and compassion to be a Firefighter. "Always Ready, Always Willing."

To John L. Bryan, Professor Emeritus, Department of Fire Protection Engineering at the University of Maryland. Prof molded me into a Fire Protection Engineer.

Thank you both.

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LIST OF ABBREVIATIONS

ac	alternating current
ACRS	Advisory Committee for Reactor Safeguards (of the NRC)
ASTM	American Society for Testing and Materials
AWG	American Wire Gage
BFN	Browns Ferry Nuclear Power Plant
BTU	British Thermal Unit
cm	centimeter
CFM	Cubic Feet per Minute
CFR	Code of Federal Regulations
CPE	chlorinated polyethylene
CPJ	TVA identifier for single conductor, XLPE/PVC low voltage cable
CPJJ	TVA identifier for multiconductor, XLPE PVC/PVC low voltage cable
CPSJ	TVA identifier for XLPE/PVC, medium voltage cable
CSPE	chlorosulfonated polyethylene
dc	direct current
DOE	(United States) Department of Energy
ECCS	Emergency Core Cooling System
EDF	Electricite de France
EPR	ethylene propylene rubber
EPRI	Electric Power Research Institute

EQ	Environmental Qualification
ERFBS	Electrical Raceway Fire Barrier System
FIVE	Fire Induced Vulnerability Evaluation
FM	Factory Mutual
FR	Fire Resistant (Kerite brand silicone rubber cable insulation)
FSSD	post-fire safe shutdown
ft	feet
GL	Generic Letter
gpm	gallons per minute
GSU	Gulf States Utilities
HCl	Hydrogen Chloride
HTK	High Temperature Kerite (silicone rubber cable insulation)
HVAC	heating, ventilation and air conditioning
IEEE	Institute of Electrical and Electronic Engineers
in	inch
kg	kilogram
kJ/m^2	1,000 Joules per square meter
kPa	1,000 Pascal
Lbs	pounds
LICA	Low Level Intensity Cobalt Array
LLNL	Lawrence Livermore National Laboratories
LOCA	loss of coolant accident

m	meter
mA	milliamp
MCM	one thousand circular mils
MCR	Main Control Room
mm	millimeter
MOV	Motor Operated Valve
mph	miles per hour
m/s	meters per second
MΩ	Mega Ohms
NEC	National Electrical Code
NFPA	National Fire Protection Association
NEI	Nuclear Energy Institute
NIST	National Institute of Standards and Technology
NPP	Nuclear Power Plant
NRC	(United States) Nuclear Regulatory Commission
NTOL	Near Term Operating License
NUMARC	Nuclear Utilities Management and Resource Council
OPL	Omega Point Laboratory
PE	polyethylene
PFA	perflouroalkoxy branched polymers
PJJ	TVA identifier for PE PVC/PVC control cable
PPE	polypropylene

psia	pounds per square inch atmosphere
PVC	polyvinyl chloride
PXMJ	TVA identifier for XLPE/Hypalon
PWR	Pressurized Water Reactor
SBR	styrene butadiene rubber
SCE&G	South Carolina Electric & Gas Company
SCETCH	Severe Combined Environment Test Chamber
SNL	Sandia National Laboratories
SQN	Sequoyah Nuclear Power Plant
SR	silicone rubber
TFE	tetrafluoroethylene
TP	Thermoplastic
TS	Thermoset
TSI	Thermal Science, Incorporated
TU	Texas Utilities Electric
TVA	Tennessee Valley Authority
UL	Underwriters Laboratories, Inc.
V	volts
VCSNS	Virgil C. Summer Nuclear Station
VTT	Valtion Teknillinen Tutkimuskeskus (Technical Research Center of Finland)
WBN	Watts Bar Nuclear Power Plant

XLPE cross-linked polyethylene

XLPO cross-linked polyolefin

$\Delta T_{ave.}$ Average Temperature Change (°C or °F)

$\Delta T_{max.}$ Maximum Temperature Change (°C or °F)

Chapter I - Theoretical Rationale

Importance of Cables in a Nuclear Power Plant

The dependable operation of electrical cables is essential to the safe operation of a commercial nuclear power plant (NPP) during normal power operations and abnormal events such as fire. Power cables transmit the electric energy necessary for motive force such as powering motors and compressors, control cables transmit the necessary signals to start and stop equipment and to control other mechanical devices such as valve positioning with motor operated valves (MOVs), and instrument cables carry the necessary signals between transmitters and remote read-out instrumentation to allow accurate monitoring of operating condutions.

Research Question and Hypothesis

The 1975 fire at the Tennessee Valley Authority's (TVA) Browns Ferry Nuclear Power Plant (BFN) demonstrated the vulnerability of electric cables installed in a NPP when exposed to elevated temperatures as a result of an unwanted fire. Since the BFN fire, the regulator, the United States Nuclear Regulatory Commission (NRC), and the nuclear utilities have debated at what point and under what conditions electrical cables become unreliable (i.e., non-functioning) as a result of the thermal insult of a fire. In order to determine this, one needs to develop and analyze the potential fire induced failures that could preclude safe shutdown of the reactor. Two scenarios are typically analyzed in the post-fire safe shutdown (FSSD) analysis. The first scenario concerns identifying cables that need to be separated by distance or fire barriers, or protected in place with electrical raceway fire barrier systems (ERFBS) to ensure that the cables the

NPP is relying on to achieve and maintain FSSD will remain functional during and after a postulated fire. The second scenario involves unprotected cables and the potential adverse affects of their failure as a result of the fire. These "associated circuits" (i.e., circuits not required to support FSSD, but whose failure could cause an upset condition) must also be analyzed. An example of an associated circuit would be a circuit controlling a MOV installed in a high to low pressure piping system. If the FSSD analysis requires that the MOV remains closed, then the cables must be protected to prevent a fire from damaging the cable (i.e., hot short) causing the valve to open and lose reactor coolant (i.e., a loss of coolant accident.[LOCA]) Another example of an unwanted associated circuit failure involves multiple cables to equipment that is not required to support FSSD supplied from a common power supply, shorting out and tripping the main breaker, rather than their individual fuses/breakers, which could affect power to equipment that is required to support FSSD. There is also a need for determining the fire-induced failure temperatures of unprotected cables in fire risk assessments. In many of these assessments, the focal point for the analyst is the critical cables (targets). The analyst postulates fire scenarios that pose a risk to the NPP. One of the areas of uncertainty in this evaluation is at what temperatures the critical cables (targets) lose their functionality. Meaningful data that can be used to predict the temperature at which cables become unreliable or fail would reduce some of the associated uncertainties in the analysis.

The NRC has decided that ERFBS capable of providing a level of performance equivalent to a fire-rated non-load-bearing wall are acceptable for all post-fire safe shutdown cable applications. That is, an ERFBS test assembly must limit the raceway's (e.g., conduit, cable tray, etc.) average temperature rise ($\Delta T_{ave.}$) of 139 °C (250 °F) or less with no single temperature point above a maximum rise ($\Delta T_{max.}$)[1] of 181 °C (325 °F) of the ambient start temperature for the required 1 or 3 hour rating. There are no requirements for electrical functional testing of the cables if the ERFBS provides this degree of protection. The fundamental questions that remain to be answered are, with the $\Delta T_{ave.}$ rise less than or equal to 139 °C (250 °F) and the single point $\Delta T_{max.}$ less than or equal to 181 °C (325 °F) as the only required acceptance criteria, is the ERFBS adequate to ensure that the protected cables remain free of fire damage and fully functional? If the answer to this question is yes, then how conservative are the temperature limitations? The results of the large body of cable testing that was performed for environmental qualification (EQ) programs (10 CFR 50.49), and some specific cable functionality testing, should provide insights. Further conservatism can be provided by the cable mass inside the ERFBS acting as a heat sink. This should have a positive effect by lowering the overall temperature rise inside the raceway when the ERFBS is exposed to the elevated temperatures of a fire. Testing performed by the TVA in cooperation with Thermal Science, Incorporated (TSI), an ERFBS vendor, provides insights on this topic.

This thesis addresses the methods and data used to evaluate the functionality of electrical cables under fire conditions. First, an historical perspective is provided to put

1 See Appendix C, "Temperature Conversions," for a discussion of how temperatures are reported in this thesis.

this problem in context. Then, a short tutorial on electrical cable fundamentals is presented. This tutorial is intended to provide the reader with a basic understanding of the physical properties and functions of electrical cables. Third, a review and analysis of the research performed in an attempt to better understand the dynamics of cable performance during fire conditions is presented. Fourth, a series of technical arguments is presented that establishes what is known at this time. Finally, supplemental information describing key parameters that need to be considered in future cable functionality testing is presented.

Chapter II - Historical Perspective

Cause for Concern - The Browns Ferry Fire

On March 22, 1975, the TVA Browns Ferry Nuclear Power Plant (BFN) experienced the worst fire in United States NPP history. Salley [1] presents the following brief summary of the event. Workers in the cable spreading room using a candle flame to detect air leakage around electrical cable penetration seals accidentally ignited one of the penetration seals and its electrical cables.[2] Because of the congested location of the penetration seal, and aided by the high differential pressure across the barrier, the fire rapidly propagated through the penetration seal and continued out along cable trays located in the Unit 1 reactor building ceiling, approximately 6.10 to 9.14 m (20 to 30 ft) above the floor. The inaccessibility of the cable trays, compounded with the fear of using water on live electrical cables, allowed the fire to burn for approximately 6½ hours. When the decision to use water was finally made, the fire was extinguished in approximately 15 minutes by two firefighters using a single 3.81 cm (1½-inch) handline. Post-fire analysis revealed that all the cables in the 10 cable trays passing through the penetration, more than 1,600 electrical cables, were damaged by the fire. Additional cables located in 26 other cable trays had also experienced fire damage. All Unit 1 and many of Unit 2 emergency core cooling systems (ECCS) were rendered

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[2] Although the use of a lighted candle to check the air flow sealing capability of an electrical penetration seal sounds irrational, an explanation of why this method was used is noteworthy. A common, effective method to determine the "air tightness" of the turbine condenser, which is operated under vacuum during power operation, is to use a lighted candle to detect air in-leakage. This practice which is successfully used on condensers in fossil fuel power plants, was inappropriately applied to penetration seals in nuclear power plants.

inoperable due to fire damage to essential cables. Although the BFN unit operators did manage to manually shutdown and cool the reactors using unconventional means, this incident revealed serious fire protection design inadequacies in commercial NPPs. The most prominent design deficiency being that a single fire could damage critical cables of redundant safety systems, rendering both trains of equipment inoperable.

Regulatory Reform

Before the fire at BFN, the U.S. Nuclear Regulatory Commission's (NRC) fire protection regulations were high-level, general design requirements. After the BFN fire, a series of operating plant inspections and thorough reviews of NPP fire protection programs was conducted. Based on this information the NRC issued new fire protection requirements in 10 CFR 50.48 and Appendix R to 10 CFR Part 50 [2]. The new regulations imposed a minimum set of fire protection program and post-fire safe shut down requirements. The primary focus of the requirements establishes fire protection criteria for systems needed to safely shutdown and maintain the reactor in a safe condition in the event of a fire. This new regulation became effective on February 19, 1981. A significant requirement of the rule was that "one train of systems necessary to achieve and maintain hot shutdown conditions from either the control room or emergency control station(s) is free of fire damage" [2]. This performance-based requirement was supplemented with three prescriptive options for achieving the safety goals. One permissible option required a minimum of 6.1 m (20 ft) of horizontal separation, free of intervening combustibles, between the redundant trains, with automatic fire detection and fire suppression systems installed in the area. The other two permissible options involved the use of either 1-hour rated fire barriers with an automatic fire detection and fire suppression systems installed in the area, or 3-hour rated fire barriers between the redundant trains. Where existing rated fire barriers were installed, or could be constructed, they were often employed. However, in many NPPs, it was not practical to construct new floor-to-ceiling rated fire barriers, nor was it practical to rewire the plant. As a solution to this new requirement, the option of installing a rated ERFBS around one of the trains of critical electrical cables was frequently selected. The concept of protecting a select train of critical electrical cables within fire-rated enclosures was new to the American NPPs in the late 1970s and early 1980s. The nuclear utilities and NRC worked at an elevated pace during this period to bring the NPPs into fire safety compliance.

Free of Fire Damage

The underlying purpose of the NRC fire protection regulation is to provide reasonable assurance that at least one means of achieving and maintaining safe shutdown conditions of the reactor will remain available during and after any postulated fire in the NPP, hence, "free of fire damage." But, in scientific terms, just what specifically does "free of fire damage" mean?

The NRC and U.S. utilities have debated the definition of "free of fire damage" as applied to electrical cables since its inception in the regulations in 1981. On April 24, 1986, the NRC issued Generic Letter (GL) 86-10, "Implementation of Fire Protection Requirements," [3] to provide guidance to the nuclear industry. In GL 86-10 the NRC staff provided guidance on the meaning of "free of fire damage" stating, "the structure, system or component under consideration is capable of performing its intended function during and after the postulated fire, as needed." This GL also contained guidance in the form of "questions and answers" from a series of previous fire protection workshops conducted by the NRC. Question and Answer 3.2.1 provided guidance on the 164 °C (325 °F) unexposed side temperature requirements of fire barriers used to protect redundant electrical cables. The industry was of the opinion that the NRC's interpretation (i.e., 164 °C, 325 °F single point) was too restrictive, since, in its opinion, electrical cable insulation does not begin to thermally degrade until 234 to 346 °C (450 to 650 °F). It was the NRC staff's opinion that 164 °C (325 °F) was a reasonably conservative estimate since, "a cable that begins to degrade at 234 °C (450 °F) is free of fire damage at 164 °C (325 °F.)" The NRC staff also noted that it would accept fire barriers exceeding the maximum temperature requirement if justification could be "provided for the use of material which does not meet the 164 °C (325 °F) criterion. This may be based on an analysis demonstrating that the maximum recorded temperature is sufficiently below the cable insulation ignition temperature."

The use of cable insulation ignition temperature as an indicator of cable functionality is imprecise as used in this response. Cables could potentially lose their functionality prior to the insulation igniting. An important physical property of the cable that needs to be considered is the degradation of the insulation and a resultant current leakage. For power and control cables this may not be a severe problem since the cable's power supply breaker set point or fuse rating is generally set slightly higher than what the cable carries during normal operation. Current leakage in the range of milliamps (mA) would probably go unnoticed. This is not true when evaluating sensitive instrumentation cables that operate on low voltage and currents.

A common instrument operating range is between 4 mA to 20 mA. For illustrative purposes, consider a gage that reads between 0% and 100%. The 0% would correspond to 4 mA and the 100% would correspond to 20 mA. If the gage was properly operating on the high end and reading 100% (i.e., receiving 20 mA input) and the cable was then exposed to a condition that caused an 8 mA leakage, the instrument would be reading 50% with a 50% error. This would be an unacceptable error in most applications. In summary, from a current leakage standpoint, power and control cables could experience a certain amount of current leakage (amps) and remain functional, whereas even small current leakage (milliamps) might render instrument cables inoperable. Therefore, it can be demonstrated that an unsafe condition would exist where instrument cables could provide erroneous information to control room operators if the cables were experiencing current leakage due to insulation breakdown from the thermal insult of a fire.

Cable Protection

Beginning in August 1991, the NRC began alerting nuclear utility licensees of fire-resistive and ampacity-derating performance problems associated with Thermo-Lag 330-1 ERFBS [4]. The first information, issued in Information Notice 91-47, "Failure of Thermo-Lag 330 Fire Barrier Material to Pass Fire Endurance Tests," was based, in part, on failures of 3 hour full-scale fire endurance tests of Thermo-Lag 330-1 fire barriers sponsored by Gulf States Utilities's (GSU) River Bend Station. Further fire endurance testing of Thermo-Lag 330-1 fire barrier systems performed by Texas Utilities Electric (TU) in support of the licensing of Comanche Peak Steam Electric Station, Unit 2, produced additional fire endurance failures [5]. On the basis of this series of failures, the NRC issued Bulletin 92-01, "Failure of Thermo-Lag 330 Fire Barrier Systems to Maintain Cabling in Wide Cable Trays and Small Conduits Free From Fire Damage," and Supplement 1, "Failure of Thermo-Lag 330 Fire Barrier Systems to Perform its Specified Fire Endurance Function," in June and August 1992, respectively [6, 7]. These bulletins determined that Thermo-Lag 330-1 ERFBS as currently installed on conduits smaller than 10 cm (4 in.) diameter and cable trays wider than 36 cm (14 in.) could not meet their design-basis test requirement as a rated fire barrier. The bulletins were followed up by GL 92-08, "Thermo-Lag 330-1 Fire Barriers," in December 1992 [8].

During this renewed period of fire testing, the question of cables being "free of fire damage" was debated to a great extent. On October 7, 1992, Allen, Salley, and Brown presented the TVA position on ERFBS testing and acceptance criteria to the NRC staff at a public meeting [9]. The TVA needed to react quickly on this issue to support the near term operating license (NTOL) for Watts Bar Nuclear Power Plant (WBN) Unit 1, the last active NPP construction project in the United States. On December 9, 1993, Salley and Brown were invited to present TVA's technical argument to the NRC's Advisory Committee for Reactor Safeguards (ACRS) at another public meeting [10]. The NRC staff following the ACRS recommendation, responded to TVA and other NPP utilities by issuing Supplement 1 to GL 86-10 on March 25, 1994 [11].

In this supplement, the NRC made it clear that the ASTM E 119 acceptance criteria for non-load bearing walls (i.e., the average temperature rise above ambient ($\Delta T_{ave.}$) is limited to 139 °C (250 °F) or less with no single temperature above a maximum rise ($\Delta T_{max.}$) of 181 °C (325 °F) of the ambient start temperature for the required 1 or 3 hour rating) was the proper method of performing the qualification testing.[3] The NRC further stipulated that the raceway should be empty (i.e., no cable fill) with the exception of an instrumented, bare copper stranded #8 AWG wire inside to record the temperature profile during the test.[4] The NRC determined that this would be a conservative approach, since the addition of cable mass would absorb heat energy and reduce the overall recorded temperatures of the ERFBS. In the event the ERFBS could not meet this minimum level of performance, guidance for performing cable functionality testing at elevated temperatures, or performing comparison evaluations between existing cable performance data and actual fire test results was provided. The functionality testing methodology involved measuring the cable's insulation resistance to provide a gross quantitative assessment of its condition at the elevated temperatures. The analysis methodology could draw from the industry's extensive EQ cable testing data base. Later, in 1995, ASTM issued E 1725, "Standard Test Methods for Fire-Resistive Barrier Systems for Electrical System Components"[12]. This ASTM standard relies specifically upon the temperature rise, with no option for cable functionality testing.

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3 The temperature rise criteria are derived from the criteria specified in Sections 48.1.1 and 48.1.2 of ASTM E119-95, "Standard Test Methods for Fire Tests of Building Construction and Materials."

4 Thermocouples are attached along the length of the bare copper stranded #8 AWG wire at 6 inch intervals. The temperature data recorded from the thermocouples provides a time-temperature plot that corresponds to the temperatures that a cable would experience during the fire exposure.

Relevance in Fire Risk Evaluations

The concept of free of fire damage is also used in fire hazard and risk analyses. In 1991, the NRC issued Supplement 4 to Generic Letter 88-20 "Individual Plant Examination of External Events for Severe Accident Vulnerability" (IPEEE) [13]. This supplement requested individual licensees to perform a fire risk analysis for their NPP. The Nuclear Utilities Management and Resource Council (NUMARC, now the Nuclear Energy Institute, NEI) in concert with the Electric Power Research Institute (ERPI) developed a methodology for performing this task. The "Fire-Induced Vulnerability Evaluation" (FIVE) published by EPRI [14], uses a cable ignition temperature functionality correlation. The report states, "In general, the temperature of 700 °F (371 °C) may be used as the failure temperature criteria for IEEE-383 qualified cables when applying the fire modeling evaluation. This temperature is the ignition temperature of IEEE-383 qualified cable. It was selected because the ignition temperature of the cable will be reached before the cable function is lost." The FIVE methodology supports this statement with reference to work performed for the NRC by Sandia National Laboratories (SNL)[5] in 1991 [15]. Reviewing SNL's research indicates that for the cables tested, the threshold for loss of cable functionality was in the range of 325 to 370 °C (617 to 698 °F). For a single point value, the authors of the EPRI document chose an approximated value on the non-conservative high end of SNL

5 Note the reference identified in the FIVE document is numbered (Ref. 9.2). This is incorrect, the correct Reference is (Ref. 9.11).

testing, specifically 371 °C (700 °F). By selecting a single temperature as a threshold for the loss of cable functionality, there was no attempt to distinguish between the various functional requirements (i.e., power, control, or instrumentation) of cables at elevated temperatures.

In summary, the issue of cable functionality is a cornerstone of FSSD. The remainder of this thesis will focus on the results of the research performed.

Chapter III - Cable Fundamentals and Industry Data

Introduction

The historic philosophy regarding cable functionality at elevated fire temperatures has relied on engineering judgment coupled with factors such as insulation ignition temperatures (e.g., GL 86-10) or generic cable classifications, (e.g., 371 °C (700 °F) for IEEE-383 qualified cables in the FIVE methodology). A more detailed review of individual cable functionality is warranted. To achieve this, a brief discussion of cable technology is in order. Basic information concerning a cable's normal function, construction, operating temperatures, and summary data as described in industry documents is presented [16,17,18]. This thesis is limited to electrical cables used in a NPP. Other technologies, such as fiber optic cables, are beyond the scope of this thesis.

Electric Cable - Function

Electrical cables perform numerous functions in a NPP. These functions include: power cables supply electricity to motors, transformers, and heaters; lighting cables supply electricity to normal lighting fixtures and flourescent lighting ballasts; control cables connect plant equipment such as MOVs and motor starters to remote initiating devices (e.g., switches, relays, and contacts), instrumentation cables transmit low voltage signals between input devices (e.g., pressure sensors) and output devices (e.g., read-out panels); communication cables (e.g., telephone lines); and heat tracing cables. The primary cables of concern for FSSD of the reactor are typically power, control, and instrumentation.[6] The function of the cable (i.e., power, control, or instrumentation) dictates its acceptable operating parameters. This is an important parameter since acceptable performance of one cable at elevated fire temperatures may not be indicative of acceptable performance for another, i.e., a cable that demonstrates acceptable performance at a certain elevated fire temperature for power applications may not be acceptable for instrumentation applications at the same temperature.

Electrical Cables - Construction

Electrical cable construction will influence the performance of the cables at elevated fire temperatures. A brief discussion of the components that make up an electrical cable is in order. Cables typically consist of one or more metallic conductors, insulation, filler, shielding, sheaths, and jacket. Each metallic conductor is encased with an insulation material. The insulation is typically made from a dielectric material (e.g., plastic, rubber.) The insulation is often considered the single most important component of the cable. This basic cable construction is shown in Figure 1. The term "sheath" is commonly used to refer to cables that have an aluminum or steel jacket rather than rubber or plastic, e.g. "armored sheathed cable." This cable construction is shown in Figure 2. Some cables may also include one or more "shields" consisting of metallic tape, composition tape, or a metallic braid. The shield is wrapped around the

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6 Lighting cables are typically not required for FSSD since the plants are required to have 8-hour emergency battery lighting units. Likewise, communications are typically performed with radios and sound-powered phones. There are a few 'communication type' cables such as coax, but they are actually applied as control or instrument cables.

insulated conductors under the jacket or sheath. Single or multiple insulated conductors with their associated shields and sheaths are grouped together within a single jacket.

Figure 1

Basic Electrical Cable Construction

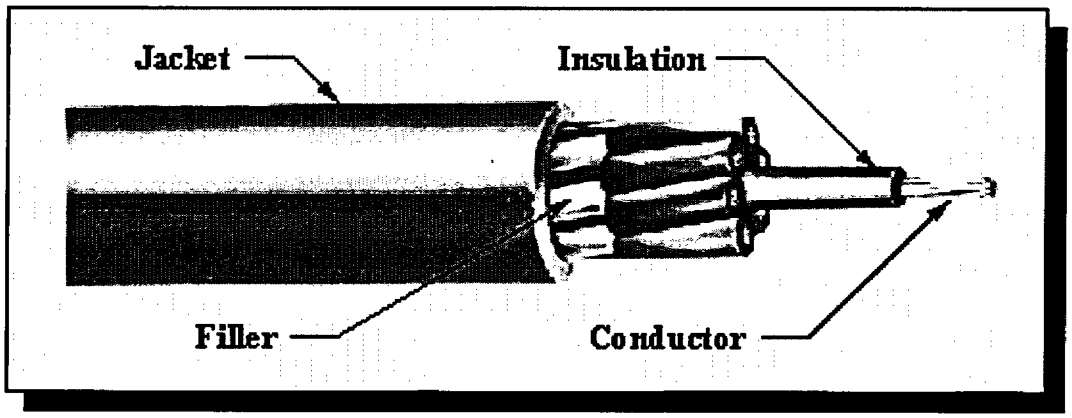
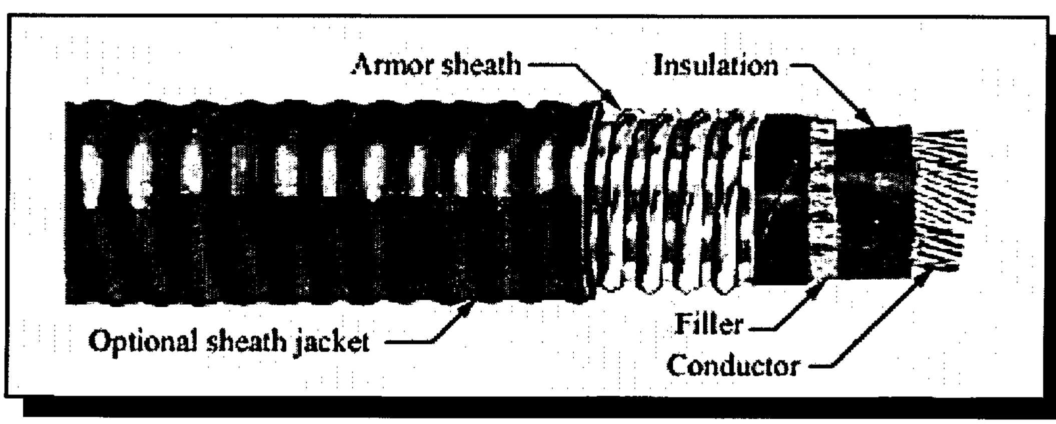


Figure 2

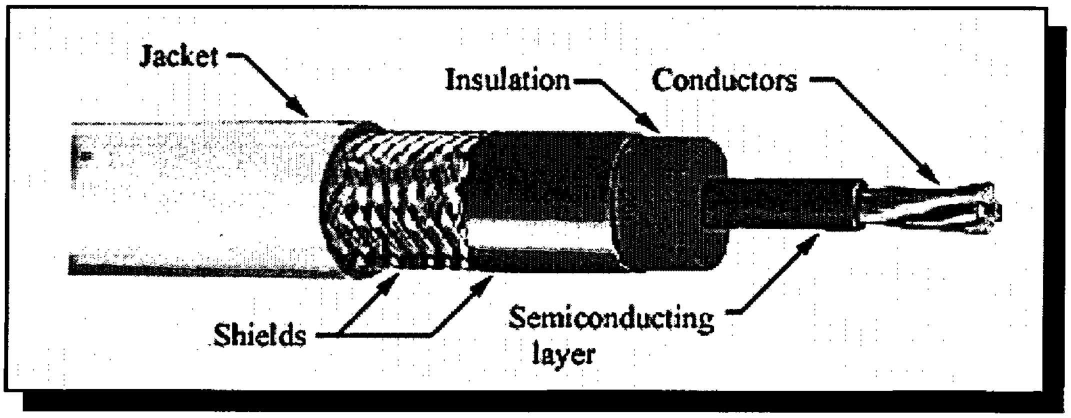
Sheathed Electrical Cable Construction



Cable jackets are typically constructed of rubber or plastic materials. The purpose of the jacket is to provide the insulated conductor(s) with physical or environmental protection, and/or increased flame retardancy.[7] An example of a shielded cable is shown in Figure 3.

Figure 3

Shielded Electrical Cable Construction



The number of insulated conductor(s) within a cable are commonly identified as follows:

1 conductor cable, (1/C),

2 conductor cable, (2/C),

3 conductor cable, (3/C) ...

Cables are also identified by their rated power voltage as shown in Table 1.

The insulation will play an essential roll in the cable's overall performance at normal and elevated temperatures. The insulation's function is to electrically separate each conductor from the others and from the ground plane. In some cases, cable jackets and cable insulation are constructed of the same materials. The combinations

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7 Note that cable jackets designed for 'increased flame retardancy' refers to slowing the flame travel across the jacket and reducing the fuel contribution from the cable once ignited. Having increased flame retardancy does not ensure functionality.

Table 1

Designation of Electrical Rated Voltages

Designation	Voltage
Low	Up to 600 V
Medium	601 to 15,000 V
High[8]	15,001 V and greater

of insulation and jacket materials will be presented with the insulation material shown first followed by the jacket material (e.g., insulation/jacket).

Historically, cable insulation and jacket materials have been separated in two broad classifications: "Thermoplastic" or "Thermosetting."

Thermoplastic Materials

Thermoplastic materials are defined as high molecular weight polymers that are not cross-linked [19]. Thermoplastic insulations are generally characterized by the distinct melting point of the insulation material. Thermoplastic materials can be repeatedly softened by heating and hardened by cooling within a temperature band that is a physical property of the material. This property is a function of the loose molecular bonding of the material. Some thermoplastic materials have a low melting point. This can be a disadvantage in that melting insulation can lead to conductor failures (e.g., conductor to conductor shorts and conductor to ground shorts) at relatively low

8 High voltage cables are typically not found inside the NPP. They may be used as a cable bus in trenches, or in the switchyard.

temperatures. Some thermoplastic insulations are also problematic in that they produce dripping, flaming fires after ignition.

Thermoplastic insulation is generally easy to manufacture, and is economical. Common thermoplastic insulations include cellular, low and high density polyethylene (PE), polyvinyl chloride (PVC), polyurethane, polypropylene (PPE), Nylon, chlorinated polyethylene (CPE), tetrafluoroethylene (TFE), Teflon, and fluorinated polymers such as DuPont's TFE copolymer with ethylene (known as Tefzel), DuPont's PFA (perflouroalkoxy branched polymers), Allied Chemical's Halar (ethylene copolymer with chlorotrifluoroethylene), and Dynamit Nobel's Dyflor (polyvinylidene fluoride).

Thermosetting Materials

The molecular chains of thermosetting plastics are tied together with covalent bonds in a network (cross-linked) [19]. Thermosetting insulations are generally characterized as softening, but not melting, during higher than normal temperature exposures. While they have softened, they tend to maintain the mechanical properties of the insulator. Some thermosetting insulation materials will, in fact, harden when overheated. Thermosetting insulations generally exhibit better low and high temperature properties, thermal aging resistance, and overload resistance than thermoplastic insulations. Thermosetting materials are vulcanized by heat (or other methods) during their fabrication process. As such, the material is substantially infusible and insoluble. The molecular structure is tightly interlocked in contrast to thermoplastic insulations. Common thermosetting insulations include ethylene propylene rubber (EPR), cross-linked polyethylene (XLPE), Dupont's Hypalon[9] (chlorosulphonated polyethylene), nitrile or rubber butadiene nitrile (NBR), styrene butadiene rubber (SBR), polybutadiene, neoprene, and silicone rubber.

In summary, thermoplastic materials are high molecular weight polymers that are not cross-linked while the polymer chains of thermosetting materials are cross-linked together in covalent bonded networks. When thermosetting resins are heated during manufacture, from ambient to upwards of 232 °C (450 °F), they undergo an irreversible chemical reaction, referred to as "curing" or "polymerization," to make the final cross-linked thermoplastic product. While thermoplastic materials can be reshaped by heating and cooling within the proper temperature ranges for the materials, thermosetting materials cannot be reshaped once they have been cross-linked. [19]

Electrical Cables - Operating Temperatures

Electrical cables generally are heated one of two ways, either internally or externally. Internal heating is caused by the electrical energy traveling along the conductor inside the insulation. This current heat flow is described as Ohmic heating [20]

$$\text{Ohmic heating} = I^2 R \qquad \text{(Equation 1)}$$

where:

'I' is the current in amperes
'R' is the resistance of the conductor in ohm/unit length.

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9 DuPont's Hypalon (chlorosulfonated polyethylene) is defined as a thermosetting insulation in cable literature such as the "Electrical Cable Handbook" [18]. However, other texts, such as "The Plastics Handbook," [19] define it as a thermoplastic material. Further review of cable vendor literature indicates that Hypalon used for cable jackets is typically a thermosetting material.

This physical property (also referred to as I^2R losses) is well understood and used for sizing cables for safe operation. Codes such as National Fire Protection Association (NFPA) 70, "National Electric Code," (NEC) provide conductor sizing information in tabular format [21]. Thus, power and control cables properly sized for their electrical loads will operate within the rated temperatures of the cable. Additional conservatism is provided in the sizing and construction of the insulated conductors for anticipated short duration events. The insulations used for power and control cables are designed for three different temperature ratings. Normal operation conditions, emergency overload, and short circuit. Normal operation design temperature is the temperature the cable can experience carrying its current during normal operation. Emergency overload temperature is the temperature the cable can experience in the situation where the load current is higher than the designed current but not expected to last more than 100 hours at any one time or more than 500 hours total for the service life of the cable. Short circuit temperature is the temperature the cable can experience during a fault current condition lasting a maximum 150 cycles. Based on a 60 Hertz system, this is less than 3 seconds. Note that the design (or rated) temperature is not typically the normal operating temperature for the cable. For example, a cable rated for 90 °C (194 °F) would be expected to be operating in the range of 60 to 75 °C (140 to 167 °F) due to all of the conservatism in selecting the cable. The same is true of the emergency overload and short circuit temperatures. These are design numbers, and due to conservative engineering practices, are not what cable is normally expected to experience.

External heating is a function of the anticipated ambient temperature the electrical cable will be expected to operate in. This is part of the requirement for the cable's operating requirements as defined by the IEEE: "Meeting Service Conditions. The cable, as installed, should be suitable for operation at maximum ambient temperature, radiation, and atmospheric conditions and normal electrical and physical stresses for its installed life, as specified" [22].

The early insulations were limited by the materials used and were nominally rated for 60 °C (140 °F). As newer insulation materials were developed, the temperature limits extended to the 90 °C to 200 °C (194 °F to 392 °F) range. Today, cables are nominally rated for 60, 75, 90, 125, 150, 200, or 250 °C (140, 167, 194, 257, 302, 392, or 482 °F respectively). In a typical NPP application for example, where a high normal ambient is temperature is 75 °C (167 °F) (non-accident conditions) a 90 °C (194 °F) or higher rated cable would be used.[10] The use of cables with a rating greater than 90 °C (194 °F) is generally limited to areas of the plant that have a very high ambient temperature or where the cable must be located in the vicinity of high heat emitting sources such as steam piping. However, other design considerations such as cable size, weight, diameter, construction, abrasion resistance, etc, may dictate the installation of a higher rated cable.

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10 The general rule of thumb is that for every 10 °C (18 °F) below the insulation's rated temperature, the useful life expectancy of the cable is doubled.

Cable Information Summary

The following provides general generic information for electrical cables, combining their construction, function, performance, and potential fire-induced failure.

Power Cables

Construction

Power cables typically constitute the largest sizes of conductors used in a NPP (#14 AWG up through 750 MCM). They may be single conductor (1/C), two conductor (2/C), or triplexed (3/C). Triplexed power cables are frequently used for 3-phase (3-Φ) applications. Multiple conductor cables (e.g., 7/C) are also used. Power cables may be low or medium voltage.

Function

Power cables are used to transmit electrical power from supplies (e.g., distribution panels, switchgear, transformers, etc.) to electrical loads (e.g., motors).

Performance

Power cables are sized to safely carry the necessary currents at the appropriate voltage.

Potential Fire Induced Failure

Power cables are the least susceptible to fire induced failure. These cables generally have the largest physical mass (based on their requirement to safely carry higher current) which allows the cables to act as a heat sink for a given thermal insult from a fire. Depending upon the cable's application, a certain amount of current leakage is acceptable. Failure to another cable or ground plane should result in a circuit interrupting device functioning (e.g., tripping of a breaker, blowing a fuse) and the loss of cable service. Energized power cables also have the potential of shorting to non-energized cables which can cause spurious operation of previously non-powered equipment.

Control Cables

Construction

Control cable conductors typically do not carry high currents and are therefore #12 AWG and smaller. Control cables are always low voltage. Control cable insulation and jacket are usually constructed from thermosetting materials. Ethylene-propylene-rubber (EPR) and cross-linked polyethylene (XLPE) insulation with Hypalon, PVC or neoprene jackets are generally used. Shields are also used when electrical interferences are a problem.

Function

Control cables are used to transmit electrical signals between control devices (e.g., switches) and end devices (e.g., motor starters, MOVs, solenoids).

Performance

Control cables typically provide intermittent operation (e.g., changing a MOV position). Some control cables also provide a feedback loop to indicate the status of a piece of equipment (e.g., a valve is in the "closed" position and is indicated on the NPP's MCR annunciator panel).

Potential Fire Induced Failure

Control cables are more susceptible to fire induced failure than power cables and less susceptible than instrument cables. This can be attributed to their size and sensitivity. In a fire they may fail (short) to other cables or the ground plane. This was demonstrated during the BFN fire where control circuits illuminated bulbs to show a MOV's position (i.e., "open" or "closed"). When the cables failed in the fire, both lights ("open" and "closed") glowed with varying intensity rather than one being illuminated while the other was dark [23]. Energized control cables may also fail during a fire which could cause hot shorts to non-energized circuits in the same cable or another control cable resulting in spurious operation of other plant equipment.

Instrumentation Cables

Construction

Instrument cables are always low voltage cables that typically carry low current on the order of 4 to 20 mA or 10 to 50 mA. Some literature sources suggest instrument cables may go as high as 4 amps [17]. The conductors inside the instrument cable are typically #16 AWG and smaller. Instrumentation cables are generally composed of single and multiple pairs of insulated conductors. The pairs of insulated conductors are often twisted together forming what is commonly referred to as a "twisted pair." Because of their sensitivity, instrument cables are generally shielded. Because of their low mass and high sensitivity, instrument cables are often the most easily affected by elevated temperatures and the first to suffer fire-induced failures.

Function

Instrument cables transmit low voltage and low current digital or analog signals between sensors (e.g., pressure, temperature, etc) and read-out display devices such as those found on the annunciator panels in the MCR.

Performance

Instrument cables are very sensitive by their nature. These cables are normally susceptible to interferences commonly referred to as "noise." Spurious signals originating from electrical or electromagnetic sources must be minimized for proper reliable operation of the cables. As such, proper shielding and grounding of instrument cables is essential.

Potential Fire Induced Failure

Instrument cables are the most sensitive to fire-induced failures because of their low mass and high sensitivity to elevated temperatures. Changes in temperature that result in current leakage through the conductor's insulation to other conductors, or to the ground plane, result in erroneous and unreliable instrument readings.

Chapter IV Analysis

Introduction

Fires and environmental upsets are two events of concern in a NPP that involve the adverse effects of elevated temperatures on the functionality of electrical cables. In a fire, the products and effects of the combustion process can expose cables to elevated temperatures. The heat energy is predominantly transferred to the electrical cables by convection. An environmental upset can expose electrical cables to a thermal insult accompanied by potential nuclear radiation and moisture as a result of mass and energy release from the rupture of a cooling system under high temperature and pressure. For example, in the event of a main steam line break, superheated steam will be discharged into the area. Similarly, a leak in the reactor coolant pressure boundary will result in superheated water (coolant) flashing to steam and heating an area. This event is commonly referred to as a LOCA. In a pressurized water reactor (PWR) these systems normally operate in the neighborhood of 15,514 kPa (2,250 psia) and 307 °C (580 °F). There has been limited research in the area of cable functionality during fire exposure. However, with the addition of 10 CFR 50.49, "Environmental qualification of electrical equipment important to safety for nuclear power plants," [24] electrical cables came under extensive review. This regulation requires that electrical equipment be qualified for operation in "environmental conditions, including temperature [does not include fire], pressure, humidity, radiation, chemicals, and submergence at the location where the equipment must perform as specified." This requirement resulted in extensive industry and cable vendor testing and qualification programs.

There has been far less research in the area of understanding cable functionality during a fire exposure due in part to the regulations. As a result of the BFN fire, 10 CFR 50, Appendix R was enacted into the regulations. The primary focus of Appendix R was to ensure that one train of equipment needed to maintain control of the reactor remained free of fire damage. Conventional fire protection systems and features such as suppression systems and fire barriers were installed to meet this new safety requirement. The Appendix R FSSD analysis assumes that cables in the fire area of concern are damaged and lost while the protected train of equipment remains functional (due to the successful operation of suppression efforts and fire barriers.) As such, there was little research and testing performed in attempt to understand the failure and effect mechanisms of electrical cables in a fire environment. Further, no standardized testing method and acceptance criteria for determining cable functionality during fire exposure has been developed. The testing that has been performed to date has typically focused on:

1. Specific cable configurations and identifying if a cable fault was credible, i.e., could a fire induced failure cause a short such that an undesirable event would occur.

2. A fire barrier system that could not restrict heat transfer such that the temperatures on the unexposed side of the barrier system were considered too high.

3. Approximating values to be used in fire probabilistic risk assessments (PRA) to determine the plausibility of fire vulnerabilities in the NPP.

The following sections discuss some of the relevant testing.

Babcock and Wilcox Research

Introduction

In 1979, Chaille of Babcock and Wilcox Company (B&W) performed simple cable continuity functionality testing for unprotected and protected electrical raceways when exposed to ASTM E 119 Standard Time/Temperature environment [25]. B&W performed this small scale testing to evaluate the performance of their Kaowool refractory blankets applied around electrical raceways.

Test Apparatus

The B&W testing was performed in a small catenary type furnace 0.90m (36 in) deep and 0.90m (36 in) wide. The furnace was fueled by two natural gas burners each capable of delivering 1.3 billion Joules (1.25 million British Thermal Units [BTU's]) per hour. A Northrop CAT Series 60 controller and Trendtrack programmer were used to control the furnace environment. Eight type K thermocouples were located on cable jackets inside the electrical raceways. A low voltage continuity light and circuit breaker arrangement monitored the integrity of a maximum 20 circuits.

Thermal Exposure

B&W programed the controller to follow the ASTM E 119 Standard Time/Temperature curve for a one hour exposure.

Cables Tested

The cable trays were filled with a mixture of IEEE 383 and non-IEEE 383 qualified cables. Each tray had an approximated 34% cable fill[11]. Chaille did not report the construction, size or assortment of the cables. Chaille did not report the cable tray size. The report states that different cable tray constructions (i.e., aluminum/steel, solid/ladder back) were used.

Electrical Performance

Electrical performance was determined by continuity testing of selected cables. It was believed that if the continuity light remained illuminated throughout the test, then the circuit remained functional. The only failures that could be observed with this monitoring are direct short circuits or physical detachment of the conductor (i.e., the conductor melts and physically separates.)

Results

Chaille reported that unprotected cables in a steel solid back cable tray lost continuity and failed approximately 8 minutes into the fire test. Challie also reported the installation of B&W Kaowool blankets had the potential to protect both IEEE 383 and non-IEEE 383 electrical cables from an ASTM E 119 fire exposure.

Summary

Chaille's testing was small scale and only tested a short 0.90m (36 in) straight section of cables. Because of this, the test can only be considered exploratory in nature

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11 In common electrical engineering terms, for power cables, a 30% cable fill (by cable cross sectional area), is considered to be a 100% allowable filled. For control and instrumentation cables, a fill of 60% is considered to be 100% allowable filled.

and not as a qualifying test for full size ERFBS. The thermocouples were located on jackets of cables enclosed completely by other cables in the cable tray and did not record the high temperatures experienced on the peripheral cables. As such, this data is not considered representative of the environment inside the ERFBS.

The validity of continuity testing as a confirmation of cable functionality has been demonstrated to be an invalid test except in the case of gross cable failures [7]. Cable continuity does not take into account critical cable functionality parameters such as current leakage in instrument cables, or current/voltage potential to ground in power cables when the insulation is degrading. Later testing illustrated this fact when the cable's insulation and jackets were consumed during ERFBS testing, but the conductor remained suspended in the raceway, thus maintaining continuity in a clearly nonfunctional cable [7]. Chaille's testing is valuable in the fact that it demonstrated that an unprotected cable tray exposed to an ASTM E 119 thermal environment could experience gross cable failure in as little as 8 minutes. As such, the application of an ASTM E 119 type fire exposure to unprotected electrical cables provides very limited results outside the fact that cables will fail in short order.

EPRI/Factory Mutual Research

Introduction

In 1981, EPRI contracted with Factory Mutual (FM) to conduct a series of tests on electrical cables. In the report "A Study of Damageability of Electrical Cables in Simulated Fire Environments," Lee [26] explored four functional properties of cables, namely insulation/jacket degradation, ignition, electrical integrity and hydrogen chloride

(HCl) production. The testing was comprehensive in that a wide range of cable samples were tested with the intended result being a method to rate or classify cables with respect to their damage potential when exposed to a varying thermal environment.

Test Apparatus

The FM combustibility apparatus was used to evaluate the potential damage from a heat source to the sample cable. The FM combustibility apparatus consists of four coaxially arranged radiant heaters which can produce an adjustable heat flux up to a maximum heat flux of 70 kW/m^2. Cable samples 0.1 m (0.33 ft) in length were placed in the apparatus for the test.

Thermal Exposure

Each cable sample was exposed to an increasing heat flux up to a maximum of 70 kW/m^2. Two samples of each cable were run for the ignition testing; the first without a pilot ignition source present in order to determine auto ignition, then the second sample with a pilot ignition source present to determine piloted ignition. The insulation degradation testing was performed without a piloted ignition source. The electrical functionality was performed with a piloted ignition source. The temperature on the cable jackets were calculated based on the measured heat flux.

Cables Tested

The cables tested in this program are listed in Table 2.

Table 2

EPRI/FM Cables Tested

Sample No.	Insulation/Jacket	Number & Size of Conductors
2	XLPE/Neoprene	7/C #12 AWG
17	XLPE/Neoprene	3/C #16 AWG
5	PE/PVC	3/C Size not specified
6	PE/PVC	5/C Size not specified
8	EPR/Hypalon	1/C #2 AWG
11	EPR/Hypalon	5/C #14 AWG
59	EPR/Hypalon	7/C #9 AWG
20	Teflon/Teflon	34/C #20 AWG
56	Teflon/Teflon	7/C #16 AWG
60	Teflon/Teflon	7/C #20 AWG
21	Silicone (Glass Braid)	1/C Size not specified
22	Silicone (Glass Braid/Asbestos)	9/C #14 AWG
58	Silicone (Glass Braid/Asbestos)	3/C Size not specified
57	Silicone (Glass Braid/Asbestos)	7/C #12 AWG

Electrical Performance

The conductors in each cable were connected in series, outside of the test apparatus with a resistor between each conductor connection. This series arrangement allowed the multiple conductor cable samples to function as one continuous circuit. A resistor was then installed at the final connection point where the voltage was continuously monitored. When this configuration was energized, there was a voltage drop of 70 V across each conductor due to the resistor. If during the test, two conductors shorted out to each other, a increase of 70 V would be detected at the monitoring connection. If a short to ground occurred, the voltage at the monitoring point would drop to zero.

Results

A summary of Lee's results is provided in Table 3.

Insulation Degradation

Lee states that all the cables with the exception of EPR/Hypalon (samples 8 and 11) experienced degradation in the range of 20 ± 4 kW/m^2. The test ranked PE/PVC (sample 6) the lowest at 18 kW/m^2, and XLPE/Neoprene (sample 2) the highest at 24 kW/m^2. The surface temperatures at the time of degradation ranged from a low of 297 °C (567 °F) for EPR/Hypalon (sample 11) to a high of 516 °C (960 °F) for XLPE/Neoprene (sample 17). Lee stated that the energy required for piloted ignition is the same order of magnitude as that for insulation/jacket degradation. However, XLPE/Neoprene (sample 2) and PE/PVC (sample 5) experienced autoignition at lower heat fluxes than the same samples exposed to piloted ignition. This contradicts Lee's rationalizations.

Ignition

The procedure was again carried out to determine the critical heat flux required for piloted and non-piloted ignition. Lee determined that all cable samples with the

Table 3

EPRI/FM Cable Test Results

Sample Number	Insulation Degradation		Ignition		Electrical Failure kW/m^2
	Critical Flux kW/m^2	Surface Temperature °C (°F)	Piloted kW/m^2	Auto Ignition kW/m^2	
2	24	488 (910)	21	4	ND
17	22	516 (960)	27	18	19
5	18	478 (892)	18	5	ND
6	18	478 (892)	23	15	24
8	11	392 (736)	NR	NI	14
11	6	297 (567)	23	NI	9
59	19	488 (910)	27	NI	17
20	18	478 (892)	NR	NI	NR
56	16	456 (853)	24	NI	NF
60	NR	NR	40	NR	NR
21	NR	NR	NR	NR	NR
22	18	478 (892)	NR	31	NF
58	NR	NR	NR	NR	NF
57	21	507 (936)	NR	27	NR

Notes:
NR = Not Reported   NI = No Ignition   ND = Not Determined   NF = No Failure

exception of Teflon/Teflon (sample 60) ignited in the range of 22 $\pm$ 5 kW/m^2. He rationalized that the pilot flame ignited the polymer vapor as the cable started to degrade. The surface temperatures of the cables were reported in the range of 297 to 534 °C (566 to 993 °F).

Electrical Failure

This test followed the same protocol as the ignition testing (including the pilot flame) with the difference being the electrical current in each conductor. Lee states that this test required the highest heat fluxes he used, i.e., 70 kW/m^2, to induce the loss of electrical integrity. However, samples 11, 17, and 59 reached piloted ignition with lower heat fluxes. The lowest heat flux for failure was 9 kW/m^2 for the EPR/Hypalon (sample 11). Some cables never reached failure. He also observed that the failures were conductor to conductor, and that some of the cables, despite insulation degradation, did not fail. A good example of this is the cables with silicone insulation. Even after the silicone has degraded (ablated), the remaining ash continued to make an acceptable insulator. Lee concluded that, "insulation/jacket degradation depends on the properties of the source material, while electrical failure is directly related to the products that are formed during degradation."

HCl production

Lee examined the production of HCl from the heated cable samples. He notes that HCl generation presents a severe hazard to NPP personnel and equipment with the release of HCl beginning at temperatures as low as 100 °C (212 °F). Lee evaluated three chlorine-containing cables, namely, PE/PVC, XLPE/Neoprene, and EPR/Hypalon. The samples were exposed to a heat flux of 60 kW/m^2 with a piloted ignition source. His results are provided in Table 4.

Table 4

HCl Production from Cables

Cable Type Insulation/ Jacket	Theoretical HCl Production % Mass of Total Insulation/Jacket	Actual HCl Production % Mass of Total Insulation/Jacket
PE/PVC	58	47
EPR/Hypalon	11	(not available)
XLPE/Neoprene	41	39

Lee concluded that halonagenated cables can produce a serious toxicity hazard to the NPP personnel and as such should not be overlooked in the fire safety analysis.

Summary

Lee attempted to introduce the concept of critical energy (E) (kJ/m^2) derived from the external heat flux (q_e'') (kW/m^2) and the exposure time in the testing. Based on this, he inverted the time (1/T) and plotted the data. However, Lee does not account for the different thermal mass of cables with the same insulation/jacket combinations. For example, samples 2 and 17 are both XLPE/Neoprene. Sample 2 is a 7/C #12 AWG, while sample 17 is a 3/C #16 AWG, yet sample 17 requires more energy for piloted ignition than sample 2 (27 vs. 21 kW/m^2). For the auto ignition test, the cable with the highest mass (sample 2) ignites at 4 kW/m^2 compared to 18 kW/m^2 (sample 17). This does not appear to be rational. The fact that he could not determine failure for sample 2, while sample 17 failed at 19 kW/m^2 further compounds the issue, especially considering the fact that sample 2 auto ignited at 4 kW/m^2. Likewise, all the reported data indicates that all the un-energized cables auto-ignited with lower heat fluxes that their piloted counterparts does not appear correct. Further, the data suggests that cables will auto ignite before electrical failure. The report does not describe the power supply used in the testing (voltage, current, ac/dc source), which introduces the question if the actual electrical potential across the cable during the test was enough to identify electrical failure, or it was so low that it acted as a continuity test only.

Tennessee Valley Authority Research

On two separate occasions, in 1984 and 1996, the TVA performed cable functionality testing at elevated temperatures. Both series of tests involved cables protected with an ERFBS and the resultant internal temperature rise when exposed to the Standard Time/Temperature curve of ASTM E 119.

TVA 1984 Cable Tests

Introduction

The first series of tests were conducted in 1984, in accordance with Underwriters Laboratories Inc. (UL) Subject 1724, "Outline of Investigation for Fire Tests for Electrical Circuit Protective Systems," Appendix B [27]. These tests were performed for the then (1984) ERFBS installed at WBN and documented in TVA Technical Report "Cable Failure Temperature Tests" [28]. In UL Subject 1724 testing, a full-scale electrical raceway (e.g. conduit, cable tray) is assembled with a test deck. Inside the electrical raceway, a #8 AWG bare stranded copper conductor is installed to simulate a electrical cable. The #8 AWG bare stranded copper conductor is instrumented with Type-K thermocouples every 0.15 or 0.3 m (6 or 12 in). The ERFBS is then installed over the instrumented electrical raceway and the complete assembly is subjected to the

ASTM E 119 Standard Time/Temperature furnace environment. The temperature of the #8 AWG bare stranded copper conductor is then recorded at one minute intervals. This time/temperature profile approximates the thermal environment an actual electrical cable would be expected to experience when protected with the ERFBS configuration. In the air oven test, actual cable samples are electrically tested for functionality while being exposed to the time/temperature profile obtained from the full-scale fire test. The temperature was measured on the cable jackets with Type T (copper-constantan) thermocouples taped to the outside of the jacket. The full-scale ERFBS fire test results demonstrated that the temperatures recorded on the #8 AWG stranded bare copper conductor installed in the ERFBS ascended from ambient to 246 °C (475 °F) at the end of the one hour fire exposure.

Test Apparatus

The hot air oven used for the testing was a Partlow "Despatch" (US TVA 266362). This type of oven is used by TVA Laboratory principally for drying type applications.

Thermal Exposure

As a conservative starting point, TVA preheated each cable sample to 90 °C (194 °F) for a minimum 15 minutes before the start of the test rather than room ambient temperature. The air oven environment then followed the internal ERFBS temperature profile with the temperature measured in the circulating air.

Cables Tested

TVA tested the cables shown in Table 5.

Table 5

TVA 1984, Cable Functionality Testing Results

Sample	Cable Type[12]	Construction (Insulation/Jacket)	Result
1	7/C #12 AWG, 600V, PJJ	PE, PVC/PVC	Fail
1X	7/C #12 AWG, 600V, PJJ	PE, PVC/PVC	Fail
2	7/C #12 AWG, 600V, PXMJ	XLPE/Hypalon	Pass
3	7/C #12 AWG, 600V, CPJJ	XLPE, PVC/PVC	Pass
4	2/C #16 AWG, w/shield Vendor "A"	XLPE/Hypalon	Pass
5	2/C #16 AWG, w/shield Vendor "B"	XLPE/Hypalon	Pass
6	1/C 400 MCM, 600V, CPJ	XLPE/PVC	Pass
7	1/C, 2/0 AWG 8 kV, CPSJ	XLPE/PVC	Pass

Electrical Performance

The 0.3 m (1 ft) cable samples were energized to 120 V ac, with the exception of power cable sample 6, (480 V ac) and sample 7 (6.9 kV ac) respectively. TVA determined this change was necessary since samples 1, 2, and 3 were used in low power or control applications, and samples 4 and 5 were used in low power instrumentation applications. Sample 6 was also a low voltage power cable and would be expected to operate at 480 V ac in plant applications. Sample 7 was a medium voltage power cable and would be expected to operate at the 6.9 kV ac range in plant applications. Shorts to

12 TVA has a unique system for identifying the insulation and jacket as shown by the PJJ, PXMJ, CPJJ, CPJ, CPSJ. The more common industry identification is provided in the adjacent column. Where two polymers are listed, (e.g., PE, PVC) the conductor has a layer of PE insulation, with a covering of PVC.

the ground plane (cable tray) were monitored across a one-ohm resistor in the ground connections and recorded on an oscillograph. The samples had weight loaded on top of the cable where it came in contact with the cable tray of the test oven. The weight was based on actual calculated TVA NPP configurations.

Results

TVA noted that sample 1 failed conductor to conductor at approximately 175 °C (346 °F). The test continued, post-failure, to 299 °C (570 °F). Examination of the sample after the test indicated that the weight had compressed the insulation and jacket to approximately 4.6 mm (0.18 in), barely enough for the thickness of the conductor. The voltage was removed 2.85 minutes after the conductor to conductor failure, and the conductors had, at that point, not yet failed to the ground plane of the cable tray. Judging by the visual inspection of the post test sample, TVA expected cable to ground would have occurred, had the conductors remained energized.

TVA reran this test with sample 1X. The weight across the intersection of the cable and tray rung was reduced from 5,694 grams to 1,537 grams (27%). In this test, the cable demonstrated its first failure (conductor to conductor) at 227 °C (440 °F), or 52 °C (94 °F) greater than sample 1. Sample 1X was removed immediately after the test and examined. The sample revealed considerable melting to the point that the insulation had begun fusing. The thickness at the intersection of the weighted cable and the tray rung was approximately 8.9 mm (0.35 in). Again, as in sample 1, the failure was conductor to conductor, with no conductor to ground plane observed.

Sample 2 (PXMJ) met the test acceptance criteria i.e., no shorts and maintained adequate insulation resistance. The cable jacket had discolored, however neither the insulation nor jacket exhibited any significant melting or burning.

Sample 3 (CPJJ) met the acceptance criteria. The jacket had experienced thermal damage similar to sample 1, however the insulation remained functionally intact despite some melting and cracking (no conductors were visible.) TVA estimated that the cable would have experienced a failure had the temperature continued to rise above 299 °C (570 °F).

Samples 4 and 5 (both XLPE/Hypalon), met the acceptance criteria, despite sample 4 exhibiting considerable cracking of the jacket, and sample 5 jacket destroyed at the cable tray rung interface with the shielding coming in direct contact with the rung.

Sample 6 (CPJ) met the acceptance criteria. The outer jacket had melted, but the insulation around the conductors remained intact experiencing only minor cracking.

Sample 7 (CPSJ) met the acceptance criteria, however, there were some complications during the testing. The high temperature tape covering the power connection, had lost its dielectric strength at approximately 186 °C (367 °F), the test was continued for 30 minutes at 246 °C (475 °F). Failure had occurred at about 9 kV, but it was through the air at the end connection and not in the cable. Post-test examination revealed that the jacket had melted and drained off, exposing the cable's shield. This supports the conclusion of the failure occurring at the connection and not in the cable.

Summary

In summary, mixed results from the cable testing, coupled with problems due to the fire barrier material's high ampacity derating, and limited fire tested design configurations, forced TVA to remove this vendor's ERFBS in 1996 and replace it with newly qualified Thermo-Lag 330-1 ERFBS.

TVA 1996 Cable Tests

Introduction

Based on the knowledge of the 1984 cable testing, TVA decided to performed a second series of tests in 1996 [29]. These tests would act as confirmatory testing for Thermo-Lag 330-1 ERFBS installed at their Sequoyah NPP (SQN) since some of the control cables needed for FSSD at SQN were 1974 vintage, TVA style "PJJ" cables and the 1984 testing performed for WBN by TVA had indicated that the PJJ style cables were some of the cables most susceptible to thermal damage.

Test Apparatus

A circulating air oven was used for this testing. The oven met the requirements of ASTM D 2436-85 "Specifications for Forced-Convection Ovens for Electrical Insulation"[30].

Thermal Exposure

The cables were conditioned for a minimum of 1 hour at roughly 27 °C (80 °F) for the cable tray and 40 °C (104 °F) for the flat plate rather than using the overly conservative 90 °C (194 °F) used in the 1984 testing. These ambient temperature values were determined to be the normal ambient temperature conditions in SQN where the cables were installed. A #8 AWG stranded bare copper conductor with two attached thermocouples was used to control the temperature inside the oven.[13] The temperature in the air oven was then lineally increased to a minimum 119.5 °C (247 °F) for the cable tray and a minimum 136 °C (277 °F) for the flat plate test assembly. These internal temperature profiles were based on ERFBS internal temperatures recorded on the #8 AWG stranded bare copper conductor in the 1996 full-scale TVA/TSI Thermo-Lag 330-1 fire tests.

Cables Tested

The PJJ style cables were manufactured to TVA specifications and consisted of approximately 20 mil PE insulation with an additional 10 mil PVC insulation around the PE insulation and a overall PVC jacket protecting the insulated cables.

Electrical Performance

The 1996 testing was again performed according to UL Subject 1724, Appendix B at TVA's Central Laboratories. The tests consisted of placing sample PJJ cables on a section of a cable tray rung, or on a flat steel plate (to simulate a cable installed in a conduit), and placing the sample in a circulating air oven. To add conservatism, the test cable had a weight installed on the cable where it contacted the rung, (point load for cable tray applications) or uniformly on top of the cable (for conduit applications), for a minimum 152.4 mm (6 in.) with a weight of 0.16 kg

13 A difference between the 1984 and 1996 TVA testing was the method used to measure the temperature inside the oven. In the 1984 testing, the temperature was measured in the air. The 1996 testing measured the surface temperature of the #8 AWG stranded bare copper conductor. The 1996 method is considered to be a more accurate representation of the thermal environment inside the ERFBS since the temperature was recorded in the same manner during the full scale fire test.

(0.35 Lb.) cable tray application or 0.14 kg (0.31 Lb.), for conduit applications. The purpose of the weight was to simulate other cables installed on top of the test cable as would be found in a cable tray or a conduit installed in a NPP. If the thermoplastic insulation began to thermally degrade, the weight would accelerate the failure to adjacent conductors and/or the ground plane established by the cable tray rung (or steel plate.) Each of the 2/C #12 AWG PJJ cables was energized with 500 V dc current to monitor the insulation's resistance (i.e., a Megger test.).

Results

The insulation on the PJJ cable in the cable tray test maintained greater than 50,000 MΩ resistance throughout the test (ambient to 119.5 °C [247 °F] at 60 minutes.) In the flat plate configuration, the PJJ cable maintained greater than 50,000 MΩ until 46 minutes (112 °C [234 °F]) where it decreased to 45,000 MΩ. The insulation resistance continued to drop as the temperature increased until a final value of 9,500 MΩ was obtained at 60 minutes (139 °C [282 °F]). Even with this reduction in insulation resistance, 9,500 MΩ is more than adequate to provide safe operation of control circuits.

Summary

In summary, this test verified (for TVA) that, even the most thermally sensitive control cables installed in a Thermo-Lag 330-1 ERFBS that minimally met the GL 86-10, Supplement 1, thermal criteria, would remain fully functional for their required 1 hour fire rating. It was also noteworthy that the simulated conduit samples (with a uniform loading of 0.14kg (0.31 Lb.) gave evidence of degradation at 112 °C (234 °F) where the simulated cable tray cable sample did not show any degradation at the higher final temperature of 121 °C (250 °F). There are two possible explanations for this. One possible explanation is the fact that the uniform loading would show a failure along the entire cable length tested where the point loaded sample concentrates on a smaller section of cable. Another possible explanation is the air oven heating profile based on the data from full-scale fire testing. In the full-scale fire testing, the protected conduit heated up more rapidly than the protected cable tray due to surface and mass factors. In the case of the cable tray, at Time = 0, the oven was at 27 °C, (80 °F) (preheat temperature of both cable tray and conduit cable samples) and increased lineally to Time = 60 minutes with a final temperature of 119 °C, (247 °F). The conduit started at Time = 0 with a temperature of 40 °C, (104 °F) and was increased lineally to 136 °C, (277 °F) at Time = 60 minutes. The greater heat soaking of the conduit cables could account for this reduction in insulation resistance at the lower temperature.

VTT Building Technology Research

Introduction

Keski-Rahkonen and Bjorkman of the VTT Building Technology, Fire Technology, working with Farin of VTT Energy evaluated the effects of elevated fire temperatures on electrical cable functionality [31]. Their research was performed for the Ministry of Trade and Industry, Finnish Centre for Radiation and Nuclear Safety, IVO International Oy, Teollisuuden Voima Oy and Finnish Fire Research Board. The goal of their study was to attempt to predict how long and at what temperature cables would remain functional during emergency conditions (i.e., in a fire environment).

Test Apparatus

Their research involved a 23.11 m (76 ft) length of cable with 1 m (3.04 ft) of the cable in a test tube furnace. The 1 m (3.04 ft) section of the cable was then heated in a time step fashion. Additional cable tests were carried out using a cubic furnace. The report does not provide details of either furnace other than they were PID controlled, and the openings where the cables entered the furnace were closed using 100 mm (3.94 in) thick mineral wool. The report does note that the furnaces, measuring equipment, and test cables were all mounted on the same metal plate in order to provide the same electrical potential. Temperature readings were taken near the center of the ceiling in the furnace and at the insulation of the test cable with Type-K thermocouples.

Thermal Exposure

The air temperature was increased in a time step fashion from an ambient 19 to 21 °C (66 to 70 °F), up to 200 °C to 230 °C (392 to 446°F). Electrical measurements were taken at each time step. The actual time/temperature steps and their durations were not reported.

Cables Tested

The focus of their study was PVC insulated, 2/C instrument cable.[14] Their report does not identify the conductor size, or manufacturer of the cable. However, in Figure 2 of their report a dimensioned cross section of the cable is provided. Based on

14 It's noteworthy that while PVC was commonly used as an insulation in Europe and Canada, it has rarely been used in safety related circuits in U.S. NPPs. The wide use of PVC in U.S. NPPs cables is as a jacket material.

this drawing, each insulated conductor has a 2.5 mm diameter (0.10 in), with 1.1 mm (0.04 in) being insulation. This leaves 1.4 mm (0.06 in) for the conductor. This translates to approximately a #16 AWG conductor.

Electrical Performance

The conductivity of the installation was measured with an insulation resistance meter and an electrometer. They used 500 V dc for resistance greater than 30 MΩ and 85 V dc when the resistance was between 0.3 MΩ and 30 MΩ.

Results

Based on the seven different PVC insulated cable samples tested, they report that the instrument cable functioned normally up to 196 °C (385 °F) where higher temperature increases caused a short circuit between the two conductors and the loss of functionality. This failure was not gradual but rather sudden. They also ran some samples of CSPE cables which produced different results, but they did not include this information in the report.

Summary

Keski-Rahkonen, Bjorkman, and Farin summarized their work by stating, "the rating of electrical performance of cables at high temperatures can be simplified to measurements of conductivity of cable insulation material, where Arrhenius-type of temperature behavior is not followed strictly but is useful as guidance." It is also worthwhile to note that their cables failed suddenly in the range of 200 °C (392 °F), rather than a gradual decline of insulation resistance. This might be attributed to the thermoplastic property of the PVC insulation.

Electricite de France Research

Introduction

In 1999, Electricite de France (EDF) [32] performed a series of cable burning tests on sheathed electrical cables. Their research was focused on minimum amount of fuel necessary to ignite the cables, the self sustained burning of the cables, and the burning rates of these cables. As a secondary test, EDF invited the American NPP owners group, NEI, to supply some cables for functionality testing.

Test Apparatus

The test assembly consisted of a stacked array of seven 500 mm wide x 50 mm high x 5,000 mm long (19.7 in. x 1.97 in. x 197 in.) wire mesh-type cable trays. The cable trays were spaced approximately 100 mm (3.94 in.) apart (top of one tray to the bottom of the next). The cable functionality test assembly was placed on top of the 52 instrumentation cables in the second cable tray from the bottom. The test cable ran the entire length of the cable tray. This cable tray array was located approximately 100 mm (3.94 in.) from a wall. This functional test assembly was located in the second tray from the bottom of the array randomly loaded with the other cables that EDF was testing for their primary research.

Thermal Exposure

A 500 mm x 500 mm (19.7 in. x 19.7 in.) pan containing 20 liters (5.28 gallons) of Heptane was located approximately 700 mm (27.56 in.) below the bottom most tray. The test was performed outside with an ambient temperature of 10 °C (50 °F) and a wind speed of less than 5 m/s (11.19 mph).

Cables Tested

NEI provided 2/C, #12AWG Rockbestos 600V, 90 °C, XLPE CSPE cables[15] for functional testing.

Electrical Performance

The functional test assembly consisted of one cable powered with 125 V on each of the two insulated conductors positioned in the center of 7 identical cables. The conductors in the 7 surrounding cables were connected back to a ground plane as shown in Figure 4.

One of the objectives of this testing was to determine if the energized conductors (in the center cable) would short to one another, or to the conductors in the 7 surrounding cables with their grounded conductors. The approximate time and temperature of the failures were also explored.

Results

The EDF reported the following conclusions for the NEI supplied cables [32]. About 6 minutes, 40 seconds after ignition of the Heptane, the cable insulation began to degrade. The air temperature in the area of the cables from the Heptane fire at this time was approximately 600 °C (1,112 °F). After 8 minutes, the two energized conductors in the functional test cable assembly shorted together. The temperature in the general area was estimated at 800 °C (1,472 °F). From 9 minutes until the end of the test (11 minutes) EDF recorded loss of insulation resistance in all of the cables in the functional

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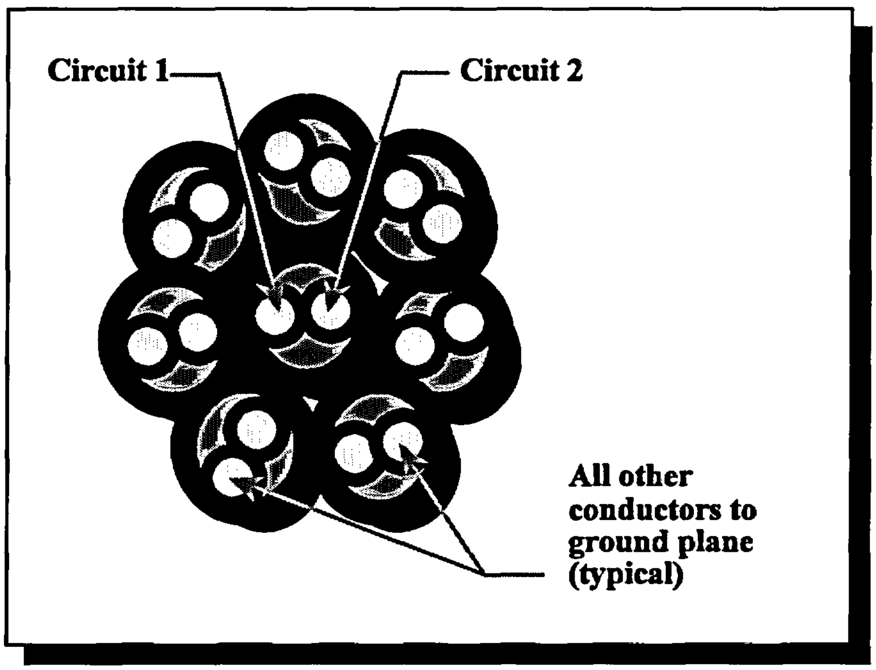
15 This type of cable is used extensively in U.S. NPPs.

test assembly at a rate of 10% every 30 seconds. However, the only direct short involved the two energized conductors in the center cable.

Figure 4

EDF Cable Functionality Test Cable - Cross Section



Summary

EDF concluded that the American-supplied cable was functional for approximately 5 minutes after the start of the exposure fire, after which it shorted conductor to conductor within the same cable. This time is associated with a surrounding air temperature of approximately 600 °C (1,112 °F).

Lawrence Livermore National Laboratory Research

Introduction

In 1992, Hasegawa, Staggs, and Doughty of Lawrence Livermore National Laboratory (LLNL) performed for the Department of Energy (DOE), an experiment titled, "Fire Tests of Wire and Cable for DOE Nuclear Facilities" [33]. This work centered around DOE specific cable configurations that would not be permitted in a NRC regulated NPP, namely the mixing of power, control, and instrument cables within the same cable tray. Because of this fundamental design difference, this test is of limited value to NPP application and as such only a brief summary of the test will be provided.

Test Apparatus

The testing was full scale conducted in LLNL fire test cell. The fire test cell measured 6.08 m (20 ft) by 3.95 m (13 ft) with a false ceiling set at 3.04 m (10 ft). The walls are lined with refractory cement and have a double wide door and viewing ports. The cell is also equipped with a 3000 cfm fan. A fully loaded 1.82 m (6 ft) long section of 0.46 m (18 in) wide with 0.1 m (4 in) rail, ladder back cable tray. The cable tray was located 0.3 m (1 ft) from the ceiling at one end of the test cell. The 0.61 m (2 ft) diameter gas burner was located at the opposite end of the test cell. This arrangement was intended to simulate a fire that would create a hot gas layer around the cable tray.

Thermal Exposure

The fire source consisted of a 0.61 m (2 ft) diameter natural gas burner. The natural gas burner was intended to simulate a remote fire burning below and off to the side of the test cable tray. The testing arrangement created temperatures as high as 800 °C (1472 °F) to 900 °C (1652 °F) at the ceiling. The researcher's goal was to have the cable tray in a hot gas layer of approximately 300 °C (572 °F)[16]. The hot gas layer reached equilibrium at approximately 240 °C (464 °F) about 0.61 m (2 ft) from the ceiling. The natural gas burner was raised off the floor to achieve the sought after temperatures.

Cables Tested

The LLNL test assembly consisted of one, 8/6 welding cable surrounded by one RG 11/u coaxial cable and two 37/C #18 AWG 600 V cables bundled together.

Electrical Performance

The welding cable was energized with 24 or 120 V dc power, and the surrounding cables were instrumented for failure (i.e., current propagating from the welding cable in the center to the surrounding cables.) This assembly was then installed in a cable tray.

Results

The test verified that in less than 5 minutes of fire exposure direct shorts, intermittent direct shorts, and high impedance shorts occurred between cables and/or the cable tray. Additionally, open circuits and the production of electromagnetic fluxes were identified.

16 The report cites that this temperature was based on previous research performed by LLNL large-scale fire tests and SNL/UL tests that demonstrated the maximum ceiling gas temperature of approximately 300 °C (572 °F) with temperatures decreasing with increasing distance from the ceiling [23].

Summary

The researchers determined that electrical faults are probable when the cables are exposed to a flame. They summarized that low impedance faults (direct contact between conductors) or high impedance faults (resistive paths set up from carbonized and metallic particulate) can occur as a result of the fire. These cable failures occurred rapidly, in some cases less than 5 minutes, based on the test fire conditions.

Sandia National Laboratories Research - 1986

Introduction

In 1986, Wheelis of SNL performed for the NRC an experiment titled the "Transient Fire Environment Cable Damageability Test Results: Phase I" [34].

Test Apparatus

The testing was performed in a temperature controlled chamber with a maximum heat up rate of approximately 93 °C (200 °F)/minute and a cool down rate of 18 °C (65 °F)/minute. A fan was located in the test chamber to provide air circulation within the chamber. The energy source used to heat the test chamber was not described in the test report. The cable tray or conduit was located 0.3 m (1ft) from the ceiling of the chamber.

Thermal Exposure

The temperature was increased in a linear fashion starting at approximately 38 °C (100 °F) to 593 °C (1100 °F) at 300 seconds. The chamber was then cooled linearly, reaching approximately 260 °C (500 °F) at 900 seconds. This profile was based on earlier research to determine the Appendix R requirement for 6 m (20 ft) separation between redundant trains of equipment with automatic suppression systems installed in the area.

Cables Tested

In this experiment Wheelis tested a 3/C #12 AWG, XLPE, 600V (IEEE 383 qualified) control or power cable, and 3/C #12 AWG, PE, 600V (Non-IEEE 383 qualified) control or power cable.

Electrical Performance

A 120 V ac three phase power supply was used with one phase connected to each of the conductors. Wheelis insulated the cables from any metallic surfaces, such that the failures could only occur inside the cable.

Results

In the process of performing the testing, the experiment was revised two times. The original test configuration had the conductor terminations inside the test chamber. During the performance of the test, Wheelis noted that the cable jackets experienced shrinkage and flexing around connections which led to electrical shorts. He referred to this condition as "end effects." The Non-IEEE 383 qualified cable failed (conductor to conductor) in the range of 4.5 to 7.17 minutes. The corresponding temperatures in the test chamber at the time of failures were 382 °C (720 °F) to 499 °C (930 °F). The IEEE 383 qualified cable either did not fail or failed at approximately 4.17 minutes. The corresponding air temperatures in the test chamber at the time of the first failure was 327 °C (620 °F). To eliminate the end effect problem, Wheelis looped the cables in the test chamber so that the connections were made outside the chamber. In this second series of tests, two of the Non-IEEE 383 qualified cable failed in the range of 4.08 to 9.25 minutes. The corresponding air temperatures in the test chamber at the time of failures were 332 °C (630 °F) to 510 °C (950 °F). Two other non-IEEE 383 qualified samples did not demonstrate any failures. The IEEE 383 qualified cable did not demonstrate any failures. Wheelis determined there was a problem with where the cables were installed in the cable trays located in the test chamber. Wheelis termed this as "cable geometry." To eliminate this variable, Wheelis removed the cable trays and suspended the cables in the test chamber. In this third series of tests, one of the Non-IEEE 383 qualified cable failed in the range of 4.67 to 5.08 minutes. The corresponding temperatures in the test chamber at the time of failures were 481 °C (900 °F) to 566 °C (1,050 °F). The other Non-IEEE 383 qualified samples did not demonstrate any failures. One of the IEEE 383 qualified cable failed in the range of 8.00 to 8.58 minutes. The corresponding temperatures in the test chamber at the time of failures were 443 °C (830 °F) to 454 °C (850 °F). Two other samples of the IEEE 383 qualified cable did not demonstrate any failures.

Summary

Wheelis' research did not produce any definitive numerical results, establish a consistent trend, or definitively prove that qualified IEEE 383 cables out perform non-qualified cables. His work is important though, in that it demonstrates the potential problems encountered in conducting cable functionality tests. Wheelis also provided two important insights into cable functionality testing. First, Wheelis reports that, "Both qualified and unqualified cables 'heal' themselves to some extent. In all the cases where failure occurred, and usually while the chamber was still cooling down, some of the electrical failures would become less severe, or completely disappear. This was attributed to the thermal expansion and then contraction of the copper conductors. As a result, cable or component damage tests that measure operability only after a test may have no relationship to operability during a test." Second, Wheelis noted that the subsurface thermocouple temperatures (installed under the cable jacket) are affected by whether they are sleeved or unprotected. He noted a temperature difference of approximately 28 °C (50 °F) between the sleeved vs. unprotected thermocouples installed on qualified cables. Wheelis also noted that the thermocouple leads provide a medium to conduct heat into the cable.

Sandia National Laboratories Fire Testing - 1991

Introduction

In 1991, Nowlen of SNL performed for the NRC an experiment titled the "Effects of Thermal Aging on the Fire Damageability of Electrical Cables"[15].

Test Apparatus

Nowlen used the Severe Combined Environment Test Chamber (SCETCH) to develop the heated environment. This chamber had been specifically developed to test equipment in a simulated fire condition environment for equipment vulnerability assessments. The SCETCH is a metal pressure vessel approximately 0.46 m (18 in) in diameter and 0.6 m (24 in) long with a small viewing window in the front. The heat source is provided by quartz heating lamps surrounding the chamber. Varying the power to the lamps controls the temperature inside the chamber. For this testing, the inner chamber wall temperatures were consistent with the desired thermal exposure. Air was circulated through the chamber via a flow-through system where the incoming air was preheated by circulation heaters. For this experiment, the wall temperature and the air temperature were maintained at the same value to simulate a spatially uniform and optically thick hot gas layer. To perform the test, a 609 mm (24 in.) sample of the cable was inserted into SCETCH one at a time at a predetermined test temperature.

Thermal Exposure

The testing was conducted with the chamber at a uniform steady-state temperature. The temperatures used for the testing were between 325 °C (617 °F) to 425 °C (797 °F), increased in increment of 5 to 25 °C (9 to 45 °F).

Cables Tested

In this experiment Nowlen tested two common cables used in NPPs: a 3/C #12AWG, XLPE, 600V, control or power cable, and a 2/C #16AWG, EPR, 600V, instrument cable. The instrument cable was a twisted shield pair with a drain in the cable.

Electrical Performance

The testing involved new cable samples and identical samples that had been exposed to accelerated thermal aging, then evaluated the difference. The aged cables were prepared using the Arrhenius theory[17] of accelerated aging. To test functionality, each of the conductors of the 3/C cable had one phase of a three phase 208 V ac power

17 The Arrhenius theory is based on subjecting a cable to elevated temperatures in order to reproduce the aging condition. This brings the cable to some desired 'aged' condition (including the end of its useful life) in a relatively short period of time.

source connected. The 2/C cable had one phase to each conductor and the third applied to the shield/drain conductor.[18] Throughout the testing leakage current between the three phases of power was continuously measured. Failure was determined when a 2 amp in-line fuse failed. The accuracy of the leakage current was approximated to be 3 mA based on measurement tolerances.

Results

Nowlen reported the following results as shown in Table 6.

Table 6

SNL Cable Functionality Fire Test Results

Cable Type	Unaged Cable Threshold Temperature °C (°F)	Aged Cable Threshold Temperature °C (°F)
3/C, #12AWG, XLPE, 600V Neoprene Jacket (Control Cable)	325-330 (617-626)	350-365 (662-689)
2/C #16AWG, EPR, 600V CSPE or Hypalon Jacket (Instrument Cable)	365-370 (689-698)	345-350 (653-662)

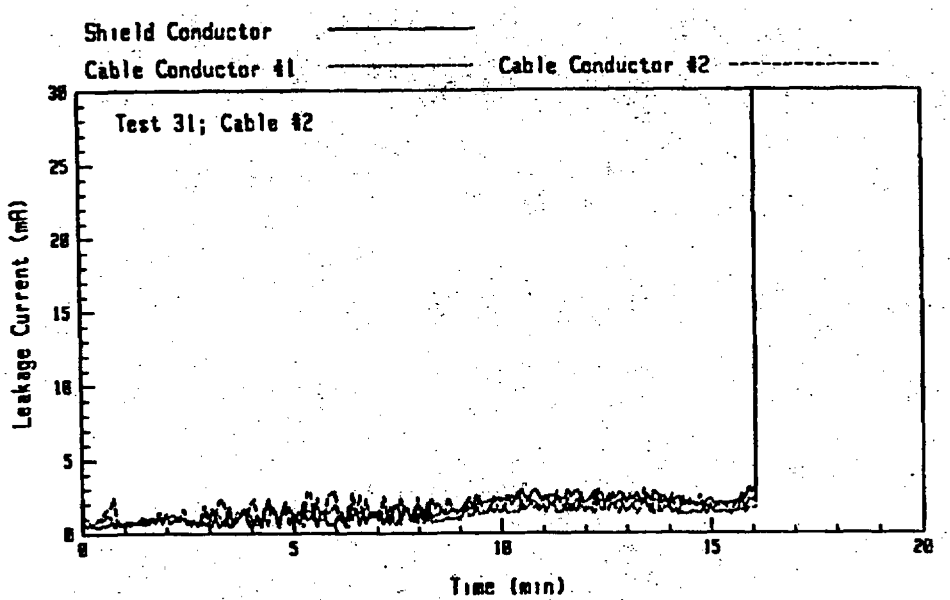
Based on the data for terminal failure provided in the report; for the 3/C, #12 AWG, XLPE, 600V (control cable), the thermal aging appeared to actually improved the cable's performance an average of 15 °C (27 °F), while for the 2/C #16AWG, EPR, 600V (instrument cable), the thermal aging reduced the cable's

18 A 'shield' is generally metallic tape, composition tape or metallic braid applied around the insulated conductors. A 'drain' is typically an un-insulated conductor in the cable to terminate the shield and 'drain' or bleed charge from the shield along its length by providing a low resistance path to ground. The purpose of this construction is reduce or control electromagnetic electrostatic effects on the conductor, or contain the electric field within the cable.

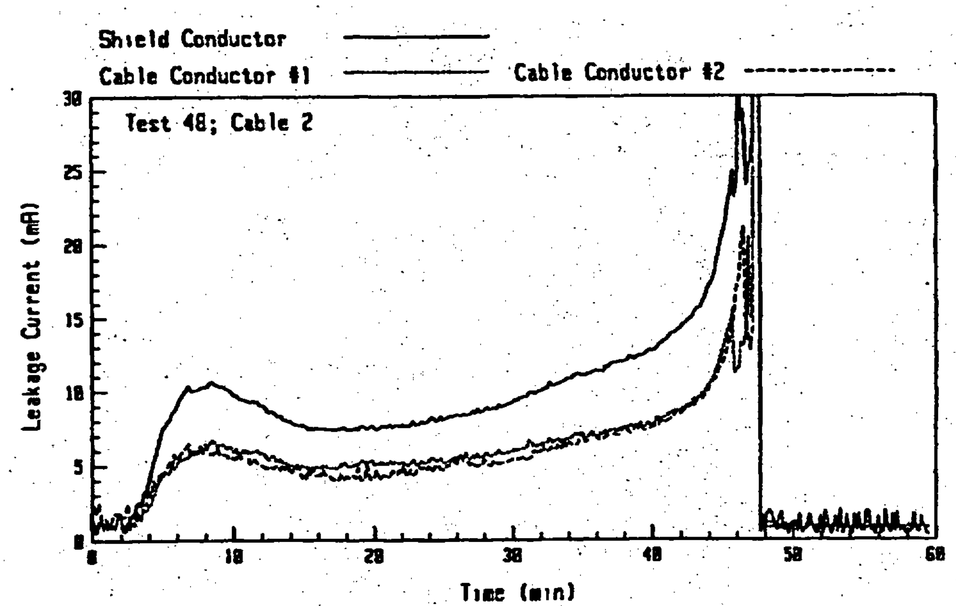
performance an average 10 °C (18 °F). Nowlen noted a consistent difference for the 3/C, #12AWG, XLPE, 600V (control cable), and that the times to failure at any given exposure were longer. For the 2/C #16AWG, EPR, 600V (instrument cable), the data suggests an increased vulnerability for aged cables as compared to new cables. The results of the current leakage tests were not as straightforward. Nowlen noted that aged cables performed quite differently than the new cables. The new cables would remain below the 3 mA level and within acceptable limits until just before cable failure. Conversely, the aged cables would exceed 10 mA leakage approximately 2 to 3 minutes after the start of the test. Current leakage would often run as high as 15 to 25 mA before ultimate failure of the 2 amp fuse. Figure 5 shows these differences for the instrument cable, and Figure 6 for the control cable. Nowlen also reported that for the unaged cable, the jackets would appreciably swell when subjected to heat. Then, after failure of the circuit, sparks from the ensuing fault would ignite the cable resulting in open flaming. The aged cables had already experienced some swelling (from the Arrhenius accelerated aging process) and as such did not experience the same level of swelling. The jackets on the aged cables would then split open and fail similar to the unaged samples. Based on these low amp losses, Nowlen cautions the use of the higher failure temperatures when the cable is employed in sensitive applications.

Figure 5

SNL Unaged and Aged Instrument Cable Current Leakage



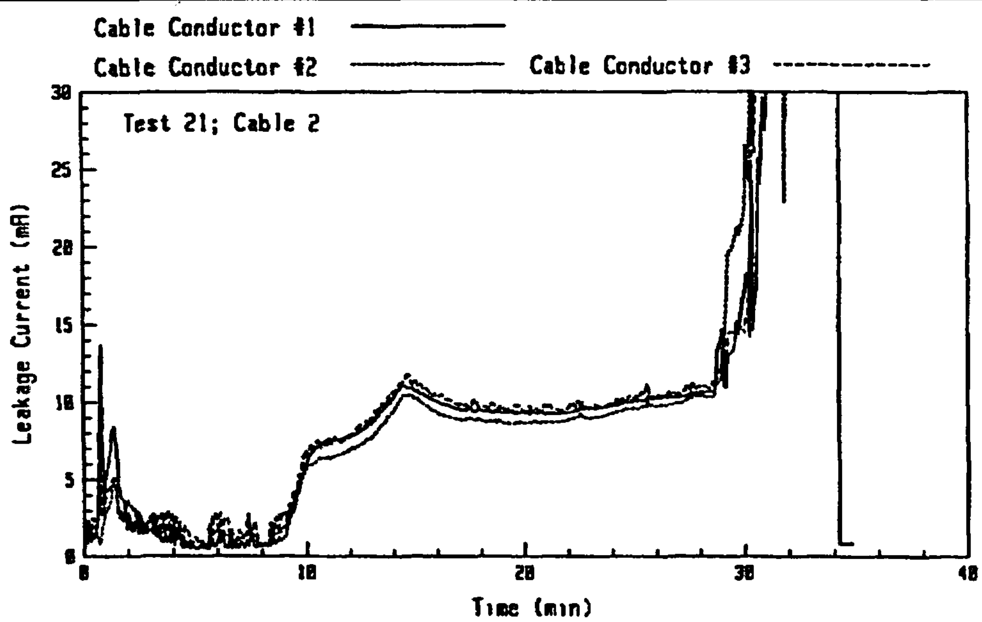
(a) Unaged Instrument Cable



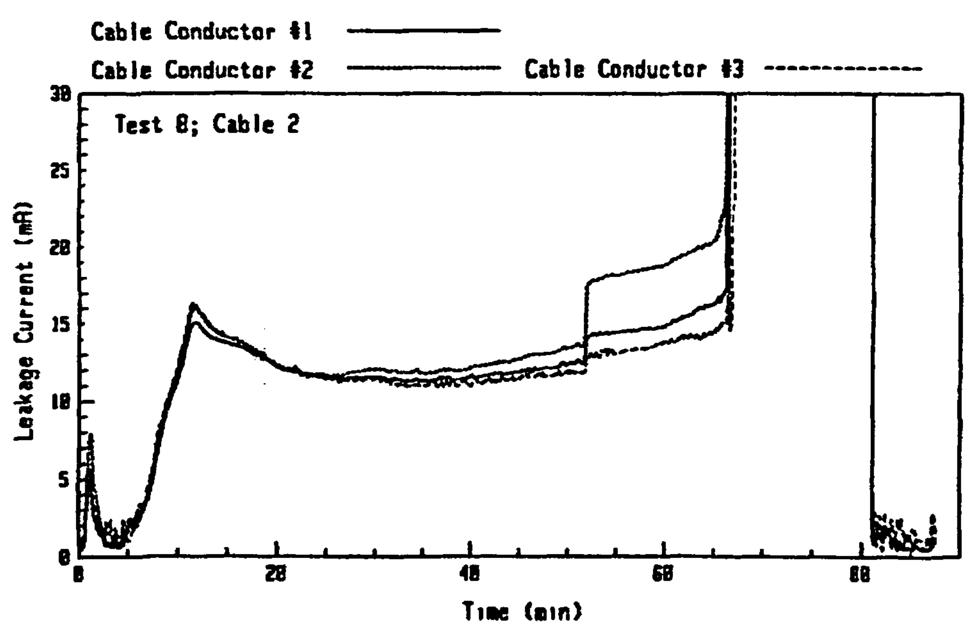
(b) Aged Instrument Cable

Figure 6.

SNL Unaged and Aged Control Cable Current Leakage



(a) Unaged Control Cable



(b) Aged Control Cable

Summary

While Nowlen's research provides interesting data, his application of the Arrhenius aging process may be suspect. The values used for the accelerated aging, i.e., 28 days at 150 °C (302 °F) for the 3/C #12 AWG, XLPE and 28 days at 125 °C (257 °F) for the 2/C # 16 AWG EPR, may have been high enough to alter the chemical composition of the cable's insulation and jacket. The test report noted that for the 3/C #12 AWG, XLPE, "Following the removal of the cable samples from the aging chamber it was noted that the neoprene jacket had developed extensive cracks and had become quite brittle. In several cases handling of the aged cable samples resulted in small sections of the jacket falling away from the cables. Visual inspection of the cable insulation revealed no such cracking. Continuity and insulation resistance testing of the aged samples prior to thermal exposure testing revealed no faults." However there was no chemical analysis of the aged samples. Earlier work performed by Lee (FM 1981) indicated that HCl production starts in the neighborhood of 100 °C (212 °F). This suggests that the artificial aging temperatures employed by Nowlen may have been high enough to produce HCl and chemically alter the test samples. This may explain the performance shift experienced between the aged and unaged samples. As such, Nowlen's results should be used with caution.

Sandia National Laboratories Equipment Qualification Cable Testing - 1991

Introduction

While Nowlen was performing fire effects research on electrical cables, Jacobus and Fuehrer also of SNL were performing cable EQ research [35]. Jacobus' and

Fuehrer's research involved exposing cable samples to the effects of a LOCA. Like Nowlen's work their research involved both new and aged cables. The test method and acceptance criteria used in the EQ work was slightly different. LOCA cable testing involves the cable samples be subjected to higher pressures and radiation exposure in addition to increased temperatures. The testing also involves the samples being subjected to submergence and mandrel bending. Electrical tests are performed on the samples during these conditions. The EQ testing may be considered more in depth due to its structuring and multifaceted approach.

Test Apparatus

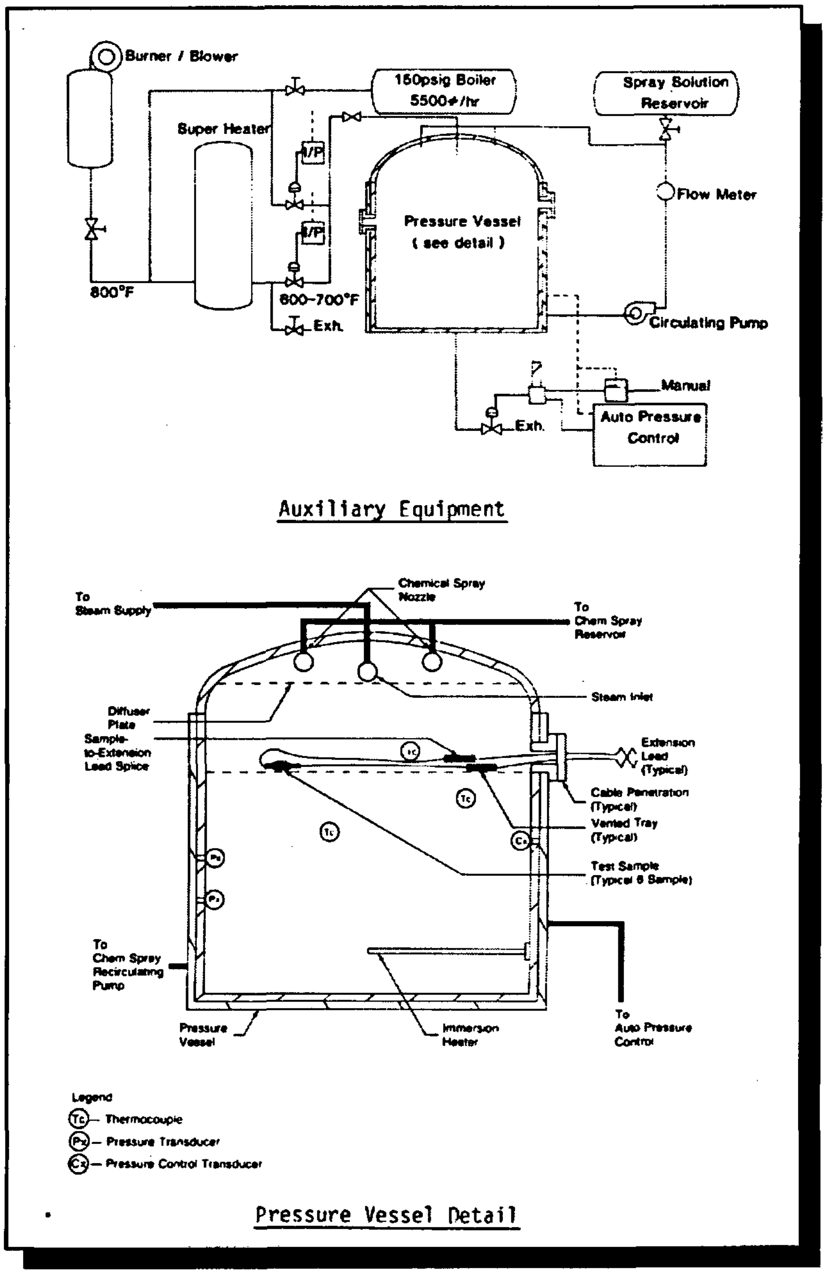
The testing was performed in Sandia's Low Level Intensity Cobalt Array (LICA) facility. The heating was performed using typical LOCA test chambers. These chambers are designed to be able to simulate temperature, pressure, and radiation conditions that would be present in a NPP after a reactor cooling line failure. The heating is performed using steam. A LOCA test chamber is shown in Figure 7.

Thermal Exposure

There were two portions of the testing that dealt with heating the cables. The first portion was used to simulate artificial aging of the cables in accordance with the Arrhenius equation. Cables were heated to 95 °C (203 °F) for three months to simulate a cable that has been in service for 20 years. Additional cable samples were heated to 95 °C (203 °F) for six months to simulate cables that had been in service for 40 years.

Figure 7

LOCA Test Chamber and Auxiliary Equipment[19]



19 This is a sketch of a typical test chamber used for LOCA and other EQ testing. The sketch is from Wyle Laboratories test report 58722-3, "Environmental Qualification Test Report of Raychem Molded Sleeve for Raychem Corporation," dated December 9, 1982.

The second portion of the testing dealt with the adverse environmental conditions the cables would experience in a LOCA. The temperature was increased approximately 10 °C (18 °F) every 15 minutes until the cables failed. This process was accomplished in the chamber using saturated steam up to approximately 165 °C (329 °F), then introducing superheated steam to obtain higher temperatures. Electrical functional testing was performed at each time step.

Cables Tested

This testing used a cross section of cables typically found inside the containment of a typical U. S. NPP. The 12 different cable types were constructed of primary insulations consisting of XLPO, EPR, SR, CSPE, and polyimide.

Electrical Performance

The cables were energized with 110 V dc (Nowlen used 208 V ac, 3 phase), and failure in the EQ test was initially defined as less than 1 kΩ resistance over an equivalent 100 m (329 ft) cable sample. Jacobus and Fuehrer then re-evaluated their data and revised the failure criteria to 0.1 kΩ per 100 m (329 ft).

Results

For the purpose of this thesis, the main point of interest is the temperatures where the cables lost their ability to be considered electrically functional. Jacobus and Fuehrer defined the failure criterion as 1 kΩ per 100 m. Their results are provided in Table 7.

Table 7

SNL EQ Testing Results based on 1 kΩ per 100 m

Insulation Type	Number of Samples	Temperature °C (°F)
XLPO	13	254-378 (489-712)
EPR	16	235-400+ (454-752+)
SR	2	396-400+ (744-752+)
Kerite FR	2	153-171 (307-340)
Polyimide	1	399 (751)

After reviewing the results, Jacobus and Fuehrer Jacobus and Fuehrer re-evaluated the failure criterion as 0.1 kΩ per 100 m. Based on this lowered failure criteria, the EPR and Kerite FR are able to remain functional at significantly higher temperatures. The results are shown in Table 8.

Table 8

SNL EQ Testing Results based on 0.1 kΩ per 100 m

Insulation Type	Number of Samples	Temperature °C (°F)
XLPO	13	299-388 (569-730)
EPR	16	370-400+ (698-752+)
SR	2	396-400+ (744-752+)
Kerite FR	2	372-382 (702-720)
Polyimide	1	399 (751)

Summary

Jacobus and Fuehrer concluded that the EPR cables typically maintained function ability at higher temperatures than the XLPO insulated cables. They also noted that the XLPO insulated cables had no insulation intact at the end of the high temperature steam exposure. However in the submergence and post-submergence dielectric testing, (performed at lower temperatures) the XLPO cables outperformed the EPR cables. Jacobus and Fuehrer also noted that a number of cables that performed well during submergence testing failed post-submergence dielectric testing (before or after the mandrel bending was applied.) They noted that the bending can introduce failures in cable samples that had withstood the testing up to that point.

Sandia National Laboratories Research - Comparison of Fire & EQ Testing

Introduction

In 1992, Nowlen and Jacobus noted that they were testing many of the same cables to similar thermal insults. After reviewing their test data, they suggested that there may be a strong correlation between fire exposure and EQ exposure with respect to electrical cable functionality [36]. The test apparatus, thermal exposure, and electrical performance criteria have been previously described for each researcher's work.

Results

To normalize their respective data, Nowlen and Jacobus chose to use the EQ aging degradation results at an "insulation resistance of 100 Ohms per 100 m of cable, or roughly twice the insulation resistance corresponding to the observed ultimate failure threshold in the Fire-Related study." Their data was within a ± 10 °C (18 °F) tolerance as presented in Table 9.

Table 9

SNL Correlation of fire Test and EQ Test Results

Cable Type	Fire Testing Unaged Cable Threshold Temperature °C (°F)	Fire Testing Aged Cable Threshold Temperature °C (°F)	EQ Testing Aging Degradation Cable Threshold Temperature °C (°F)
3/C, #12AWG, XLPE, 600V (Control Cable)	325-330 (617-626)	350-365 (662-689)	320-322 (608-612)
2/C #16AWG, EPR, 600V (Instrument Cable)	365-370 (689-698)	345-350 (653-662)	375 (707)

Summary

In summary, the work of Nowlen and Jacobus suggests a strong link between unaged cables exposed to the dry convective heating of a fire (test) and the superheated steam thermal insult of an EQ test. Though the thermal exposure is different (wet vs. dry), Nowlen and Jacobus argue the exposure is fundamentally the same. When the cables are protected by an ERFBS such as Thermo-Lag 330-1, the physical exposure correlation (i.e., cables are exposed to moisture in the thermal excursion) is further strengthened.

South Carolina Electric & Gas Company - Kaowool Testing 1999

Introduction

Kaowool is a ceramic fiber blanket insulation material commonly used to line furnaces. Kaowool has been used by a limited number of NPPs to protect their required FSSD circuits. The material is commonly manufactured in 2.54 cm (1 in) thick blankets. The blankets are wrapped around the electrical raceway and associated supports to form an ERFBS. One, two or three layers have typically been used in order to achieve the desired fire resistance. In 1999 South Carolina Electric & Gas Company (SCE&G), the licensee of the Virgil C. Summer Nuclear Station (VCSNS), contracted Transco Products, Inc. to perform a full scale fire test on the Kaowool ERFBS installed at VCSNS. The SCE&G design used 3 layers of Kaowool in attempt to provide a rated 1-hour ERFBS. The testing is documented in OPL report "Kaowool Triple Wrap Raceway Fire Barrier Test for Conduits and Cable Trays" [37].

Test Apparatus

The testing was performed in OPL's full-scale fire test furnace. The surfaces of the electrical raceways were instrumented with thermocouples prior to the installation of the Kaowool ERFBS. A #8 AWG stranded bare copper conductor with thermocouples mechanically attached every 15.24 cm (6 inch) was installed in each raceway along with the electrical cables. Select electrical cables were meggered prior to the test to establish their baseline performance. The instrument used to determine the insulation resistance (IR) was a Associated Research "Meg-Check" Model 2956A, with a voltage range of 1 to 5 kV, and an ohm range of 0.1, 1, 10, 100 MΩ.

Thermal Exposure

The testing was performed following the Standard Time Temperature curve of ASTM E119 for a period of 1 hour.

Cables Tested

The SCE&G testing included electrical cables for two purposes. First, the cables provided the minimum cable mass as installed in VCSNS. This minimum heat sink will provide the best system performance. Second, if the raceway exceeds the maximum allowable temperature rise, the electrical cables could be functionally tested in an effort to demonstrate they are free of fire damage and, therefore, remained functional. The size and types of cables tested are shown in Table 10. The cables used were manufactured by the Kerite company. Kerite identifies their material as Fire Restive (FR) insulation and jacket. The FR insulation and jackets are manufactured of extruded thermosetting vulcanized flame retardant synthetic rubber. One cable (3/C #8AWG), used High Temperature Kerite (HTK) insulation. HTK is also a extruded thermosetting vulcanized flame retardant synthetic rubber.

Electrical Performance

Approximately one half of the 6.08 m (20 ft) cables were in the protected electrical raceways inside the furnace. Selected cables were meggered before the start of the test, immediately after the thermal exposure (i.e., 1 hr), and finally immediately after the hose stream test was completed. The cables meggered at a potential of 1 kV dc for all three tests. The resistance between conductors, in ohms, was measured starting at the highest scale (100 MΩ) working downward to the lowest scale (0.1 MΩ) when changes were necessary.

Results

The results of the testing is shown in Table 10.

Table 10

SCE&G 1999 Kaowool Protected Cables Functionality Test Results

Cable #/C AWG	Insulation / Jacket	Insulation Resistance in Megaohms (MΩ)			Temperature Bare #8 °C (°F)	
		Pre-test	Post-test	Post-hose	Ave.	Max.
2/C #9	FR/FR	200K	Fail[1]	Fail[1]	442 (828)	609 (1128)
4/C#12	FR/FR	200K	11 to 13	1 to 2	122 (252)	184 (363)[2]
5/C #12	FR/FR	200K	Fail[1]	0.32	122 (252)	184 (363)[2]
3/C #8	HTK/FR	∞	∞	100K[3]	122 (252)	184 (363)[2]
5/C #12	FR/FR	100K	Fail[1]	Fail[1]	237 (458)	329 (606)

Notes:

1. Fail is defined as no resistance measured at the lowest scale (0.1 MΩ) with 1 kV applied. For test purposes, it's considered the conductor shorted.
2. See discussion for external raceway temperatures.
3. One of the three conductors failed the post-hose stream test meggering. The problem was thought to be with a splice outside the test deck that was inadvertently wetted.

The 2/C #9AWG failed the post-fire test and post-hose stream megger testing. This could be expected considering the average and maximum final temperatures at the end of the 1 hour fire test. The final average temperature was 442 °C (828 °F) with 609 °C (1128 °F) being the highest single temperature recorded. The 5/C #12 AWG also failed the megger test for both the post-fire test and post-hose stream test. The average and maximum temperatures recorded inside the Kaowool protected raceway are not considered extreme for a thermosetting insulated cable (237 °C [458 °F] and 329 °C [606 °F], respectively). The thermosetting insulated 4/C #12 AWG performance requires additional analysis based on the megger testing results at the end of the testing. Again, the average and maximum temperatures recorded are not considered that extreme for thermosetting insulated cables (i.e., 122 °C [252 °F] average with 184 °C [363 °F] as the single highest temperature recorded during the 1 hr. fire exposure.)

It is noteworthy that the temperature recorded on the outside of the raceway (under the Kaowool ERFBS) exceeded the average allowable temperature rise of 139 °C (250 °F) at 46 minutes into the 1 hr fire test. The average temperature at the end of the test was 245 °C (473 °F) with the maximum single point temperature recorded at 344 °C (651 °F). Although the meggered cables were randomly located inside the cable tray with other cables, the cables could have been in contact with the metallic raceway. This provides further evidence that the NRC decision to apply ASTM E 119 acceptance criteria to the metallic raceway surface under the ERFBS is conservative [11]. The HTK insulated cable, installed in the same Kaowool protected cable tray, remained operable at higher temperature experienced at the end of the fire test, thus outperforming the FR insulated cables.

The one 5/C #12 AWG FR/FR cable also demonstrated some curious results. The cable failed the post-test meggering, but recorded 0.32 MΩ resistance in the post hose stream testing. This behavior has typically been associated with thermoplastic insulated conductors, where as the cable cools, the insulation solidifies and becomes functional again. However, the FR/FR cable is thermosetting. Thermosetting cables will often exhibit additional failures during the post-hose stream testing as any moisture enters the cracks in the thermosetting insulation and forms a path to the ground plane. A possible explanation of the 5/C #12 AWG FR/FR cable regaining IR after failing the post-test meggering could be the mechanical impact of the hose stream test disturbing the conductors within the cable.

Electrical Analysis

As shown in Table 10, the 4/C #12 AWG FR/FR cable demonstrated a degrading IR at the post-test megger reading (11 to 13 MΩ), and a further degradation at the post-hose stream test megger reading (1 to 2 MΩ). With these lower IR values the cable must be qualified for use in the rated 1 hr ERFBS in accordance with GL 86-10, Supplement 1 [11]. Generic Letter 86-10, Supplement 1 provides equations to evaluate the specific cable application. The guidance of GL 86-10, Supplement 1 are derived from IEEE 690, "IEEE Standard for the Design and Installation of Cable Systems for Class 1E Circuits in Nuclear Power Generating Stations" [38]. IEEE 690 is the standard used to establish the requirements for the design, installation, and testing of installed electrical cables in a NPP. After an electrical cable is installed in the NPP, the cable must be tested to verify that it was not damaged during installation.[20] IEEE 690, Appendix A, Section A10, "Acceptance Testing of Installed Cables - Recommendations," states that

20 An example of possible damage to a new electrical cable would be skinning or nicking the jacket and insulation during a cable pull through a conduit. This damage may not be visible (since the cable is inside the conduit) and must be quantified by other means.

the insulation resistance for the new cable installation should be measured. The following equation is provided:

$$R \text{ in } M\Omega = (\text{rated voltage in kV} + 1) * (1000/\text{ length in ft}) \quad \text{(Equation 2)}$$

Given that the cable length is known and the IR is recorded at the end of the test, the equation can be rearranged as follows to solve for the maximum voltage:

$$\text{Rated voltage in kV} = [(1000/\text{ length in ft})/(R \text{ in } M\Omega)] - 1 \ . \quad \text{(Equation 3)}$$

This method is applicable to new cable installations. Generic Letter 86-10, Supplement 1 further defines this relationship with the following expression:

$$IR \text{ in } M\Omega \geq [(K + 1 \ (M\Omega) * 1000 \ (ft)) / \text{Length } (ft)] \qquad \text{(Equation 4)}$$

Where:

$$K = (1 \ M\Omega / kV) * [\text{Operating Voltage (expressed in kV)}]$$

Assuming the 4/C #12 AWG FR/FR cable is used in a implied 120 V control application,[21] solving for K gives:

$$K = (1 \ M\Omega / kV) * (0.120 \ kV)$$

$$K = 0.12 \ M\Omega$$

Solving for the minimum acceptable IR gives:

$$IR \text{ in } M\Omega \geq [((0.12 + 1) * 1000) / 20]$$

$$IR \text{ in } M\Omega \geq 56$$

Reviewing the test data from Table 10 (Post-Test = 11 to 13 MΩ and Post-Hose Stream = 1 to 2 MΩ) indicates that this cable would not meet the Pass/Fail criteria of IEEE 690 for new installations or the NRC guidance provided in GL 86-10,

21 Based on the size of the cable and its construction, this would be the most likely application of the cable.

Supplement 1. However, it must be remembered that the cable has experienced a severe thermal insult, (as opposed to testing a new cable installation per IEEE 690) and the cable still has 1 MΩ resistance. If the cable's application only required 10^5 Ω or less resistance, further electrical engineering analysis may be able to justify the cable is functional.

Thermo-Lag 330-1 ERFBS

Introduction

Thermo-Lag 330-1 is an subliming, ablative material. The chemical composition of Thermo-Lag 330-1 is proprietary to TSI. This material can be installed on electrical raceways containing FSSD electrical cables to limit their exposure to the heat transfer from a fire. The material is manufactured in nominal (5/8 ± 1/8 in) flat panels (for use on cable trays and junction boxes), and in half round sections (sized for use on conduits).

When exposed to the heat flux and elevated temperature of a fire, the Thermo-Lag 330-1 reduces the heat transfer rate by dissipating the heat energy. In this process, the ablative agent is consumed through sublimation and mass loss, which when properly designed provides cooling and forms a thermal shield. The first installations of this material in NPP applications did not fully recognize the physical properties and limitations of the material, nor did they understand the full benefits of the material. Following a series of full-scale test failures, the NRC alerted each NPP licensee through a series of Generic Letters and Bulletins. There were two primary modes of failure. First, on conduits less than (4 in), the temperatures recorded on the raceway exceeded the maximum allowable limits, and second, joints on the barriers where two sections of the material butted, were opening during the fire test. The TVA undertook an extensive testing program to understand the material. Salley and Brown at the TVA designed, engineered, tested, and qualified a series of Thermo-Lag 330-1 ERFBS for use in TVA's NPPs [39].

Test Apparatus

All TVA Thermo-Lag 330-1 tests were conducted in a full-scale fire test furnace used to conduct ASTM E-119 testing. Each test was run at a neutral to slight positive furnace pressure. All testing was conducted at OPL, San Antonio, Texas.

Thermal Exposure

The thermal exposure for these tests was the ASTM E-119 Standard Time Temperature curve. TVA tested and qualified both 1 and 3 hour designs.

Cables Tested

The majority of the TVA testing was performed with empty raceways. This is considered to provide the worst case arrangement from a heat transfer standpoint since any cables inside the Thermo-Lag protected raceway would act as a heat sink and lower the overall temperatures inside the raceway. TVA did perform a series of tests with cables in order to gain an understanding of the function of mass inside the Thermo-Lag 330-1 ERFBS.

Electrical Performance

TVA's philosophy was that the fire testing and electrical functionality testing were dependant but should be conducted separately. The primary reason for this decision was testing setups. If a megger test was performed on cables installed in the ERFBS during the fire test and a cable would short to the raceway, the thermocouples on the raceway would be subjected to the 500 V dc and corrupt the fire test data. Further, TVA could use the thermal profile recorded on the #8 AWG stranded bare copper conductor inside the protected raceway to perform air oven testing. This also provided TVA with the option to test different cable types for use in the particular ERFBS design.

Results

The TVA testing confirmed that conduits 10.16 cm (4 in) and larger could be successfully protected with a single layer of material. However, for smaller conduits an additional layer of Thermo-Lag 330-1 would be required. TVA testing also determined that a simple modification of adding an external layer of stainless steel mesh and trowel grade Thermo-Lag 330-1 material could alleviate the joint failure problems. Many of the TVA Thermo-Lag 330-1 ERFBS designs featured this external stress skin layer of stainless steel mesh covered with trowel grade Thermo-Lag 330-1 material. TVA testing further revealed that the external stainless steel mesh provided superior performance of the material. The external layer of stainless steel mesh effectively controlled and directed the Thermo-Lag's subliming, ablative reaction to that of a more effective ablative shielding process as shown in Figure 8.

This design change from the vendor's recommended installation procedure effectively drives the chemically released moisture in toward the raceway, thus maintaining the raceway (and enclosed cables) in the neighborhood of 100 °C (212 °F) rather than attempting to cool the fire (furnace) environment. This in effect established an effective thermal plateau as illustrated in Figure 9. The protected raceway would remain in this region for a period of time dependant upon the raceway's size, content (i.e., cable mass) and thickness of the Thermo-Lag 330-1 material.

Figure 8

TVA Designed Thermo-Lag 330-1 ERFBS

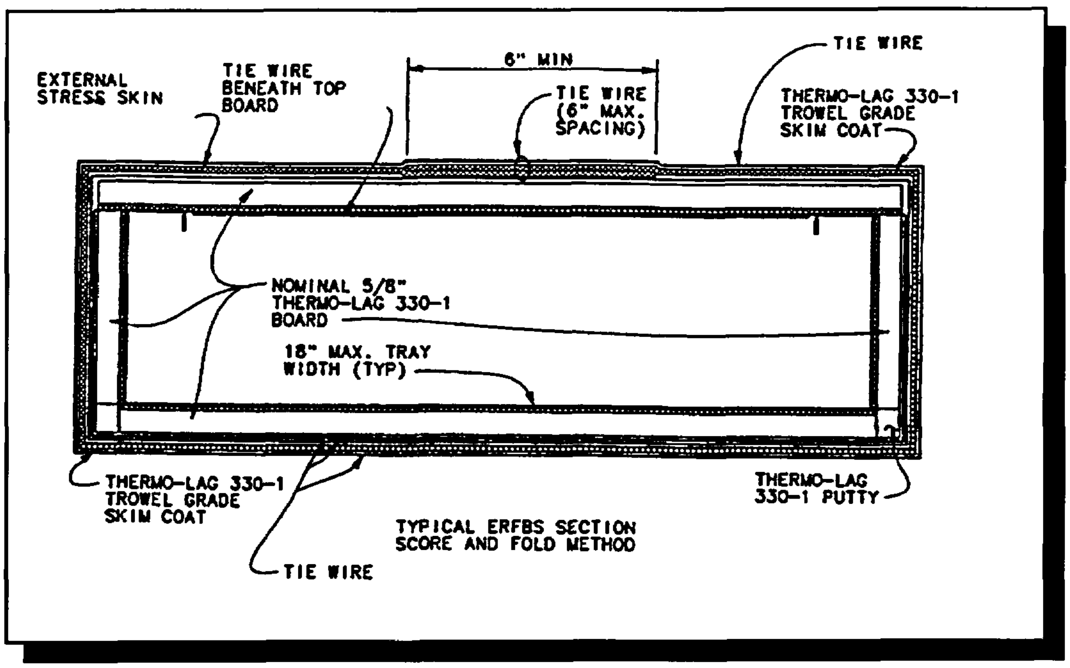
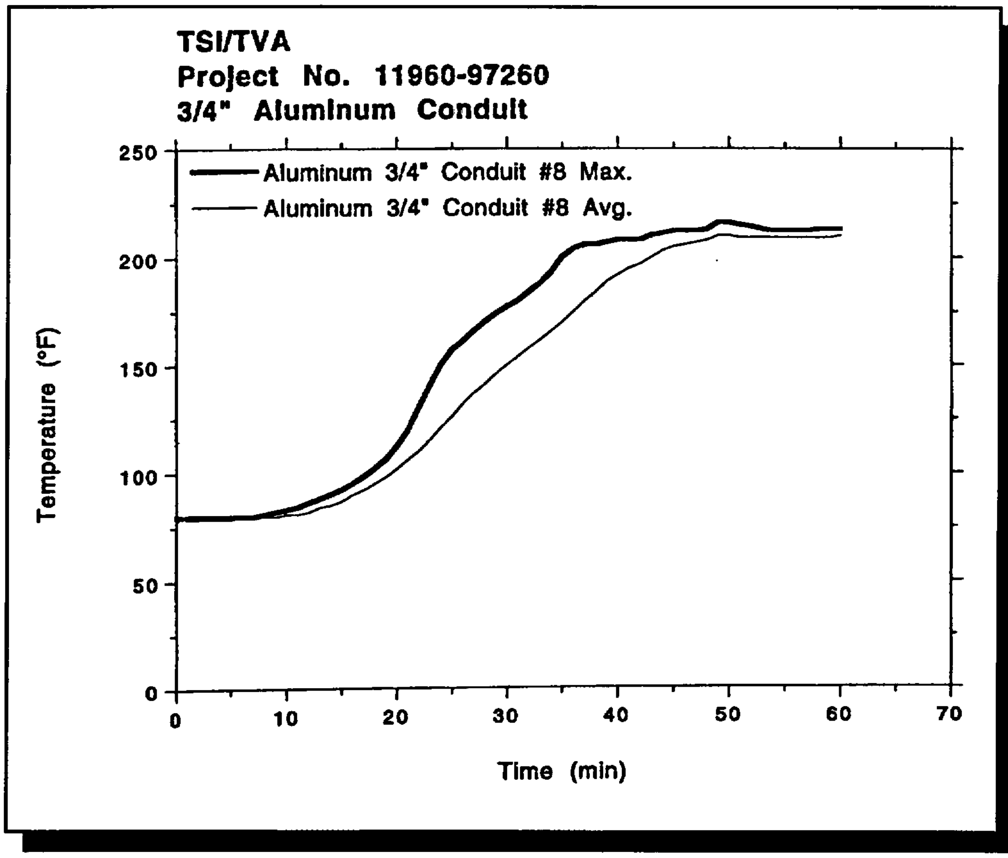


Figure 9

TVA Thermo-Lag 330-1 Thermal Performance



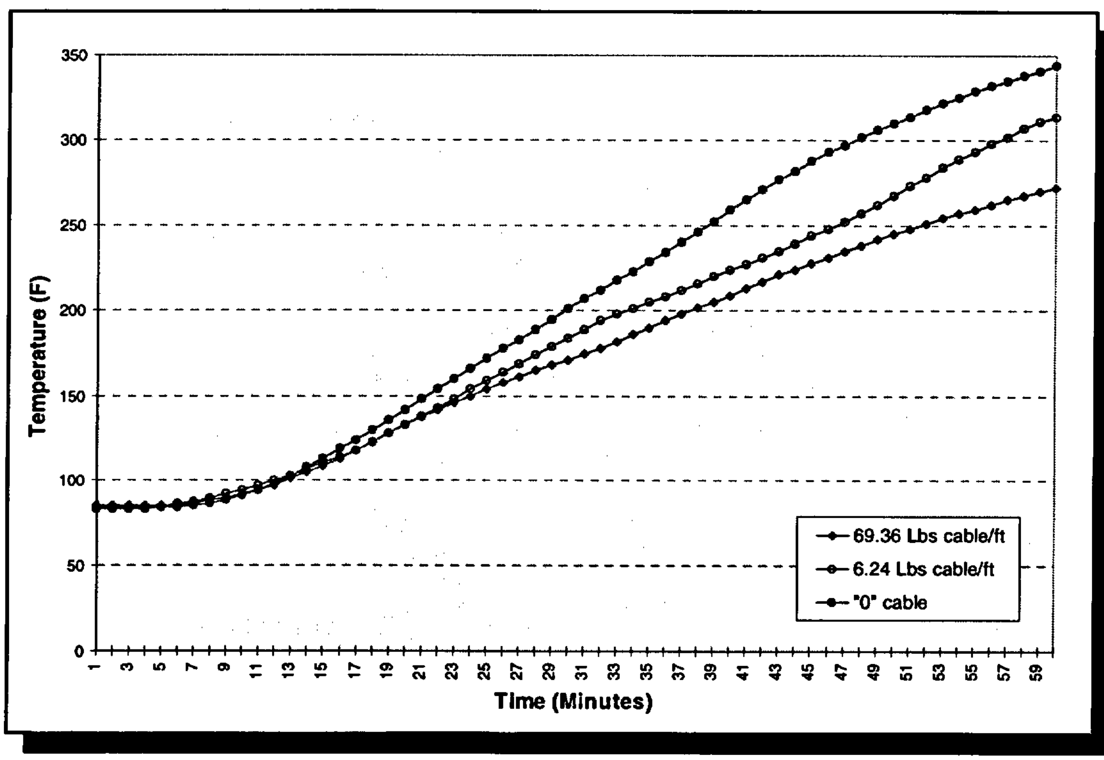
Effects of Cable Mass in the Thermal Performance of ERFBS

As a part of the TVA Thermo-Lag 330-1 ERFBS program, Salley and Brown investigated the effects of cable fill on the thermal performance of the ERFBS [40]. The following is their description of the cable tray testing and resultant relationships.

The first three Phase II fire tests of the joint TVA/TSI program were dedicated to cable tray configurations. TVA test 6.1.7 "Fire Endurance Test of Thermo-Lag 330-1 Fire Protective Envelopes (Three 18 in. Cable Trays and a 3 in. Conduit)" [41] consisted of three 18 inch wide, ladder back, steel cable trays with identical upgraded ERFBS and varying cable fill. The left tray in the test deck represented a maximum filled tray (i.e., 289 4/C #16 AWG [69.36 Lbs. cable/linear ft]). The center tray in the test deck was filled with a single layer of cables (i.e., 26 4/C #16 AWG [6.24 Lbs. cable/linear ft]). The protected cable trays were constructed by the same installers and subjected to the same test fire in order to reduce as many variables as possible. The right tray in the test deck represented an empty tray i.e., no cables). The results of the fire test are shown in Figure 10.

Figure 10

Effects of Cable Mass on Cable Tray ERFBS Performance



At the end of the test, the only thermocouples to exceed the acceptance temperature were those on the instrumented bare #8 AWG copper cable inside the empty tray. This occurred at 56 minutes into the 1 hour test. The ambient temperature at the start of the test was 28 °C (83 °F) which dictated a maximum average temperature of 167 °C (333 °F) at 60 minutes (ambient temperature plus 121 °C (250 °F) allowable rise). By plotting the weight of each cable tray system (i.e., the weight of the tray and cables and not including the weight of the Thermo-Lag 330-1 ERFBS which was approximately the same for each tray) versus its temperature at 60 minutes, an expression for the effects of cable mass can be developed (lumped heat formation).

$$\dot{q}'' A = mCp\, \partial T/\partial t \qquad \text{(Equation 5)}$$

$$\partial T/\partial t = \dot{q}'' A / mCp$$

$$T - T_\infty = \dot{q}'' A / mCp\,(t)$$

$$T = T_\infty + \dot{q}'' A / mCp\,(t) \qquad \text{(Equation 6)}$$

where:

m = mass of raceway (m_r) + mass of cable (m_c)
$\dot{q}''$ = rate of heat transfer
A = area
Cp = specific heat

The correlation of the curves could be further defined as follows:

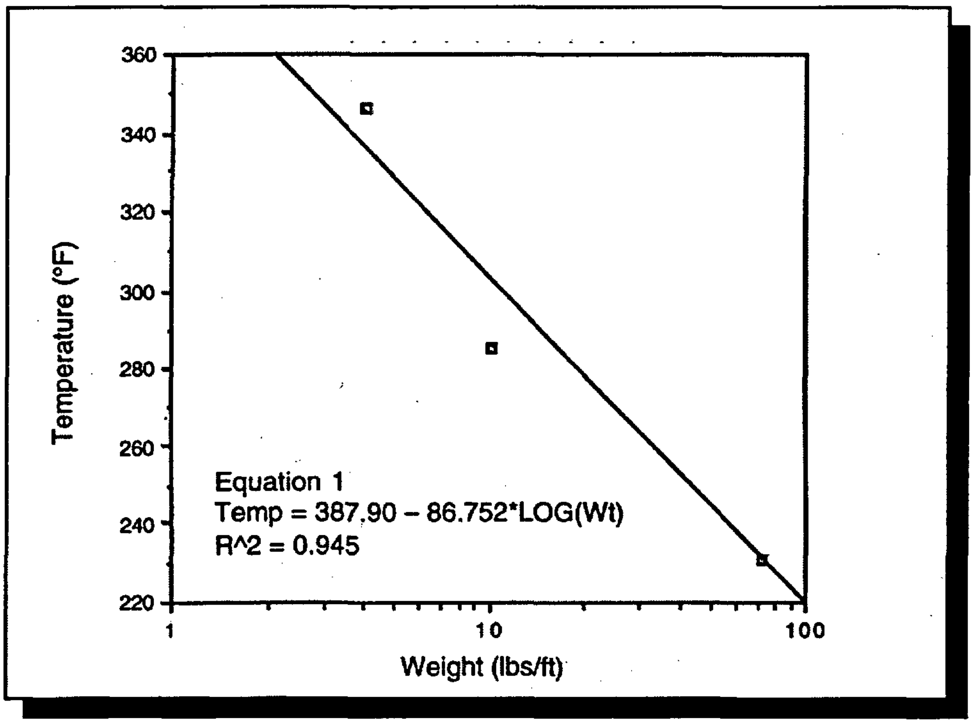
$$\dot{q}'' A = (m_r\, Cp_r + m_c\, Cp_c)\ \partial T/\partial t \qquad \text{(Equation 7)}$$

$$T = T_\infty + \dot{q}'' A/(m_r\, Cp + m_c\, Cp_c)\, t \qquad \text{(Equation 8)}$$

The test laboratory, OPL, developed an exact equation using a computer model based on a "best fit" curve approach with a logarithmic relationship from the data shown in Figure 11 (i.e., results of linear regression, method of least squares).[22]

Figure 11

Cable Tray System Weight vs Endpoint Temperatures - Test 1



The equation is:

$$\text{Final Temp.} = 387.9 - 86.75 * \text{Log (Weight)} \quad \text{(Equation 9)}$$

where:

Final Temp. = Degrees Fahrenheit[23]
Weight = Lbs/ft of cable tray and cables

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22 The constants developed for these equations were originally based on the British Units and no International System of Units (SI) conversions were performed.

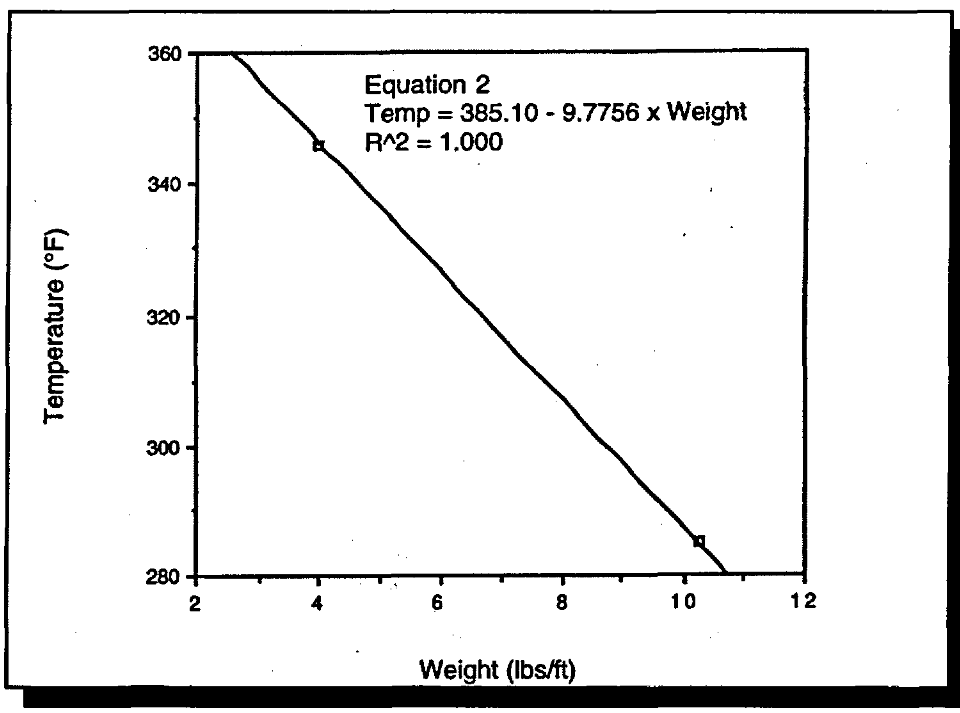
23 The ambient starting temperature of 83 °F must be used for the equation to be valid. The figure has been simplified (i.e., the ambient temperature subtracted) to graphically show the allowable temperature rise (i.e., Δ T =250 °F).

This equation is valid for 18 inch wide cable trays protected with the TVA designed Thermo-Lag 330-1 ERFBS having cable fills ranging from 6.24 Lbs/ft up thru 69.36 Lbs./ft.

Further review was performed on the results of the single layer filled cable tray (6.24 Lbs/ft of cable) and the empty cable tray (0.0 Lbs./ft of cable.) This was determined to be necessary since the effects of adding cables over the first layer becomes less important due to the cable insulation slowing the heat transfer to the copper conductors. This data is shown in Figure 12.

Figure 12

Cable Tray System Weight vs Endpoint Temperatures - Test 2



Conservatively, a plot was constructed of the temperatures for the empty cable tray (0.0 Lbs./ft of cable) and the single layer cable tray (6.24 Lbs./ft of cable). The resulting linear equation given below conservatively predicts the system's thermal response at low cable fills (i.e., less than 6.24 Lbs./ft of cable).

Final Temp. = 385.10 - 9.7756*(w) (Equation 10)[24]

where:

Final Temp. = Degree Fahrenheit[25]
w = total weight of cable tray and cables (Lbs/ft)

Solving this linear equation in the range of acceptable temperatures indicates that a cable tray system with a weight of 5.33 Lbs/ft would maintain acceptable temperatures for 60 minutes. Subtracting the weight of the cable tray (4.00 Lbs./ft) from the system yields a cable loading of 1.33 Lbs./ft. Based on the cables used in the test (4C #16 AWG = 0.24 Lbs./ft), a minimum of 6 cables are needed to produce acceptable temperatures (i.e., $\Delta T \leq 250$ °F).

The TVA has also performed similar tests on Thermo-Lag 330-1 ERFBS for aluminum conduits as installed at SQN [42]. The testing consisted of three, 76.2 mm (3 in.) diameter aluminum conduits with identical minimum 12.7 mm (½ in.) thick Thermo-Lag 330-1 ERFBS. Conduit "B" had no cable fill, conduit "C" had five 7/C #16 AWG (0.85 Lb/linear ft) cables installed, and "D" had 16 7/C #16 AWG

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24 The constants developed for these equations were originally based on the British Units and no International System of Units (SI) conversions were performed.

25 The ambient starting temperature of 83 °F must be used for the equation to be valid. The figure has been simplified (i.e., the ambient temperature subtracted) to graphically show the allowable temperature rise (i.e., $\Delta T = 250$ °F).

(2.70 Lb./linear ft) cables installed. Figure 13 shows the plot of the system weight vs. endpoint data for the surface of the conduit while Figure 14 shows the plot of the system weight vs. endpoint data for the bare copper conductor located inside the conduit.

Figure 13

Conduit System Weight vs. Endpoint Temperatures - Measured on the Conduit

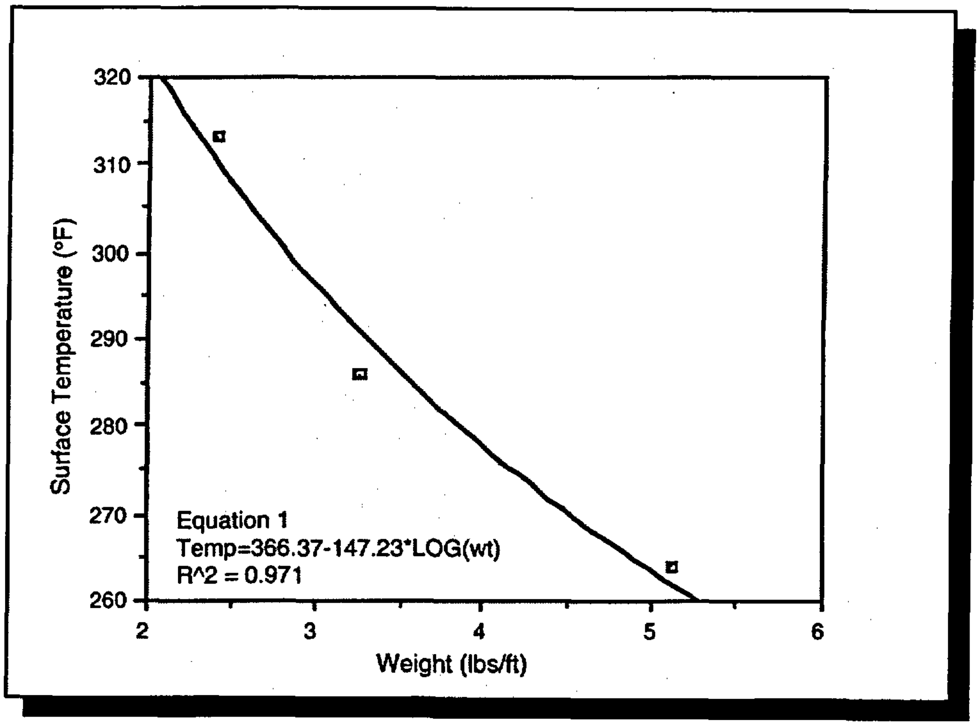


Figure 14

Conduit System Weight vs. Endpoint Temperatures
Measured on the Bare Copper Conductor Inside the Raceway

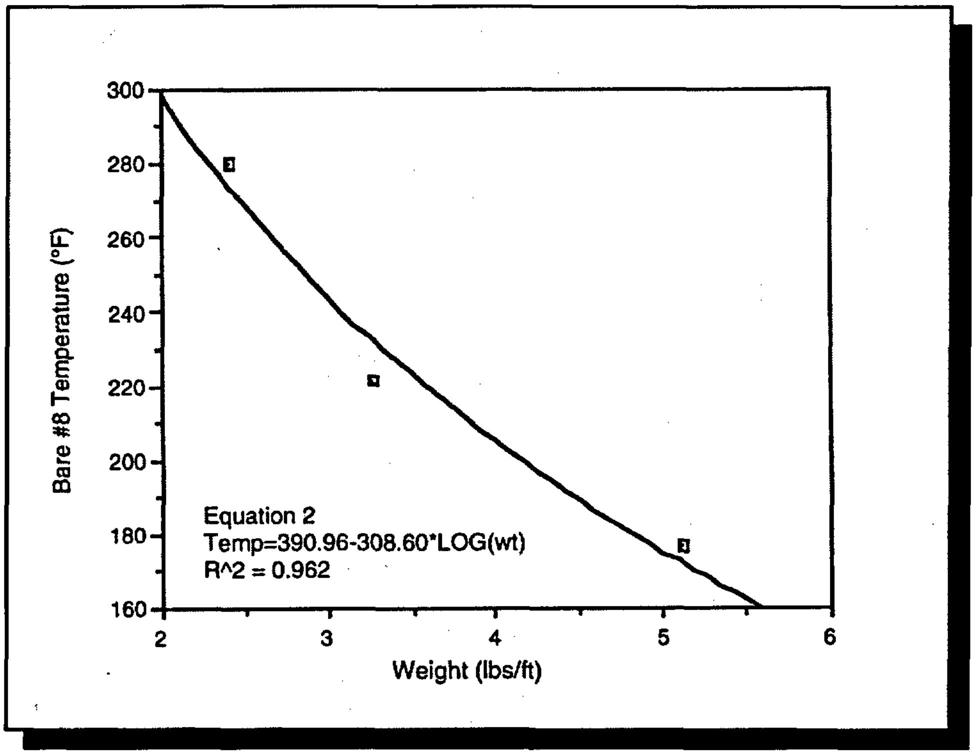


Table 11 shows the temperatures recorded at the end of the 1 hour ASTM E 119 fire exposure.

Table 11

Effects of Cable Mass on ERFBS Thermal Performance

Conduit (Number of Cables)	Average External Conduit Temperature °C (°F)	Average Internal Conduit Temperature °C (°F)
B (0)	138 (280)	156 (313)
C (5)	105 (221)	141 (286)
D (16)	81 (177)	129 (264)

Reviewing the temperature profiles, the plots demonstrated that the rate of temperature rise was inversely proportional to the cable mass. Performing a linear regression, method of least squares, OPL developed the following relationships to predict the end point temperature based on cable mass:

External Conduit Temperature (°F) = 366.37 - 147.23*Log (w +2.41) (Equation11)

Internal Conduit Temperature (°F) = 390.96 - 308.60*Log (w +2.41) (Equation 12)

where:

Temperature = final temperature in °F at 60 minutes of exposure with an assumed starting ambient temperature of 65 °F

w = weight in pounds of cable per linear foot (Lbs/ft)

Another noteworthy observation is the average external surface temperature of the aluminum conduit compared to the average internal temperature as shown in Table 12. The cable fill not only reduces the external temperature rise of the raceway as shown by the values in Table 11, but an even greater temperature reduction occurs inside the raceway (Table 12).

Table 12

ERFBS Protected Conduit - External Raceway Surface vs. Internal Area Temperature Differential as a Function of Cable Mass

Conduit (Number of Cables)	External vs. Internal Temperature Difference as a Function of Cable Fill C° (°F)
B (0)	18 (64)
C (5)	36 (97)
D (16)	48 (118)

In summary, the TVA research demonstrated that properly designed and installed Thermo-Lag 330-1 provides an effective ERFBS. The TVA research also provides insight to the effects of thermal mass inside a protected electrical raceway, and the temperature gradients across the assembly.

Fire Exposure in a NPP

The thermal exposure to the cables has a major impact on the functionality of the cables, and as such is a subject all to its own. A short discussion on the thermal exposure is necessary in this thesis for completeness. Thermal exposure as related to cable functionality can be divided into two broad categories; exposure of cables protected by ERFBS and exposure of cables that are not protected.

Thermal Exposure of Protected Cables

A fire protection engineering topic that continually generates debate is that of the thermal exposure used in fire testing. Many engineers, code organizations, regulators, and others have expended considerable effort and resources to research this topic. At the request of the NRC, Cooper and Steckler of the National Institute of Standards and Technology (NIST) researched this topic in 1996 to determine the impact on the Thermo-Lag ERFBS issue [43]. The objective of their work was to "propose a methodology for developing and implementing NPP-specific descriptions of fire environments and associated ASTM-type furnace test methods." They determined that a set of specific NPP time/temperature curves could be developed for different areas within the plant based on the hazard present and the compartment's configuration. However, this would require an extensive commitment of time and resources to undertake. Further, if such a series of time/temperature curves was available, the economic worth of multiple testing of a single ERFBS design to each of the new curves would be questionable. Currently there are two recognized time/temperature curves available, the ASTM E 119 Standard Time/Temperature curve (Figure 15) and the ASTM E 1529 Hydrocarbon Time/Temperature curve (Figure 16) [44, 45]. Currently, regardless of the hazard, the only fire test curve used for NPP applications is the ASTM E 119 Standard Time/Temperature curve. Section 1.3 of ASTM E 119 makes known the proper use of the test, "This standard should be used to measure and describe the response of materials, products, or assemblies to heat and flame under controlled conditions and should not be used to describe or appraise the fire-hazard or fire-risk of materials, products, or assemblies under actual fire conditions. However, results of the test may be used as elements of a fire-hazard assessment or a fire-risk assessment which takes into account all of the factors which are pertinent to an assessment of the fire hazard or fire risk of a particular end use" [45].

After a full-scale ERFBS test has been completed, the thermal response data as measured inside the raceway can be used to define the input time/temperature profile for a more specific cable functionality test as described in GL 86-10, Supplement 1 [11] or Underwriters Laboratories (UL) Subject 1724, "Outline of Investigation for Fire Tests for Electrical Circuit protective Systems" [27]. A conservative generic test curve for the internal temperatures of a rated ERFBS can be constructed for cable functionality verification. Recall that GL 86-10 Supplement 1 [11] allowed a maximum average temperature rise of 139 °C (250 °F) for the rated period (1 or 3-hour for NPP application). The 139 °C (250 °F) temperature rise over the 1-hour period can be linearly approximated as a 2.02 °C (4.17 °F) rise per minute (Figure 17) and for 3 hour applications as a 0.67 °C (1.39 °F) rise per minute (Figure 18). The test temperature at the start of the cable functionality test can be based on the ambient temperature of the compartment in which the cables are installed. Typically, for areas of a NPP in operation during the summer months, ambient temperature values ranging from 20 °C (68 °F) up to 50 °C (122 °F) can be used.

Figure 15

ASTM E 119 Standard Time/Temperature Curve

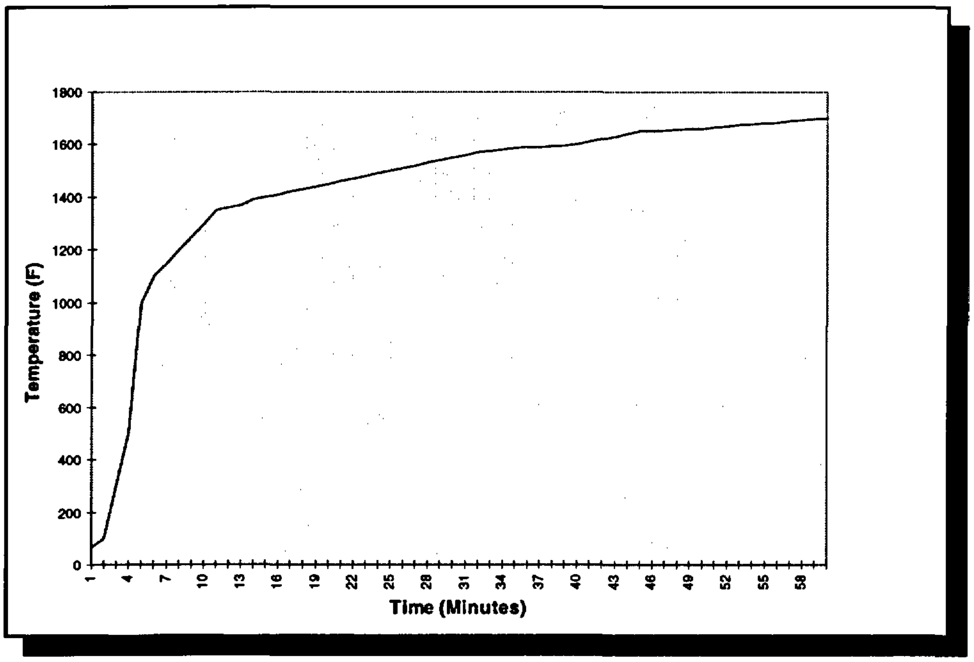


Figure 16

ASTM E 1529 Hydrocarbon Time/Temperature Curve

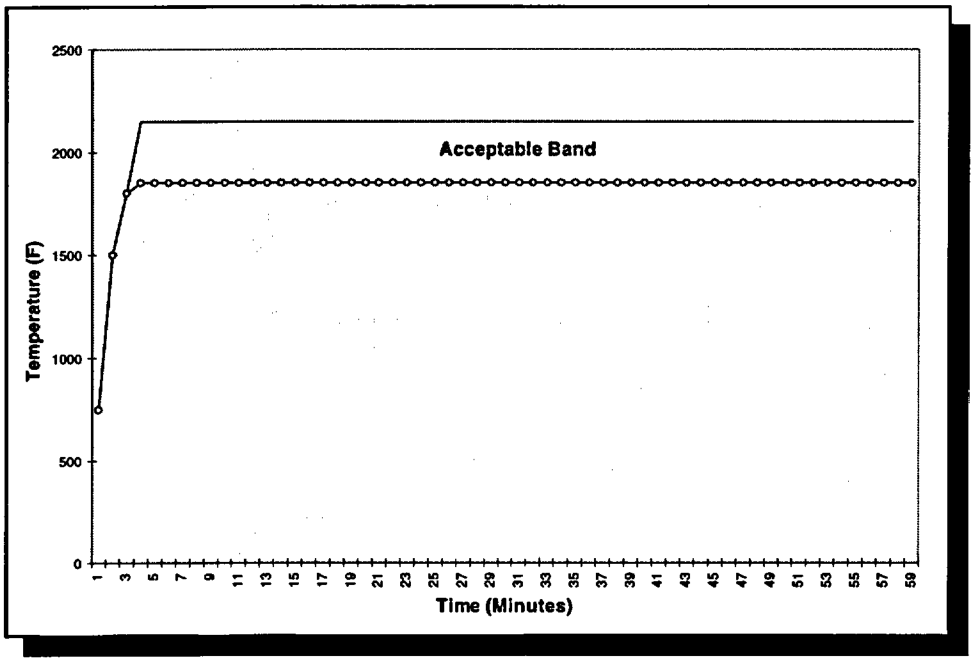


Figure 17

1 Hour ERFBS - Rate of Internal Temperature Rise

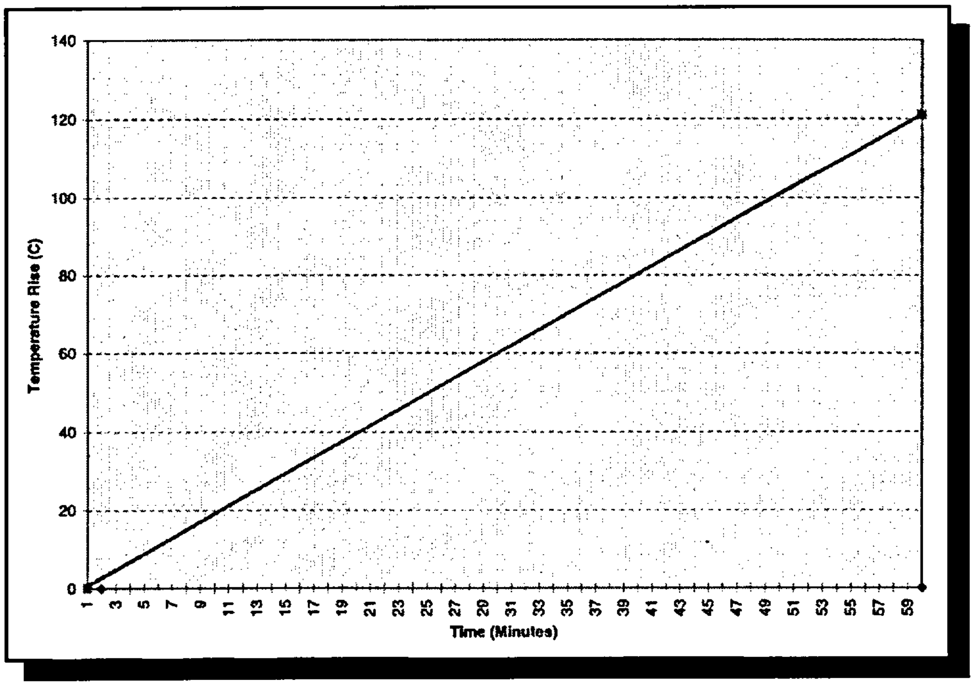
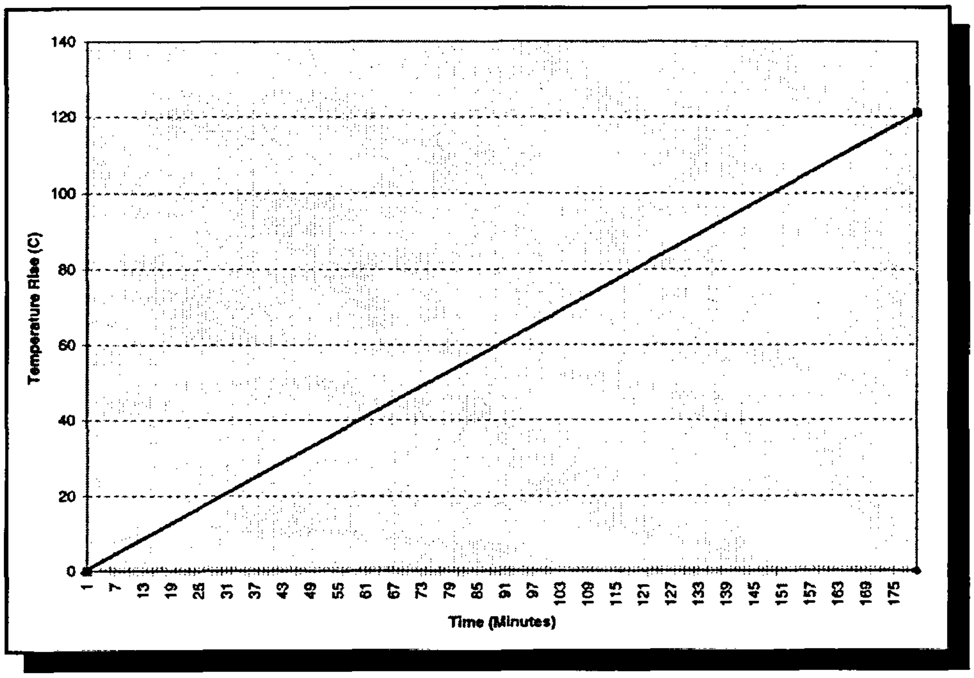


Figure 18

3 Hour ERFBS - Rate of Internal Temperature Rise



Thermal Exposure of Un-protected Cables.

More recent work has been performed by EPRI in their FIVE methodology [14]. In the FIVE method, fundamental fire modeling techniques are presented in an attempt to conservatively approximate fire growth and resultant temperatures in a compartment. The method provides guidance on developing site specific evaluations for "Target-In-Plume Scenarios" and "Target-Outside-Plume Scenarios." Based on this style of methodological analysis, time/temperature profiles can be constructed for the specific application.

Chapter V - Results

This thesis has presented a wide range of information concerning the functionality of protected and non-protected electrical cables during a thermal insult. In this chapter the results from the individual experiments are compiled in an attempt to determine if there are any trends or correlations. The cable data will be catalogued by the cable's function. This is based on the most common applications of cables in NPPs. Cables smaller than #14 AWG are designated as "Instrument Cables," #14 AWG and #12 AWG are designated as "Control Cables," and cables larger than #12 AWG are designated as "Power Cables." The following tables should be viewed with caution for the following reasons:

1. There was no standardized testing methodology or acceptance criteria.

2. The researchers recorded the temperatures at different locations. Some recorded the temperature of the surrounding air (SNL, EDF) others calculated the temperature of the cable surface while exposed to a radiant heat flux (FM), others recorded the temperature on a surrogate bare copper conductor located with the test assembly (TVA 1996, SCE&G 1999), while others recorded the temperature on the cable jacket (TVA 1984, VTT).

3. With the exception of the EDF testing, unprotected cables (i.e., no ERFBS) that were exposed to open flame from a ASTM E-119 type furnace or an open heptane pan fire were not included. The EDF testing provided the lowest failure temperature and is included in the Control Cable Thermal Performance (Table 14) for illustration. When the air temperature is used as the measurement of failure, the thermal inertia and

resulting thermal lag of the actual temperatures on the cables is neglected. This is significant, since the fire curve is developing exponentially, while the surface of the cable jacket is acting as an insulator, delaying the heat transfer to the insulation. As such, the recorded rapidly rising temperature (of the surrounding air) will be substantially higher than the temperature of the cable insulation surface.

Table 13

Instrument Cables Thermal Performance

Laboratory	Cable Size	Insulation Type	TP or TS[1]	Temperature °C (°F) and Location[2]
FM 1981	3/C #16	XLPE/Neoprene	TS	516 (960) [C]
	34/C #20	Teflon/Teflon	TP	478 (892) [C]
	7/C #16	Teflon/Teflon	TP	456 (853) [C]
TVA 1984	2/C #16	XLPE/Hypalon	TS	299+ (570+)[3] [J]
	2/C #16	XLPE/Hypalon	TS	299+ (570+)[3] [J]
VTT 1996	2/C #16	PVC/PVC	TP	196 (385) [J]
SNL 1991	2/C #16	EPR/CSPE	TS	365-370 (689-698) [A]

Notes:

1. Thermoset = TS; Thermoplastic = TP
2. Location of the temperature measurement, Air = [A], Jacket = [J], Bare copper conductor = [B], Calculated from heat flux = [C].
3. This was the highest temperature used in the test. TVA did not run the cables to failure.

Table 14

Control Cables Thermal Performance

Laboratory	Cable Size	Insulation Type	TP or TS[1]	Temperature °C (°F) and Location[2]
FM 1981	7/C #12	XLPE/Neoprene	TS	488 (910) [C]
	5/C #14	EPR/Hypalon	TS	297 (567) [C]
	9/C #14	Silicone/Glass	TS	478 (892) [C]
	7/C #12	Silicone/Glass	TS	507 (936) [C]
TVA 1984	7/C #12	PE/PVC	TP	175 (346) [J]
	7/C #12	PE/PVC	TP	277 (440) [J]
	7/C #12	XLPE/Hypalon	TS	299+ (570+)[3] [J]
	7/C #12	XLPE/PVC	TS	299+ (570+)[3] [J]
TVA 1996	2/C #12	PE/PVC	TP	139+ (282+)[4] [B]
EDF 1999	*2/C #12*	*XLPE/CSPE*	*TS*	*600 (1112)[5] [A]*
SNL 1986	3/C #12	XLPE	TS	481-566 (900-1050) [A]
	3/C #12	PE	TP	332-510 (630-950) [A]
SNL 1991	3/C #12	XLPE	TS	325-330 (617-626) [A]
SCE&G1999	4/C #12	SR/SR	TS	<184 (<363) [B]

Notes:

1. Thermoset = TS; Thermoplastic = TP
2. Location of the temperature measurement, Air = [A], Jacket = [J], Bare copper conductor = [B], Calculated from heat flux = [C].
3. This was the highest temperature used in the test. TVA did not run the cables to failure.
4. This was the highest temperature used in the test. TVA did not run the cable to failure. The sample showed signs of degradation but did not fail.
5. The EDF testing used open flaming as a heat source.

Table 15

Power Cables Thermal Performance

Laboratory	Cable Size	Insulation Type	TP or TS[1]	Temperature °C (°F) and Location[2]
FM 1981	1/C #2	EPR/Hypalon	TS	392 (736) [C]
	7/C #9	EPR/Hypalon	TS	488 (910) [C]
TVA 1984	1/C 400MCM	XLPE/PVC	TS	299+ (570+)[3] [J]
	1/C 2/0	XLPE/PVC	TS	299+ (570+)[3] [J]
SCE&G1999	3/C #8	HTK/HT	TS	184+ (363+) [B]

Notes:

1. Thermoset = TS; Thermoplastic = TP
2. Location of the temperature measurement, Air = [A], Jacket = [J], Bare copper conductor = [B], Calculated from heat flux = [C].
3. This was the highest temperature used in the test. TVA did not run the cables to failure.

In general, the thermoset cables performed better than the thermoplastic cables.[26] In the case of the instrument cables, the PVC/PVC showed the earliest failure at elevated temperature 196 °C (385 °F), while the earliest failure of thermoset cable, EPR/CSPE, occurred in the range of 365 to 370 °C (689 to 698 °F). The same holds true for control cables. The first thermoplastic cable (PE/PVC) to fail occurred at 175 °C (346 °F), while the first thermoset cable (FR/FR) to fail occurred at 184 °C (363 °F). In general, the trend suggests that a cable constructed with thermoset insulation will perform better than an equivalent cable constructed of a thermoplastic insulation.

26 Power cables are classically constructed of only thermosetting insulation.

In general, instrument cables are considered to be more sensitive to thermal effects than control or power cables. However, the temperature data presented here does not support that conception. In evaluating just the FM data, instrument cables (3/C #16 XLPE/Neoprene) withstood up to 516 °C (960°F), where control cables (5/C #14 EPR/Hypalon) failed at 297 °C (567 °F). Both are classified as thermoset cables. Two important parameters are not included with this assertion. First, the testing did not electrically monitor the cables considering their operating parameters, i.e., instrument cables are sensitive to milliamp leakage, while control cables may be able to remain functional with full amp leakage. Second, for a given heat flux, the thermal inertia of the cables is not factored into the testing. Cable jackets, the amount of insulation material, and the mass of the copper conductor all affect the cable's performance.

Nowlen and Jacobus have suggested there is a strong correlation between the results from cable fire testing and EQ testing [36]. The SCE&G testing of the 4/C #12 AWG FR/FR cable supports this concept. The SCE&G 4/C #12 AWG cable performance became questionable at approximately 184 °C (363 °F) when measured with a potential of 1 kV dc. The EQ testing performed by Jacobus on similar FR/FR insulated cables with an acceptance criteria of 1 kΩ /100m determined the cable remained functional in the approximate range of 153 to 171 °C (307 to 340 °F). These values are in agreement between the two types of testing. This further strengthens the argument that regardless of the thermal insult source, the cables will exhibit very similar electrical performance when tested with a strong electrical potential.

The TVA Thermo-Lag testing clearly demonstrated the importance of mass in side an ERFBS. ERFBS that show marginal performance will perform better if the cable mass is increased inside the assembly. Therefore, ERFBS that were qualified with significant cable mass during the testing should be viewed with caution.

Chapter VI - Summary

This thesis has demonstrated that, while there has been some research performed in an attempt to evaluate the impact of a fire exposure on cable functionality, there are many unanswered questions. The concept put forth by Nowlen and Jacobus that there is a correlation between cable fire test data and cable EQ test data is supported, providing a similar electrical potential is used to determine functionality. A standardized testing method and acceptance criteria needs to be developed in order to gain a uniform understanding of a cable's true performance. Suggestions regarding a standardized testing method are provided in Appendix A. By developing this standard and testing a variety of cables, additional understanding of the cable performance will be gained. Greater confidence will be gained concerning the performance of cables protected by ERFBS, and uncertainties in fire risk assessments can be reduced with more accurate cable functionality data.

This thesis also supports the NRC's position that applying ASTM E 119 acceptance criteria for non-bearing walls and partitions to the raceway inside an ERFBS is conservative and therefore reasonably safe.

Chapter VII - Conclusion

This thesis has presented a wide range of information concerning the functionality of protected and non-protected electrical cables during a thermal insult. From this information a series of theoretical arguments can be postulated. As such, the conclusions are presented as a series of plausibility arguments that could be further developed into rules or engineering judgments by future users.

Argument 1. The NRC's decision to use ASTM E 119 fire wall acceptance criteria for qualifying ERFBS for any cable use is reasonable and conservative.

The testing performed by the TVA [29] in 1996 demonstrated that starting with the typical warm ambient temperatures found inside a NPP (26 to 40 °C [80 to104 °F]) then raising the temperature inside the ERFBS to a maximum rise of 139 °C (250 °F) in 60 minutes, the thermally most sensitive protected cable (PJJ) would remain fully functional. Substituting the results of Keski-Rahkonen, Bjorkman and Farin [31] research into the TVA experiment, (196 °C [385 °F] for PVC insulated cables) the cables would also remain fully functional. Further conservatism exists in the thermal mass of the specific cable fill inside the ERFBS. Argument 2 further develops this concept.

Argument 2. The amount of cable mass in a ERFBS will affect the rate of temperature rise inside the enclosure, with higher cable masses resulting in lower temperature rises.

TVA [41] demonstrated that for ERFBS protected cable trays, the final temperature at 60 minutes would be approximately 46 °C (115 °F) less for the fully loaded cable tray in contrast with the empty cable tray. TVA [42] demonstrated similar results for a 76.2 mm (3 inch) diameter aluminum conduit. The final average internal temperature of the maximum-filled conduit was 45 °C (81 °F) lower than the filled conduit. Additional conservatism exists in the fact that the temperatures inside the raceway will, on average, be lower than those measured on the raceway's outside surface. Table 12 illustrates this difference varying from 18 to 48 °C (64 to 118 °F) as a function of cable fill. Therefore it can be concluded that the cable fill is a significant factor when evaluating the overall thermal performance of ERFBS.

Argument 3. Given an equivalent thermal exposure, electrical cables will lose their functionality at different rates based on the cable's function, size and construction.

This argument has been supported throughout this thesis. Chapter III discussed the basic functional requirements and acceptable operating parameters of electrical cables. The acceptable current leakage for a given cable function is a distinguishing parameter. The loss of milliamps in an instrumentation cable can cause the cable to be unreliable, where control and power cables may be fully functional with current leakages measured in amps.

The size of the cable is also an important parameter, especially when the cables are protected by an ERFBS (as previously discussed in Argument 2). Larger cables have greater mass, acting as a thermal heat sink requiring more energy to raise the cable's temperature. As such, larger, heavier cables will heat up slower, and remain functional for a longer period of time.

The construction of the cable will influence its functionality when exposed to a thermal exposure. Insulation and jackets degrade at different rates based on the physical properties of the material. TVA and Lee demonstrated the effects of this physical parameter. TVA [28] demonstrated that in the case of thermoplastic insulation, the insulation of individual conductors can actually melt and mix within a multiconductor cable. Lee [26] demonstrated that in the case of some thermoset jackets, such as silicone, the material can thermally decompose but its remaining char material could provide enough dielectric protection to insulate the individual conductors allowing the cable to remain functional. As a general trend, thermoset materials tend to outperform thermoplastic materials given equivalent thermal exposure. The presence of a bare ground conductor, drain, or shield will influence the functionality. This concept is further defined in Argument 7.

Argument 4. Data developed from Argument 3 can be used in fire hazard risk assessments to reduce uncertainty in the analysis.

At this writing, the nuclear power industry generically uses 371 °C (700 °F) as the temperature at which IEEE 383 qualified cables become fire damaged and, therefore, nonfunctional. This value is non-conservative based on the SNL referenced testing [15]. However, a more significant problem is that the use of a single value treats all (IEEE 383) cables as equal. This unverified assumption introduces a high level of uncertainty in the fire risk analysis. The FIVE methodology is based on fire modeling approximations. In those fire modeling approximations are inherent assumptions which may be considered uncertainties. Performing the analysis with the fire modeling uncertainties coupled with the cable functionality uncertainties substantially diminishes the overall accuracy of the evaluation. As such, the fire modeling uncertainties should remain separate from the cable functionality uncertainties. The cable functionality parameters can be significantly defined for the fire risk analysis if only the function (power, control, or instrumentation) of the cable was identified. Differences in the mechanical protection of the installed cable (cable tray or conduit) also have an impact. Therefore, in future NPP fire risk evaluations, cable functionality uncertainties should be evaluated on their own merit, and an array of more precise values should be developed to use as input to the fire modeling.

Argument 5. Temperature data developed as a part of EQ testing can be used with caution to approximate cable performance during fire exposure.

In GL 86-10 Supplement 1 [11], the NRC has stated that this approach may be valid to justify cable functionality in ERFBS that have exceeded allowable temperature limits. Nowlen and Jacobus [36] have suggested that there is a possible correlation between the thermal performance of a cable exposed to fire or EQ testing. The results of their testing of select cables shows promise for this correlation. Comparing the 1999 SCE&G fire test results for 4/C #12 AWG FR/FR cables (184 ° [363 °F]) to the 1991 SNL EQ test results for a similar Kerite FR insulated cable (153 to 171 °C [307 to

340 °F] provides another example where EQ test data can be used to approximate a cable's performance during a fire exposure. However, more work is necessary before this data can be used as "handbook" level of quality. Arguments 8, 9, and 10 discuss this concept further.

Argument 6. Given multiple conductors with no ground, shield, or drain conductor in a single cable, the conductors will fail to each other before failing to an external ground plane.

This fact has been demonstrated in the test results reviewed as a part of this thesis. TVA [28], VTT Building Technology Research [31], EDF [32], SNL [15] and EPRI [26] research have confirmed this argument. The TVA research is especially valid in confirming this principle, since the test cable had an external weight applied to it at the point where it came into contact with the ground plane (cable tray rung). Therefore, it can reasonably be concluded that a cable will experience internal shorts prior to external shorts.

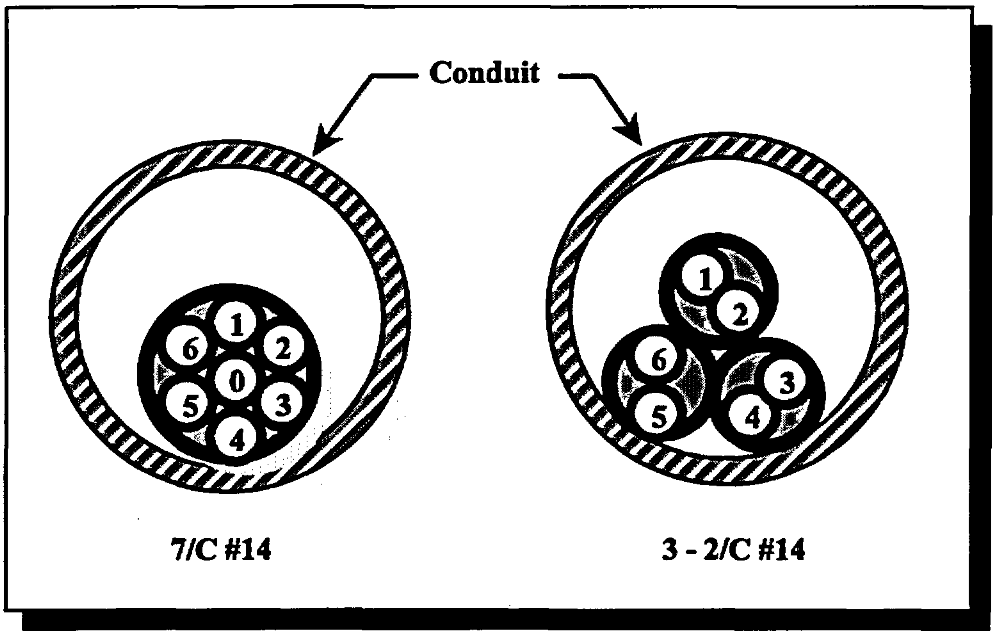
Argument 7. Given an equivalent thermal exposure, there is a higher likelihood multiple conductors within a single cable will short together rather than short to the conductors of adjacent cables, or an external ground. This will occur more quickly in a multiple conductor cable, than an equivalent number of conductors in separate cables performing the same function.

This is an extension of Argument 6. Figure 19 shows two possible configurations of providing 3 pairs of circuits to a device. In one conduit is a 7/C cable[27], in the other are three, 2/C cables. In the 7/C cable, the only material separating the conductors is the insulation on each conductor, thus when the insulation begins to fail, the conductors can short to each other. In the case of the three cables, the pairs can short together, but shorting between pairs (e.g., conductor #2 to #3) is less likely due to the added protection of the jacket, distance between the cables and potential for the conductors to short to the raceway before shorting to each other. This argument will impact the probabilities of failure when analyzing potential short circuits and their consequences.

27 Due to the geometry of assembling a cable, a 6/C is not likely to be encountered. The 7/C cable is a common geometry, in that the 6 surrounding insulated conductors around a center insulated conductor maintain the circular profile of the cable.

Figure 19

Multi-Conductor Cable Configurations



Argument 8. Using higher voltages in the testing will induce failures quicker than if lower voltages are used. Testing cables at voltages equal to, or higher than those installed in the NPP, qualifies the actual installed cables. The converse is not true.

Review of the cable functionality testing performed to date indicates a wide variety of different voltages used in testing. TVA [28] attempted to use realistic voltages, (i.e., voltages representative of those that would be experienced in a typical NPP application), as high as 6.9 kV on medium power cables, where other researchers such as Lee [26] used lower voltages (70 V) than the cables would experience in normal application. The higher voltage has a greater energy potential, and as such, would find a fault in the insulation quicker. As discussed in this thesis, many of the cables experience cracking of the insulation and/or jackets [15] or melting and fusing together of the insulation [28, 34] during the thermal insult. If the appropriate potential electrical energy is not present during the testing, such faults may not be detected and reported.

Argument 9. The physical and chemical properties of the insulation and jacket must be further evaluated to have a complete understanding of the cable failure process.

The testing that has been reviewed as a part of this thesis has, for the most part, focused on the physical aspects of cable functionality. The physical properties of insulation material such as melting of thermoplastic insulation have been discussed. Lee's research [26] did evaluate the chemical process in the production of HCl from certain cables during the thermal insult. The principle focus of his work appeared to relate to the potential health effects on NPP personnel. Lee also noted that in the cable functionality testing, two cable samples (#2 XLPE/Neoprene, and #5 PE/PVC) gave abnormal results. Lee postulated that, "We are not certain of the cause of this abnormality; however, it could be a result of the generation of HCl from within the cable accelerating the insulation degradation process, causing early electrical failure [26]" Based on Table 4, Lee's explanation is probably correct. However, when Nowlen's research [15] is reviewed, the cable aging process involved; "Artificial aging of the control cables (XLPE/Neoprene) was performed at a temperature of 150 °C (302 °F). The cable samples were aged at this temperature for a total of 28 days." and, "Artificial aging of the instrument cables (EPR/Hypalon)was performed at a temperature of 125 °C (257 °F). The cable samples were aged at this temperature for a total of 28 days."

Recall that Lee suggested that the polymers used in cable insulation begin to decompose and release HCl at temperatures as low as 100 °C (212 °F). Table 4 indicates that HCl production and mass loss for the XLPE/Neoprene was 41%, and for the EPR/Hypalon, 11%, respectively. Therefore, the aging process used in Nowlen's work [15] could be suspect. Further, HCl is considered a strong acid [46]. The interaction between the copper conductor, insulation, and jacket of Nowlen's test cables could have been chemically altered by the HCl production during the accelerated aging process. As such, the cables tested would not be representative of those actually installed in typical NPP applications. In summary, understanding cable functionality goes beyond the physical parameters of the cable, to the chemical properties of the materials used in construction of the cable.

Argument 10. Cable functionality involves more variables than just temperature, and, as such, is a complex phenomenon. A testing standard should be developed to minimize the effect of the variables, and establish logical acceptance criteria.

This thesis has explored the fundamental variables that affect the functionality of an electrical cable when exposed to the thermal insult of a fire. The cables function, size, construction, protection, geometry, age, and the thermal exposure all affect its functionality. In order to properly evaluate the performance of different cables a testing standard that addresses the critical variables should be developed. Suggestions on developing a test standard are provided in Appendix A.

Appendix A - Future Testing Recommendations

One of the difficulties in evaluating the functionality of electrical cables during a fire event is that the individual testing of the cable samples has been performed to different testing and acceptance criteria. Cable functionality is a subject of enough importance that it merits its own testing standard. An industry group such as ASTM or IEEE should develop this standard. Points to consider in the standard are listed below.

1) Testing Voltage

The testing should use a voltage equal to or greater than the cable will be subjected to in its installed application. Testing with lower voltages is not conservative or representative of the actual use. A conservative approach would be to use the rated voltage of the cable.

2) Age of Cable Sample

The question of whether an aged cable sample will lose its functionality before a new cable remains unanswered. Nowlen's [15] work provided conflicting results. This may be the result of the cable aging process. The question of artificial aging should also be further researched. Lee's [26] demonstration of HCl production should be included in the aging process. The current generation of NPPs in the U.S. is starting to file for 20 year life extensions. This would put the total plant life at 60 years, 20 years past their design life. Properly aged cable samples should be tested along with new samples to determine the worst case condition.

3) Testing Geometry

The majority of cables were tested in the flat position. This may not be the actual configuration in the NPP, or the worst case scenario. Jacobus [35] noted in his EQ testing that "dielectric tests and mandrel bends can induce failure of otherwise functional cable." Testing the cables at their minimum bend radius would provide a conservative approach since the insulation and jacket material would be compressed on the inside of the bend and stressed on the outside of the bend.

4) Cables Should be Weighted During Testing.

The UL Subject 1724 [27] and TVA testing [28, 29] used this approach. Installed configurations could have the cable of concern located in the bottom of the raceway with other cables weight on top of it. The TVA testing [28] clearly demonstrated thermoplastic materials will be displaced during the thermal insult. A cable test configuration that has the cable making a maximum bend on to a ground plane with weight at the point of contact would resolve this concern and provide a bounding configuration.

5) Acceptance Should be Defined by the Functionality Requirements

This thesis has discussed the difference in allowable current leakage based on the cables function. Conservative acceptable allowances should be determined for each (power, instrument or control) function.

6) <u>End Effects Should be Explored</u>

Wheelis [34] noted that failures occurred at the cables splice to the power feeds. TVA [28] noted the loss of the electric tape dielectric strength over connections. To eliminate this potential problem a series of tests on spliced cables should be performed. The weak link in cable functionality may be splices located in junction boxes.

7) <u>Generic Test Curves Could be Developed</u>

Cable samples should be tested to failure to obtain the maximum amount of functionality data. A generic curve much like the one's used for qualifying cables for use inside an ERFBS should be developed. The curves shown in Figures 17 or 18 could be extended at their linear rates. It is postulated that this gentle temperature rise will produce more accurate failure temperatures rather than a sudden heat up due to the thermal lag of the cable mass heating.

8) <u>Cable Geometry</u>

Wheelis [34] defined cable geometry as the location of the test cable with respect to other cables. He noted that other cables could shield the test cable from the heat flux giving inaccurate results. To eliminate this concern, each cable sample should be tested independently.

Appendix B - TVA Position on ERFBS Testing

TENNESSEE VALLEY AUTHORITY

WATTS BAR NUCLEAR PLANT

POSITION ON FIRE TESTING CRITERIA FOR

FIRE BARRIER SYSTEMS USED TO PROTECT

ELECTRICAL CABLING REQUIRED FOR

1OCFR5O APPENDIX R COMPLIANCE

BACKGROUND

There is considerable discussion between the NRC, nuclear utilities and manufacturers of fire barrier systems on the appropriate test method and acceptance criteria for electrical fire barrier systems. The NRC has based its methodology and criteria on National Fire Protection Association (NFPA) 251, "Standard Method of Fire Tests of Building Construction and Materials," Chapter 7, "Tests of Nonbearing Walls and Partitions."[1] Thermal Science, Inc. (TSI), the manufacturer of Thermo Lag, and most nuclear utilities, have based their methodology and criteria on American Nuclear Insurers (ANI) "Standard Fire Endurance Test Method to Qualify a Protective Envelope for Class lE Electrical Circuits."[2] Other manufacturers of fire barrier Systems, such as 3M and Thermal Ceramics, Inc., have typically used Underwriters Laboratory (UL) test methods and acceptance criteria such as UL Subject 1724, "Outline of Investigation for Fire Tests for Electrical Circuit Protective Systems."[3] The American Society for Testing and Materials (ASTM) has recognized the need to develop a unique test method and acceptance criteria for electrical fire barrier systems. They have been working for approximately the last five years on this issue but have not issued a standard.

DISCUSSION

The Code of Federal Regulations (CFR), Title 10 Part 50 Domestic Licensing of Production and Utilization Facilities, Appendix R, Fire Protection Program for Nuclear Power Facilities Operating Prior to January 1, 1979, paragraph III.G.2 provides the requirements for fire protection and safe shutdown capability. If redundant trains are located in the same fire area and a licensee does not provide alterative or dedicated shutdown systems for the redundant equipment in that fire area, the three acceptable methods of ensuring that one of the trains is free from fire damage are:

a.) Separation of cables and equipment and associated non-safety circuits of redundant trains by a fire barrier having a 3-hour rating. Structural steel forming a part of or supporting such fire barriers shall be protected to provide fire resistance equivalent to that required of the barrier;

b.) Separation of cables and equipment and associated non-safety circuits of redundant trains by a horizontal distance of more than 20 feet with no intervening combustible or fire hazards. In addition, fire detectors and an automatic fire suppression system shall be installed in the fire area; or c.) Enclosure of cable and equipment and associated non-safety circuits of one redundant train in a fire barrier having a 1-hour rating. In addition, fire detectors and an automatic fire suppression system shall be installed in the fire area.[4]

A fire wall design that has passed on appropriate test method (e.g., NFPA 251) is considered a "rated" barrier. Components which penetrate fire walls, such as mechanical and electrical penetrations, fire doors, and HVAC fire dampers have test standards. There are presently no generally accepted test method and acceptance criteria specifically applicable to fire barrier enclosures applied to electrical cable systems. Existing methods intended for other purposes have been utilized to test such barrier systems, but none of these standards are fully appropriate to this unique application of fire barrier materials. In an attempt to define a test method for electrical circuit protection, American Nuclear Insurers (ANI) prepared "Guidelines for Fire Stop and Wrap Systems at Nuclear Facilities". However, this test method was intended to be used "for insurance purposes only."[2] The method and acceptance criteria in the ANI document are not definitive.

POSITION

The fire test methodology and acceptance criteria for electrical cable systems should be unique to these systems. Underwriters Laboratory currently has an appropriate test method (Subject 1724), which addresses the uniqueness of electrical cable fire barrier systems. This test method was developed by UL specifically to address issues such as Appendix R electrical fire barrier rating requirements. The scope of the test method is:

a.) Measurement of temperature changes within the electrical circuit protective system caused by the heat transfer through the electrical circuit protective system to the electrical conductor or raceway, or both, during the external fire exposure test.

b.) Determination of the integrity of the electrical circuit protective system during the external fire exposure and water hose stream test.

c.) Determination of the ability of insulated electrical conductors to maintain electrical circuit integrity at the temperature conditions present within the electrical circuit protective system during the external fire exposure test and during the water hose stream test.[3]

Details such as thermocouple types and placements are discussed in this test method. The test follows the standard time-temperature curve specified in ASTM E 119, as used in other fire endurance tests (e.g., NFPA 251). The test allows the use of the actual installed cables or a No.8 AWG (3.38 mm^2) bare copper conductor to simulate the electrical circuits. With the bare conductor method the thermocouple measurements can be correlated to actual cable qualification tests as described in Appendix B of UL Subject 1724.

TVA considers that UL Subject 1724 is the most appropriate test method currently available for determining the fire resistance rating of electrical fire barrier systems. TVA will use UL Subject 1724 with the following clarifications to perform tests of Thermo-Lag 330 electrical circuit protective systems intended for use at Watts Bar:

a.) The exterior surface temperature of the electrical raceway will be recorded (cold side of the barrier). If the average temperature recorded by the exterior thermocouples is less than 250 °F (121 °C) above their initial temperature and no individual thermocouple is in excess of 325 °F (163 °C) above its initial temperature, the fire barrier will be considered acceptable for use with any type cable.[5]

b.) Section 6, Internal Fire Exposure Test, will not be used. TVA considers that this portion of the testing is not necessary, since an internally generated cable tray fire would be extremely unlikely. Circuits are protected with a fuse or breaker that will actuate prior to the jacket of a faulted cable reaching its auto-ignition temperature (for existing designs) or reaching its insulation damage temperature (for new designs) for all credible low impedance and bolted faults.[6] No other ignition sources exist within the protective barrier.

c.) Section 5, Hose Stream Test. TVA will follow the criteria for hose stream testing described in NUREG-0800 using one and one-half inch fog nozzle set at a discharge angle of 15° with a nozzle pressure of 75 psi and a minimum discharge of 75 gpm.[7] TVA considers that this would accurately represent the mechanical impact, erosion and cooling effects that would exist in TVA's nuclear power plant environment. The hose stream test shall be performed within ten minutes of the completion of the fire test. The duration and application will follow the requirements of UL 1724 Table 5.1. The nozzle will be located a maximum of ten feet measured horizontally from the outside edge of the testing assembly. Acceptance shall be based on the fire barrier system remaining intact with minimal material flaking. (The alterative test called for by the UL document, involving a one and one-eighth inch solid bore National Standard Playpipe operating at 30 psi, is not a realistic simulation of the challenge to barrier systems as installed in a nuclear power plant).

REFERENCES

1. National Fire Protection Association (NFPA) 251, "Standard Method of Fire Tests of Building Construction and Materials" 1990 Edition.

   Note: For the purposes of this paper NFPA 251(90) is considered equivalent to ASTM E 119-88 "Standard Test Method for Fire Tests of Building Construction and Materials".

2. American Nuclear Insurers/Mutual Atomic Energy Reinsurance Pool (ANI/MAERE) RA "Guidelines for Fire Stop and Wrap Systems at Nuclear Facilities" Revision 0, November 1987.

3. Underwriters Laboratories, Inc. (UL) Subject 1724, "Outline of Investigation for Fire Tests for Electrical Circuit Protective Systems" Issue Number: 2, August 1991.

4. Code of Federal Regulations, Title 10, Part 50, Energy, January 1, 1992.

5. Based on a NFPA 251(90) acceptance criteria for Nonbearing Walls and Partitions.

6. Tennessee Valley Authority (TVA), "Watts Bar Design Criteria - WB-DC-30-13, 1OCFR50 Appendix R Type I, II, and III Circuits" Revision 2, February 13, 1990.

7. U.S. Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation, Standard Review Plan, NUREG 0800, Rev.2, July 1981, Section 9.5.1 Fire Protection Program, page 9.5.1-29.

Appendix C - Temperature Conversions

A word of caution is in order about converting temperatures between Celsius (°C) and Fahrenheit (°F). For conversion between the temperature scales:

$$°F = (°C * 1.8) + 32$$

$$°C = (°F - 32) / 1.8$$

For example, to convert the temperature 250 °F to °C;

$$°C = (250\ °F - 32)/1.8$$

$$= (218) / 1.8$$

$$= 121.11 \sim 121\ °C$$

However, to establish a ratio such as a temperature rise (ΔT);

$$°F = (°C * 1.8)$$

$$°C = (°F / 1.8)$$

For example, to convert a temperature rise (ΔT) of 250 °F to °C;

$$°C = (250\ °F / 1.8)$$

$$= 138.89 \sim 139\ °C$$

Note that ASTM E 119-95a "Standard Test Method for Fire Tests of Building Construction and Materials" properly applies these conversions as illustrated in "Tests of Nonbearing Walls and Partitions" Section 18.1.3, "Transmission of heat through the wall or partition during the fire endurance test shall not have been such as to raise the temperature on its unexposed surface more than 250 °F (139 °C) above its initial temperature."

NFPA 251-95 "Standard Method of Fire Tests of Building Construction and Materials" does not make this same conversion, "Transmission of heat through the wall or partition during the fire endurance test shall not be sufficient to raise the temperature on its unexposed surface more than 250 °F (121 °C) above its initial temperature. For the purposes of this thesis, the conversions of ASTM E 119-95a will be used throughout.

This thesis has attempted to use SI units as the primary units of measurement with the British units in the parenthesis with one noteworthy exception: the TVA effects of cable mass on ERFBS performance. The TVA NPPs were designed, built, and operate using British units as a standard. The research work was performed to establish TVA's ERFBS design basis, and as such used British units. Therefore, the information is presented in this manner. To use this information in an SI application, it will be easier to convert the SI inputs (temperature in °C and mass in kg) to British units (temperature in °F and weight in lb where 1 lb = 2.2 kg), solve the equations, then convert the final answer to SI units.

References

1. Salley, M. H., "Perspectives on the Implementation of Fire Protection Risk Informed Performance Based Regulations in the United States Nuclear Power Industry," SFPE Symposium on Risk, Reliability, and Uncertainty in Fire Protection Engineering, Baltimore, MD, May 12-14, 1999.

2. U.S. Nuclear Regulatory Commission, Section 50.48 of 10 CFR, "Fire Protection," and Appendix R, "Fire protection Program for Nuclear Power Facilities Operating Prior to January 1, 1979, to 10 CFR Part50.

3. U.S. Nuclear Regulatory Commission, Generic Letter 86-10, "Implementation of Fire Protection Requirements," April 24, 1986.

4. U.S. Nuclear Regulatory Commission, Information Notice 91-47, "Failure of Thermo-Lag Fire Barrier Material to Pass Fire Endurance Test," August 6, 1991.

5. U.S. Nuclear Regulatory Commission, Information Notice 92-46, "Thermo-Lag Fire Barrier Material Special Review Team Final Report Findings, Current Fire Endurance Tests, and Ampacity Calculation Errors," June 23, 1992.

6. U.S. Nuclear Regulatory Commission, Bulletin No. 92-01, "Failure of Thermo-Lag 330 Fire Barrier System to Maintain Cabling in Wide Cable Trays and Small Conduits Free From Fire Damage," June 24, 1992.

7. U.S. Nuclear Regulatory Commission, Bulletin No. 92-01, Supplement 1, "Failure of Thermo-Lag 330 Fire Barrier System to Perform its Specified Fire Endurance Function," August 28, 1992.

8. U.S. Nuclear Regulatory Commission, Generic Letter 92-08, "Thermo-Lag 330-1 Fire Barriers," December 17, 1992.

9. Allen, J. E., Salley, M. H., Brown, K. W., "TVA Position on Fire Testing Criteria for Fire Barrier Systems Used to Protect Electrical Cabling Required for 10CFR50 Appendix R Compliance," Presented at a Public Meeting with the NRC Staff, Rockville, MD., October 7, 1992

10. Salley, M. H., Brown, K. W., "TVA Position on Fire Testing Criteria for Fire Barrier Systems Used to Protect Electrical Cabling Required for 10CFR50 Appendix R Compliance," Presented at a Public Meeting with the NRC ACRS, Bethesda, MD., December 9, 1993.

11. U.S. Nuclear Regulatory Commission, Generic Letter 86-10, Supplement1, "Fire Endurance Test Acceptance Criteria for Fire Barrier systems used to Separate Redundant Safe Shutdown Trains within the Same Fire Area," March 25, 1994.

12. ASTM E 1725-95 "Standard Test Method for Fire-Resistive Barrier Systems for Electrical System Components," Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia, PA., 1995

13. U.S. Nuclear Regulatory Commission, Generic Letter 88-04, Supplement 4, "Individual Plant Examination of External Events (IPEEE) for Severe Accident Vulnerabilities - 10CFR 50.54 (f)," June 28, 1991.

14. Electric Power Research Institute, "Fire-Induced Vulnerability Evaluation (FIVE)," Final Report, TR-100370, Revision 1, September, 1993.

15. Nowlen, S. P., "An Investigation of the Effects of Thermal Aging on the Fire Damageability of Electrical Cables," Sandia National Laboratories, NUREG/CR-5546, SAND90-0696, May, 1991.

16. Electric Power Research Institute, "Power Plant Practices to Ensure Cable Operability," Final Report, NP-7485-s, July, 1992.

17. Petty, K. A., Electric Power Research Institute, "Power Plant Electrical Reference Series, Volume 4, Wire and Cable," 1987.

18. Bungay, E. W. G., McAllister, D., "Electrical Cable Handbook," Second Edition, CRC Press, Boston, MA., 1990.

19. Harper, C. A., "Modern Plastics Handbook," McGraw-Hill, New York, New York, 2000.

20. Del Toro, V., "Electrical Engineering Fundamentals," Prentice-Hall, Inc., Englewood Cliffs, NJ., 1972, pp.10 to 14.

21. NFPA 70-96, "National Electric Code," National Fire Protection Association, Quincy, MA., 1998

22. IEEE 383-1974 "Standard for Type Test of Class 1E Electrical Cables, Field Splices, and Connections for Nuclear Power Generating Stations," Institute of Electrical and Electronics Engineers, Inc., 1974.

23. U. S. Congress, "Browns Ferry Nuclear Plant Fire," Hearing Before the Joint Committee on Atomic Energy, Congress of the United States, Ninety-Fourth Congress, First Session, September 16, 1975.

24. U.S. Nuclear Regulatory Commission, Section 50.49 of 10 CFR, "Environmental Qualification of Electrical Equipment Important to Safety for Nuclear Power Plants."

25. Chaille, C. E., "Ceramic Fiber Blankets as Fire Protection for Complete Fire Engulfment of Cable Trays and Conduits Containing Grouped Electrical Conductors," IEEE Power Generating Committee, Summer Meeting, Vancouver, B.C., Canada, July 15-20, 1979.

26. Lee, J. L., Electric Power Research Institute, "A Study of Damageability of Electrical Cables in Simulated Fire Environments," Research Project 1165-1-1, Final Report, March, 1981

27. Underwriters Laboratories, Inc., Subject 1724, "Outline of Investigation for Fire Tests for Electrical Circuit Protective Systems," Issue Number 2, August, 1991.

28. Tennessee Valley Authority, "Cable Failure Temperature Tests," Report Number E386-84-3037, Central Laboratories Services, Chattanooga, TN., March 19, 1984.

29. Tennessee Valley Authority, "Compressive Load Test for Cables Protected with a Thermo-Lag Fire Barrier System - Sequoyah Nuclear Plant," Final Report Number 96-0892, Central Laboratories Services, Chattanooga, TN., June 1, 1996.

30. ASTM D 2436-85 "Specifications for Forced-Convection Ovens for Electrical Insulation"

31. Olavi, K. R., Bjorkman, J., Farin, J., "Derating of Cables at High Temperatures," Fire & Safety 1997, Fire Protection & Prevention in Nuclear Facilities, London, United Kingdom, February 24 - 26, 1997.

32. EDF, "Loss of Insulation Test on an Electric Cable During a Fire," Technical Note: E-N-S-IN-99-00412, April 16, 1999.

33. Hasegawa, H. K., Staggs, K. J., Doughty, S. M., "Fire Tests of Wire and Cable for DOE Nuclear Facilities," Lawrence Livermore National Laboratories, UCRL-ID-110598, September, 1992.

34. Wheelis, W. T., "Transient Fire Environment Cable Damageability Test Results," Sandia National Laboratories, NUREG/CR-4638/1 of 2, SAND86-0839/1 of 2, September 1986.

35. Jacobus, M. J., Fuehrer, G. F., "Submergence and High Temperature Steam Testing of class 1E Electrical Cables," Sandia National Laboratories, NUREG/CR-5655, SAND90-2629, May, 1991.

36. Nowlen, S. P., Jacobus, M. J., "The Estimation of Electrical Cables Fire-Induced Damage Limits," Sandia National Laboratories, SAND92-1404, Fire and Materials First International Conference and Exhibition, Washington, D.C., September 24-25, 1992.

37. Transco Products Inc. "Kaowool Triple Wrap Raceway Fire Barrier Test for Conduits and Cable Trays" Report Number 12000-105900, Omega Point Laboratories, San Antonio, TX., May 5, 2000.

38. IEEE 690-1984 "IEEE Standard for the Design and Installation of Cable Systems for Class 1E Circuits in Nuclear Power Generating Stations"

39. Salley, M. H., Brown, K. W., "Thermo-Lag Electrical Raceway Fire Barrier Systems Testing and Qualification," Tennessee Valley Authority, WATTec 21ST Annual Technical Conference, Knoxville, TN. February 24, 1994.

40. Salley, M. H., Brown, K. W., "Fire Endurance and Ampacity Testing of One and Three-Hour Thermo-Lag Electrical Raceway Fire Barrier Systems," Tennessee Valley Authority, ASME International Joint Power Generation Conference, Minneapolis, MN., October 10, 1995.

41. Tennessee Valley Authority and Thermal Science Inc. Joint Testing Project, "Fire Endurance Test of Thermo-Lag 330-1 Fire Protective Envelopes (Three 18 in. Cable Trays and a 3 in. Conduit)" Report Number 11960-97185 Omega Point Laboratories, San Antonio, TX., November 15, 1994.

42. Tennessee Valley Authority Testing Project, "Fire Endurance Test of Thermo-Lag 330-1 Fire Protective Envelopes (1in., 3in., and 4in. Diameter Conduits)" Report Number 11210-98892, Omega Point Laboratories, San Antonio, TX., February 9, 1996.

43. Cooper, L. Y., Steckler, K. D., "Methodology for Developing and Implementing Alternative Time-Temperature Curves for Testing the Fire Resistance of Barriers for Nuclear Power Plant Application," National Institute of Standards and Technology, NUREG-1547, NISTR 5842, August, 1996.

44. ASTM E 119-95a "Standard Test Method for Fire Tests of Building Construction and Materials," Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia, PA., 1995

45. ASTM E 1529-93 "Standard Test Method for Determining Effects of Large Hydrocarbon Pool Fires on Structural Members and Assemblies," Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia, PA., 1995

46. Brown, T. L., LeMay Jr., H. E., "Chemistry - The Central Science," 2nd Edition, Prentice-Hall, Englewood Cliffs, NJ., 1981, pp. 450 to 452.