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Circuit Analysis - Failure Mode and Likelihood Analysis

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ABSTRACT

Under existing probabilistic risk assessment (PRA) methods, the analysis of fire-induced circuit faults has typically been conducted on a simplistic basis. While exceptions do exist, a typical fire PRA will assume that given damage to any power or control cables, the associated circuits simply become unavailable. This approach does not address, for example, the potential that certain failures might cause spurious component actuations. In particular, certain cable failure modes, referred to as hot shorts, might lead to spurious operations. Those fire PRAs that have considered potential spurious operations have relied on methodologies that have significant uncertainties with regard to the scope of the assessments, the underlying methods, and the assumptions employed. Nonetheless, some of these fire PRAs have shown that cable hot shorts can be a significant risk contributor.

This report describes the results of a task to address weaknesses in existing fire PRA circuit analysis methods. An extensive review of available cable failure data has been performed and the current state of knowledge regarding cable failure modes and likelihood is characterized. A framework for advanced methods of cable failure mode and likelihood analysis is also presented. Advanced tools for performing PRA circuit analysis that explicitly treat different cable failure modes and the resulting circuit and system impact are outlined. Example applications of the proposed circuit analysis methods are provided.

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Foreword

This report presents an extensive review of available cable failure data and characterizes the current state of knowledge regarding cable failure modes and likelihood. It also describes a recent testing program to enhance available data that was sponsored by the Nuclear Regulatory Commission (NRC) staff and conducted in conjunction with a testing program sponsored by the Electric Power Research Institute (EPRI) and the Nuclear Energy Institute (NEI). This report also presents a framework for advanced methods of cable failure mode and likelihood analysis, and outlines advanced tools for performing PRA circuit analysis that explicitly treat different cable failure modes and the resulting circuit and system impact.

The report provides a possible method to resolve the conductor to conductor short issue (particularly including the situation where one of the conductors is at a higher electrical potential than the other, often referred to as the “hot shorts” issue) by allowing realistic consideration of the effects of electric cable damage. The effects considered are not limited to the previous, generally made assumption that any equipment with fire-damaged cables is unavailable to perform its safety function. Instead, effects considered include other failure modes that are possibly more severe, such as the spurious opening or closing of valves, starting of pumps, etc. The method considers these effects in a realistic manner, using a stepwise process to take into account the probability that a fire will cause cable damage, the probability that cable damage will cause each of the individual cable damage states (e.g., open circuit, short to ground, hot short), and the probability that each of the cable damage states will cause each of the possible system failure modes (e.g., unavailability, inadvertent actuation). Thus, the method provides reasonable conservatism by requiring consideration of all significant system failure modes while allowing use of reasonable probabilities for those failure modes.

The NRC staff believes that the information contained in this report will be useful to a broad variety of readers. The staff will use the report's insights when performing or reviewing any future fire risk assessments, and will consider the report's recommendations when updating the current NRC fire PRA research plan. Furthermore, the staff will broadly disseminate the report, recognizing that the report's detailed discussions of available data and methods to use in applying that data may be useful to others who are performing fire risk analyses.

LIST OF ACRONYMS

AWG	American Wire Gage
BWROG	Boiling Water Reactors Owners Group
CCDP	Conditional Core Damage Probability
CDF	Core Damage Frequency
CPT	Control Power Transformer
ECCS	Emergency Core Cooling System
EMI/RFI	Electro-Magnetic Interference / Radio Frequency Interference
EPRI	Electric Power Research Institute
EQ	Equipment Qualification
EPR	Ethylene-Propylene Rubber
FMECA	Failure Modes and Effects Criticality Analysis
GL	Generic Letter
IEEE	Institute of Electrical and Electronic Engineers
IPEEE	Individual Plant Examination of External Events
IR	Insulation Resistance
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (translates as “Institute for Radiological Protection and Nuclear Safety,” France, formerly known as IPSN)
MCR	Main Control Room
MOV	Motor Operated Valve
NEI	Nuclear Energy Institute
NFPA	National Fire Protection Association
OPL	Omega Point Laboratories
PE	Poly Ethylene
PRA	Probabilistic Risk Assessment
PVC	Poly-Vinyl Chloride
RES	Office of Nuclear Regulatory Research (USNRC)
SNL	Sandia National Laboratories
SOV	Solenoid Operated Valve
UL	Underwriters Laboratories
USNRC	United States Nuclear Regulatory Commission
XLPE	Cross-Linked Poly Ethylene
XLPO	Cross-Linked Poly Olefin

1 INTRODUCTION

1.1 Background

One of the important parameters in a fire probabilistic risk assessment (PRA) is the conditional probability of a specific fault mode (e.g., loss of function, spurious actuation) of a selected component, given (assuming) that a postulated fire has damaged an electrical cable associated with that component. In general, evaluation of this parameter can require the analysis of a number of cable failure scenarios, where each scenario involves a particular fire-induced cable failure mode and the propagation of the effects of this failure through the associated electrical circuit. The cable failures of interest involve the following conductor failure modes: loss of continuity, short to ground, and conductor to conductor short (including hot short as a special case of conductor to conductor shorting). Section 2.2 explicitly defines each of these failure modes.

While a short to ground or open circuit failure may render a system unavailable, a hot-short failure might lead to other types of circuit faults including spurious actuations, misleading signals, and unrecoverable losses of plant equipment. These circuit faults, taken singly or in combination with other faults, may have unique and unanticipated impacts on plant safety systems and on plant safe shutdown capability that are not always reflected in current fire PRAs.

A fire PRA is commonly quantified using a three-term model to estimate the fire-induced core damage frequency (CDF). These three terms are (1) the frequency of the postulated fire or class of fires (f_i), (2) the conditional probability that the postulated fire will cause damage to some set of plant equipment ($P_{ed,j|i}$), and (3) the conditional probability that given the postulated equipment damage (plus any potentially important random equipment failures or equipment outages) the plant operators will fail to recover the plant and core damage would result ($P_{CD:k|i,j}$). This is expressed mathematically as follows:

$$\mathrm{CDF} = \sum_i f_i \left(\sum_j P_{ed,j|i} \left(\sum_k P_{CD:k|i,j} \right) \right)$$

In terms of plant equipment damage, by far the most commonly considered class of equipment assumed to be damaged in a PRA fire scenario are electrical cables (power, instrument and control). Damage to electrical cables and the resulting systems impact is also the primary focus of this report. In general, a fire PRA will assess the likelihood that a cable (or set of cables) is failed by a fire ($P_{ed,j|i}$) based on the application of a competing two-process timing model; namely, fire growth and damage versus fire suppression.

The fire growth and damage assessment commonly involves the use of fire modeling tools. These tools may be relatively simple (e.g., closed form equations) or may involve an integrated compartment fire model. Most of the common approaches apply a single-valued damage threshold of temperature and/or heat flux to predict the onset of cable failure. That is, when the cable reaches a predetermined temperature, and/or is exposed to a threshold heat flux, failure of that cable is assumed.[1] A transient calculation predicts the time to damage relative to the time of fire ignition. Under current methods, the likelihood that the fire will be suppressed within a given time (e.g., in a time shorter than the estimated damage time) is based on an independent

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[1] Some studies conservatively assume failure when the air temperature near the cable reaches the defined temperature threshold. This avoids the need to model the cable's thermal response.

assessment of the response of fixed fire suppression systems (if available) and the manual fire brigade. These two pieces of information, time to damage and time to suppression (each potentially given as distributions), are folded together to estimate the conditional probability that the cable (or a set of cables) will be damaged given the postulated fire.

At this stage the analysis moves into the realm of plant response analysis. The next step in the PRA quantification process is to analyze consequences of the predicted cable failures on the plant, and in particular, the probability that core damage will result ($P_{CD:k|i,j}$). It is at this stage that the question of circuit analysis and cable failure modes comes into play. This topic is taken up in the section immediately below.

1.2 Circuit Analysis and Fire PRA

As noted above, the overall objective of a fire PRA is to quantify the potential impact on plant operations due to fires that occur within the plant. The discussion presented immediately above has covered the general process of fire risk assessment up to the point where the analyst has postulated a fire and predicted that some cable damage will occur as a result of that fire. The next question to be answered is how these cable failures will impact the plant systems. The answer to this question derives from an analysis of fire-induced circuit faults[2]. The role of circuit analysis as discussed in this report is to:

- identify the possible cable failure modes for potentially risk significant cables assumed to be damaged during a given fire scenario,

- determine the impact of failure modes on the associated systems and components,

- identify the potential risk significant circuit fault modes, and

- quantify the conditional probability that risk significant system and component failures will be manifested, given that cable damage has occurred.

In most of the fire PRAs performed to date, circuit analysis has been performed in a simple manner. In most cases, the analysis assumes that if any of the cables associated with a given circuit or system are damaged due to a fire (i.e., the cables fail), then the circuit or system is rendered unavailable. This approach neglects the potential for spurious actuations entirely, and is arguably the most optimistic approach. At the opposite end of the spectrum are studies such as the USNRC-sponsored analysis of the LaSalle reactor [1]. In that study, the quantification assumes that all cable failures result in components faulting to their worst-case position. This is certainly a more conservative approach, and is arguably the most conservative potential approach one might take.

Between these two extremes lies a third approach that has been implemented in some fire PRAs. Under this approach the potential for specific cable failure modes (e.g., hot shorts) and circuit fault modes (e.g., spurious actuations) is handled as a numerical probability. That is, some studies have attempted to quantify the relative likelihood of a fire-induced spurious actuation, and to quantify the risk contribution for such

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[2] In the remainder of this report, this analysis will be referred to as “circuit analysis.”

scenarios explicitly. The earliest known documentation of this approach is presented in NUREG/CR-2258 [2]. This particular study has been widely cited, and is discussed in detail in Section 5.1.

NUREG/CR-2258 makes a number of observations and assumptions that have not been contradicted by the current study. A general conclusion is cited that initial faults involving conductor-to-conductor hot shorts are relatively likely for multiconductor cables, and this conclusion is supported by the current study (see Section 5.2 below). Furthermore, the observation that not all hot shorts will lead to spurious actuations also is confirmed by the current study (see Section 4.2). Indeed, in most cases, specific combinations of two or more shorting conductors are required to cause an actuation. Hence, directly equating the nominal conductor-to-conductor cable failure mode probability to the spurious actuation circuit fault probability, while generally conservative, is not entirely appropriate.

In some situations, the assumptions made in the circuit analysis may have a substantial impact on the fire PRA results.[3] Given the large uncertainties associated with the current quantification methods, and the desire to identify effective risk management alternatives for cases where the fire risk is found to be significant, it is desirable to develop improved circuit analysis methods.

1.3 Task and Report Structure

To develop improved circuit analysis methods, Sandia National Laboratories (SNL) has completed a task entitled "Tools for Circuit Failure Mode and Likelihood Analysis." The task was performed in support of the U.S. Nuclear Regulatory Commission (USNRC) Office of Nuclear Regulatory Research (RES) Fire Risk Research Program.[4] The original objectives of this task, as described in the USNRC fire research plan [3], were as follows:

- Develop an improved understanding of the mechanisms linking fire-induced cable damage to potentially risk significant failure modes of power, control, and instrumentation circuits.
- Develop improved methods and data for estimating the conditional probabilities of key circuit faults, given damage to one or more cables.
- Develop sample estimates of the conditional probabilities of key circuit fault modes applicable to currently operating U.S. nuclear power plants.
- Gain risk insights concerning fire-induced circuit faults, especially those associated with cable hot shorts.
- Identify areas where additional work needs to be done to improve understanding of the risk associated with fire-induced circuit faults.

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[3] For example, in one advanced reactor design fire PRA, hot short scenarios (leading to medium or large loss of coolant accidents due to spurious valve operation) contribute over 95% of the fire-induced core damage frequency for that design.

[4] USNRC Job Code Number Y6037.

Based upon information collected during execution of the task, which showed the sparsity of quality data on cable failure modes under fire conditions, SNL efforts have focused on the first, second, and last objectives. The third and fourth objectives have been addressed, but to a more limited extent. This report summarizes the results of the task. The overall structure of the report follows that of the circuit analysis task and is illustrated in Figure 1-1.

Section 2 discusses cable behavior during a fire including identification of the modes of cable failure that might occur given a fire, characterization of the factors that will contribute to or mitigate the potential for each failure mode, and the conditional probability that, given a cable failure, a particular mode of failure will be observed. Section 2 is supplemented by Appendix A which reviews current test data relevant to the estimation of cable failure modes and likelihoods, and by Appendix D which discusses the results of a recent set of fire tests designed to assess the spurious actuation likelihood for a prototypical motor-operated valve (MOV) control circuit.

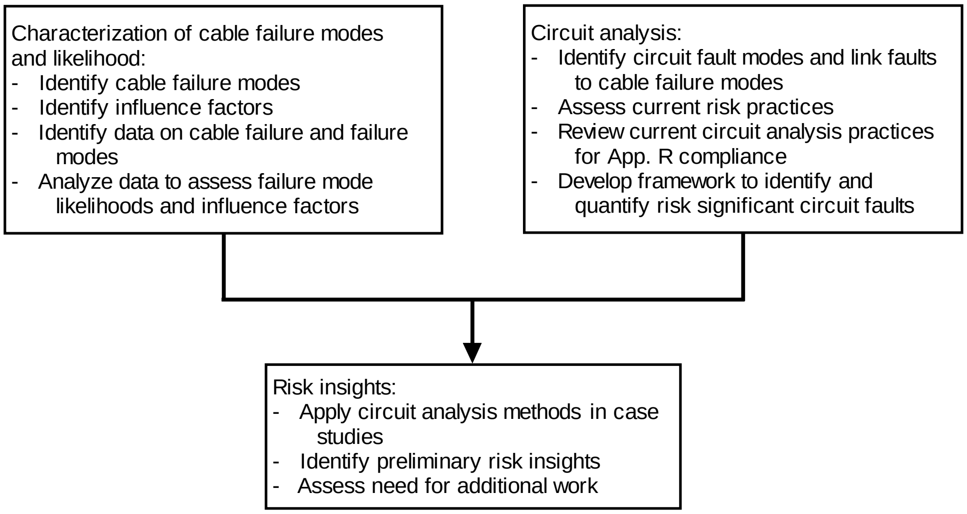

Figure 1-1. Overall structure of the circuit analysis task.

Section 3 discusses some of the circuit fault modes that can result from the different modes of cable failure and identifies circuit design features that may impact the likelihood of these circuit fault modes. The listing is not exhaustive; rather, it is intended that the discussion will illustrate, through examples, the methods by which potential circuit fault modes can be identified and assessed. A systematic approach is also proposed for identifying the impact of fire-induced cable failures on component behavior at a specific plant. This approach is based on Failure Modes and Effects Criticality Analysis (FMECA) [4].

Section 4 discusses the need to integrate the results of the circuit analysis into the overall process of fire PRA and proposes a framework for identifying risk-significant circuit faults. Preliminary risk insights are also identified and discussed. Since circuit analysis is a time-consuming process, screening methods are needed to appropriately limit the scope of the circuit analysis to those components important to fire risk. Overall screening includes qualitative screening steps that can utilize existing circuit analyses performed for Appendix R[5] [5] and additional assessments as required using an FMECA approach.

Section 5 expands on the discussions in Section 2. In particular, Section 5 documents the current state of knowledge regarding cable failure modes and likelihood based largely on the data review documented in Appendix A and D. Section 5 also proposes an approach for estimating cable failure mode likelihoods that would also help to guide any potential future testing programs where cable failure mode data might be sought.

Section 6 summarizes the results and conclusions of the circuit analysis studies completed to date and recommends further work needed to support circuit analysis efforts including uncertainty reduction. As discussed in the research plan [3], Task 1 of the USNRC fire risk research program and the studies completed to date represent a first step in a detailed study of the issue of circuit faults and their treatment in fire PRA.

1.4 Terminology for Fire-Related Circuit Analysis

The terminology applied to fire-induced cable failure and circuit fault analysis has been both loosely and inconsistently defined by past documents. Industry, the regulatory authorities, and researchers have often applied similar terms with very different meanings implied and with varying degrees of precision and consistency.

One objective of this report is to establish a clearly defined terminology in order to avoid confusion in future applications. It is not possible to fully harmonize the language as used in all of the various circuit analysis related documents. The purpose of this subsection is to clarify terminology as it is used in this report. The intent was to establish and maintain consistency with, in particular, the spirit of the previous documents and, to the extent possible, the actual wording of the most recent documents.

The proposed terminology is based on a review of past literature on the specific subject of fire induced cable failures and circuit analysis. This review included USNRC regulatory documents (Appendix R [5], GL86-10 [6], GL92-08 [7]), past research publications (e.g., NUREG/CR-2258 [2]), the Boiling Water Reactor Owner's Group (BWROG) and Nuclear Energy Institute (NEI) circuit analysis documents [8,9], and the National Fire Protection Association (NFPA) 805 standard [10].

1.4.1 Proposed Circuit Analysis Structure and Terms

Given a PRA fire scenario, this report presents the circuit analysis problem as comprising three elements or tasks. The proposed terminology will reflect this structure in that there is a unique set of terminology associated with each analysis task. The three tasks are cable failure analysis, circuit fault analysis, and

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[5] Note that Appendix R does not represent the licensing basis for all plant fire protection programs. However, Appendix R is the most common fire protection licensing basis, and other licensing bases will share many common aspects with the Appendix R requirements, including in particular the safe shutdown requirements which are of primary interest to this report. Hence, in this report, Appendix R will be used as a surrogate reference for the particular licensing basis applicable to a given licensee.

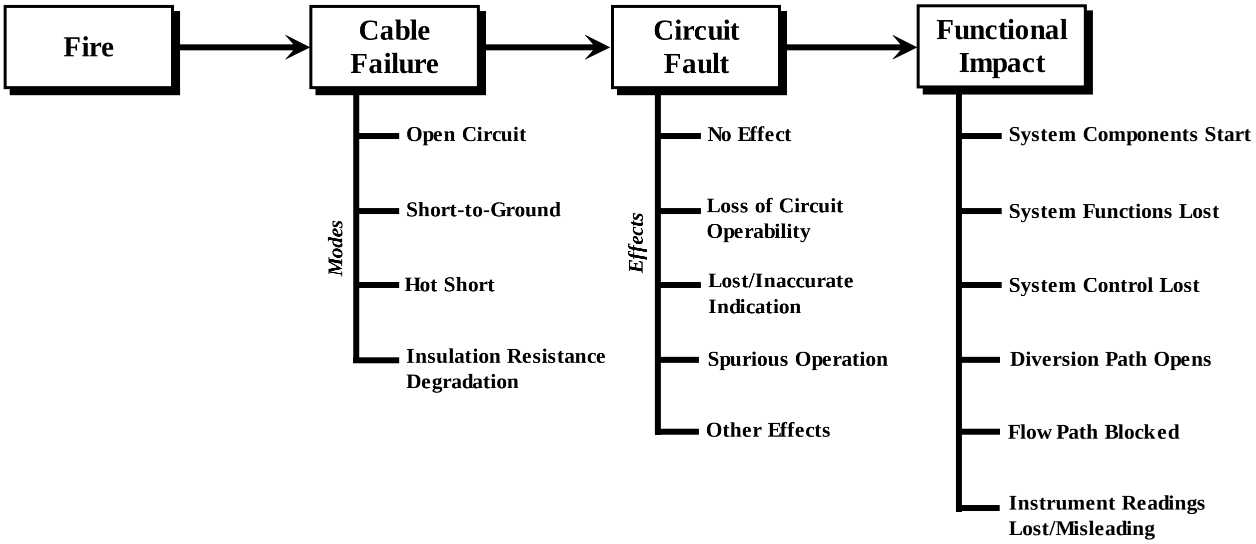

Figure 1-2. Circuit analysis process structure and associated terminology. Note that the listing of circuit fault effects and functional impacts is not exhaustive. They are presented as illustrative examples only.

functional impact assessment and quantification. This structure is illustrated in Figure 1-2. Note that the structure will involve iterative interactions between these three tasks as follows:

- Advanced **cable failure** analysis methods represent an expansion in scope of the fire damage analysis typically conducted as a part of a fire PRA. A typical PRA fire damage analysis estimates the physical extent of damage and time to failure for electrical cables exposed to fire. The expansion in scope necessary to support advanced circuit analysis explicitly considers the electrical behavior of the cables given failure. That is, the ideal advanced cable failure analysis predicts when cable failure occurs, the relative likelihood that specific modes of cable failure would occur given failure, how long a particular failure mode is likely to persist, and the overall occurrence frequency of each cable damage state or failure mode (including fire frequency, fire severity, mitigation by detection and suppression before damage, etc.).

- The electrical **circuit fault** analysis determines how each circuit will respond to the various modes of cable failure that may be observed. The result is expressed in terms of the potential **circuit fault modes**. The circuit fault analysis also feeds information back to the cable failure analysis task in the form of specific modes of cable failure that may be of particular interest to the PRA. When combined with the information on cable failure frequency and failure mode likelihood estimates, the analysis provides occurrence frequency estimates for each of the circuit fault modes of potential interest to the risk quantification.

- The final task assesses the **functional impact** of the circuit faults on the potential for plant safe shutdown and quantifies the CDF contribution for the postulated fire scenarios. This task lies in the domain of PRA plant systems modeling and event/fault tree analysis and quantification. This task also identifies the risk important plant systems and communicates that information for use in the circuit fault and cable failure analysis tasks. In particular, the functional impact analysis identifies system impacts that may be of risk significance so that the circuit fault analysis can assess the potential for such undesired impacts to be realized.

1.4.2 Circuit Analysis Terminology

This report distinguishes the terms **failure** and **fault** in a very specific context. A failure is defined as "a state of inability to perform a normal function" [Webster's, 1981]. Consistent with this definition, this report discusses failures in the context of a specific component, typically a cable. For example, a cable failure implies that the cable can no longer perform its intended design function. In contrast a fault is defined as "a physical imperfection or impairment" [Webster's, 1981]. This report discusses faults in the context of a total electrical circuit or system. For example, a circuit fault implies the impairment or imperfect operation of that circuit and its associated system. Given the overall circuit analysis process structure and this clarification, the following terminology is defined in the context of each element of the overall analysis.

- **Cable failure:** Cable failure implies that the cable is no longer able to perform its intended function which is to maintain the electrical integrity and electrical continuity of the associated circuit sufficient to ensure proper operation of the circuit. For a cable to perform its intended function, each individual conductor within the cable must maintain both electrical integrity and continuity. Hence, cable failure implies that one or more of the cable conductors have lost electrical integrity or electrical continuity. In the case of electrical integrity, the specific criterion for cable failure (e.g., minimum insulation resistance) must be established in the context of the circuit under consideration. Several **modes** of cable failure are of interest:

  - <u>Loss of conductor continuity:</u> A cable failure involving the loss of electrical continuity in an individual conductor (i.e., the conductor is broken and the signal or power does not reach its destination). This terminology is fully consistent with general electrical trade jargon. <u>Special Note:</u> A loss of conductor continuity may also be referred to in some documents as an 'open circuit' failure. This highlights a potential area of terminology conflict in that open circuit may also refer to a circuit fault effect rather than a cable failure mode, namely, the opening of a protective circuit device such as a fuse or breaker. This report will use the term open circuit in the context of a circuit fault mode.

  - <u>Conductor to external ground short circuit:</u> A cable failure condition where one (or more) conductor(s) shorts directly to an external ground. In this context, an external ground is a ground source that is not associated with the insulated conductors of the cable. External grounds may be available by virtue of the cable raceway (tray or conduit), an explicitly grounded armor sheath, a grounded drain wire, or a grounded shield wrap. (An insulated conductor that is grounded by design would be considered an internal ground in this context and would be associated with conductor-to-conductor short circuits.) This mode of cable failure may be accompanied by a surge of current to ground, particularly in higher voltage circuits, that is often damaging to the conductor. In common electrical terms this may be referred to as a ‘ground fault’ or a ‘line to ground fault.’ Also note that a short to ground may be characterized by either a high- or low-impedance electrical contact.[6]

  - Conductor to conductor short circuit: A cable failure mode where two or more insulated electrical conductors form a low-impedance short circuit that does not involve an external ground (e.g., the raceway - see conductor to external ground short circuit). The shorting may involve either the conductors of a single multiconductor cable (an intra-cable conductor-to-conductor short circuit), or the conductors of two or more separate cables (an inter-cable conductor-to-conductor short circuit). Special Notes: This definition makes no distinctions regarding the nature of the conductors involved in shorting. For example, one (or more) conductors may be grounded by design in which case the effect of the conductor to conductor short circuit would be the same as a conductor to external ground short circuit. See also hot short.

  - Hot short: A specific subset of conductor-to-conductor short circuits in which at least one conductor is energized, no conductors are grounded, and at least one conductor is not normally energized. That is, a hot short implies a conductor to conductor short circuit in which one or more non-energized, non-grounded conductors become energized due to the cable failure.

  - Loss of insulation resistance: A cable failure mode involving a breakdown in the electrical quality of the insulation of one or more conductors (e.g., due to elevated temperature conditions) such that a low impedance short circuit is not formed, but electrical isolation is degraded. The extent of insulation resistance, or IR, breakdown required to constitute cable failure can only be defined in terms of the circuit of interest. For example, an instrumentation circuit may display an unacceptable loss of accuracy even given some substantial residual resistance in the associated conductors. Special Notes: This term does not derive from general electrical trade jargon, but rather from Equipment Qualification (EQ) studies [e.g., 11]. This mode of cable failure may roughly correlate to a "high impedance short circuit" as used in other works to refer to such failures in power cables. As used in the current report, the term is more general, applying equally to power, control, and instrument cables.

- **Circuit fault:** A circuit fault is undesired or unplanned behavior in an electrical circuit induced by the failure of one or more elements of the circuit, in particular, including the failure of an associated electrical cable. In the current report this term refers to effects that postulated cable failures will have on the associated electrical circuits and components. There are many potential **circuit fault modes** that might be observed including the following:

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[6] The distinction between high- and low-impedance shorts reflects the “quality” of the electrical connection formed. Some shorts may retain little or no residual resistance (low-impedance). Electrical trade jargon may referred to such shorts as ‘hard,’ ‘dead,’ or ‘bolted’ shorts. Some shorts may involve a relatively poor electrical connection that retains substantial residual resistance (high-impedance). The criteria for the level of residual resistance that constitutes a low- versus high-impedance short must be established in the context of the circuit under consideration.

- <u>No effect:</u> Some cable failures may have no impact on the operability or availability of a system.

- <u>Loss of circuit operability:</u> Some cable failures may lead to a total loss of circuit operability. This would be common, for example, in cable failures that trip circuit protection features such as fuses and breakers and/or failures that lead to a loss of control or motive electrical power sources. Loss of operability may also result from failures involving instrumentation and control interlocks and permissive signals. For example, the failure of an oil pressure signal cable in such a manner that a false-low oil pressure was indicated may lead to the loss of function of an associated pump or motor due to an oil pressure interlock. Also note that a loss of function may be recoverable through manual intervention.

- <u>Loss of indication:</u> In some cases cable failures may leave a system or component nominally operational, but will compromise the indication functions of the circuit. This may lead, for example, to status indicating lights going dark.

- <u>Inaccurate indications:</u> Some cable failures may result in misleading or even conflicting control and instrument signals. For example, position indicating lamps for a circuit may simultaneously light indicating both the open and closed (or running and stopped) condition of a component. For instrumentation circuits a relatively low level of degradation in the IR of signal carrying conductors may be sufficient to substantially bias an instrument’s readout.

- <u>Spurious operation:</u> Spurious operation is the undesired or unplanned operation or activation of a system or component. While spurious operations are most commonly associated with cable hot short failures, various cable failure modes may lead to spurious operations, and not all hot shorts will lead to a spurious operation. For example, in certain plant designs, a loss of power to control relays may result in the spurious operation of plant systems. Such power losses may result from various cable failures. For hot short induced spurious operations, the hot short must typically involve certain combinations of conductors dependant on the circuit design.

- <u>Time dependent fault effects:</u> It should be noted that each of the circuit fault effects identified above may be time (and action) dependent. One example that will be illustrated in the body of this report is a case where certain combinations of conductor hot shorts might not cause any of the above cited circuit faults <u>until</u> such time as the control switch is actually manipulated. In the example, the operation of the control switch leads to a loss of control power (a fuse will blow) and ultimately a loss of system function.

- <u>Open circuit fault:</u> In the context of a circuit fault mode, an open circuit condition would typically be associated with either a loss of conductor continuity cable failure or opening of over-current protective features (e.g., fuses or breakers). An open circuit fault would prevent electrical power or signals from reaching their intended destination.

- **Functional Impact** refers to assessing the impact of the circuit faults on the plant's systems, components, and functions. This portion of the analysis lies in the domain of the plant systems modeling and risk quantification analyses. Depending on the systems and components involved in the fire exposure, and on the nature of the electrical circuits, there are a variety of potential functional impacts that may be relevant to the risk quantification. Functional impact is discussed in greater detail in Section 4. Functional impacts of potential interest include (but are not limited to) the following:

    - System's components start
    - System's function lost
    - Systems's function not controllable
    - Diversion path opens
    - Flow path blocked
    - Instrument reading lost or misleading

1.4.3 Other Terms Related to Fire-Induced Damage to Electrical Cables and Circuits

The following is a list of other terms relevant to the topics covered by this report:

Armored Cable: A cable that is provided with a robust outer sheath (i.e., beyond a simple polymeric jacketing material) for additional physical protection. The armor is generally metallic, and most commonly takes the form of either a sheath of braided metal wires or a spiral wound metallic band (similar to a flexible conduit). The armor sheath may be further covered by an additional layer of jacketing material.

Cable: In this context, the term cable refers to assemblies designed to conduct electrical current. Hence, a cable is an assembly of one (single-conductor cable) or more (multiconductor cable) insulated electrical conductors (generally copper or aluminum) which may or may not be surrounded by an outer jacket. (This definition excludes fiberoptic type cables which are not of interest in the current context.)

Cable Failure Mode: The manner in which a cable failure is manifested; the behaviors observed among conductors upon cable failure. Cable failure modes include loss of conductor continuity, conductor-to-conductor short circuits, conductor-to-external ground short circuits, and loss of insulation resistance.

Cable Insulation: The material that immediately surrounds the individual conductor(s) of a cable and provides electrical isolation of the conductor. Modern cables commonly use polymeric materials for cable insulation (see thermoset and thermoplastic).

Cable Jacket: A secondary sheath designed to provide physical protection of the cable and cable insulation. A jacket may be applied to individual insulated conductors and/or as an overall sheath for a grouping of two or more conductors. The jacket is not designed or intended to provide electrical isolation of the conductors although it is typically constructed from an electrically insulating polymer.

Circuit Fault Mode: The manner in which a circuit fault is manifested in the circuit. Circuit fault modes include loss of motive power, loss of control, loss of or false indication, open circuit conditions (e.g., a blown fuse or open circuit protective device), and spurious operation.

Drain Wire: An electrical conductor within an overall cable that is not insulated. Drain wires are commonly grounded and are commonly included in certain types of control and instrument cables.

Hot Probe Method: A method of circuit analysis in which the analyst assumes the presence of an energized conductor (the hot probe) capable of causing spurious operation of the circuit under analysis. The hot probe approach postulates that this energized conductor might come into contact with other conductors associated with the circuit under analysis and assesses the potential circuit fault modes that might thereby arise.

Intra-Cable Conductor-To-Conductor Short Circuit: A specific subset of conductor-to-conductor short circuit cable failures wherein all conductors involved in a given short circuit are within one multiconductor cable.

Inter-Cable Conductor-To-Conductor Short Circuit: A specific subset of conductor-to-conductor short circuit cable failures wherein the short circuit formed involves the conductors of two or more separate cables.

Maintained Spacing: A method of routing cables in cable trays such that there is no stacking of the cables, and each cable is individually strapped down to the tray. Gaps between cables ensure that they do not come into physical contact with each other. This method is most common for large power cables.

Shield: A conducive sheath or wrap around an insulated conductor or group of conductors within a cable. A shield is typically formed of either a metallic foil or a braided sheath of metallic wires. Shields are commonly applied where electromagnetic interference is a potential concern (e.g., communications and instrument circuits).

Spurious Operation: A circuit fault mode wherein an operational mode of the circuit is initiated (in full or in part) due to failure(s) in one or more components (including cables) of the circuit.

Thermo-Plastic: A Polymer that is capable of being repeatedly softened by increase of temperature and hardened by decrease of temperature, the change upon heating being physical rather than chemical. The major types of thermoplastic materials are olefin (including polyethylene, polypropylene, and flouroplastics); vinyl (including polyvinyl chloride, polystyrene, acrylonitrile-butadiene-styrene (ABS), and acrylic); aromatic (including polycarbonate, parylene, phenoxy, polysulfone and polyimide). Other thermoplastic materials are polyamide (nylon), acetal, and chloronated polyether [12].

Thermo-Set: A Polymer that changes into a substantially infusible or insoluble product when cured by application of heat or chemical means. The major types of thermosetting materials are phenolic (including phenol-formaldehyde); amino (melamine-formaldehyde and urea-formaldehyde); epoxy; polyurethane; and polyester. Other thermosetting materials are allyl, silicone, and furane [12]. Cross-linked polyethylene and ethylene-propylene rubber, common cable insulation materials, are also considered thermo-sets.

2 CABLE FAILURE MODES

Fires can cause cable failures, and cables can fail in more than one way. Different modes of cable failure can, in turn, produce different circuit faults. The risk implications of a given circuit fault are dependent upon the associated component's function. This section provides a description of the types of cables commonly encountered in nuclear plant applications and the modes of cable failure that might be observed. This section also discusses the potential impact of various cable failure modes on power, control, and instrumentation circuits. Factors that can influence the potential for each of the identified cable failure modes occurring as a result of a fire are also identified. A qualitative assessment of the importance of each of these factors is presented based on an assessment of current knowledge gained through a review of electrical failures observed during cable fire tests (both large and small-scale) and actual fire incidents, and, where data is lacking, on the judgement of the authors.

2.1 Description of Cables

There are three primary functional types of cables in a nuclear power plant; namely, power, control, and instrument cables.[7] Virtually every system in the plant is dependent on the continued operation of one or more electrical cables. The cables of concern to this study are comprised of one or more electrical conductors generally either aluminum or, more commonly, copper.[8] Each conductor is electrically isolated by a layer of electrical insulation. For modern cables the insulation is generally a polymeric, silicone-based, or rubber-based material of some type. Most cables will also have an integral protective over-jacket. The jacket serves a strictly utilitarian purpose (physical protection) and has no electrical function.

Cables can also be categorized by their physical configuration. The most common types are single conductor, multiconductor, and triplex. A single conductor cable is just as the name implies; a single insulated metal conductor which will typically also have an integral over-jacket. A triplex cable is a grouping of three single conductors that are manufactured together and are often twisted around a centrally located uninsulated core wire. The core wire may be connected to the circuit ground. Triplex cables are common, in particular, in three-phase power applications.

Multiconductor cables are more varied and may come with virtually any total conductor count. This is limited only by practical considerations such as the overall physical diameter and handling ability. The most common configurations encountered in a nuclear plant are two-, three-, seven-, and twelve conductor configurations. The three-, seven-, and twelve-conductor configurations are popular with manufacturers because they result in an overall cable product that maintains an essentially round outer profile as illustrated in Figure 2-1. Another common configuration in instrument cables in particular involves some number of "twisted/shielded pairs" within a protective jacket. The shield in this case refers to a conductive wrap such as a metal foil, wrapped around, in this case, conductor pairs. This is common in sensitive instrument circuits

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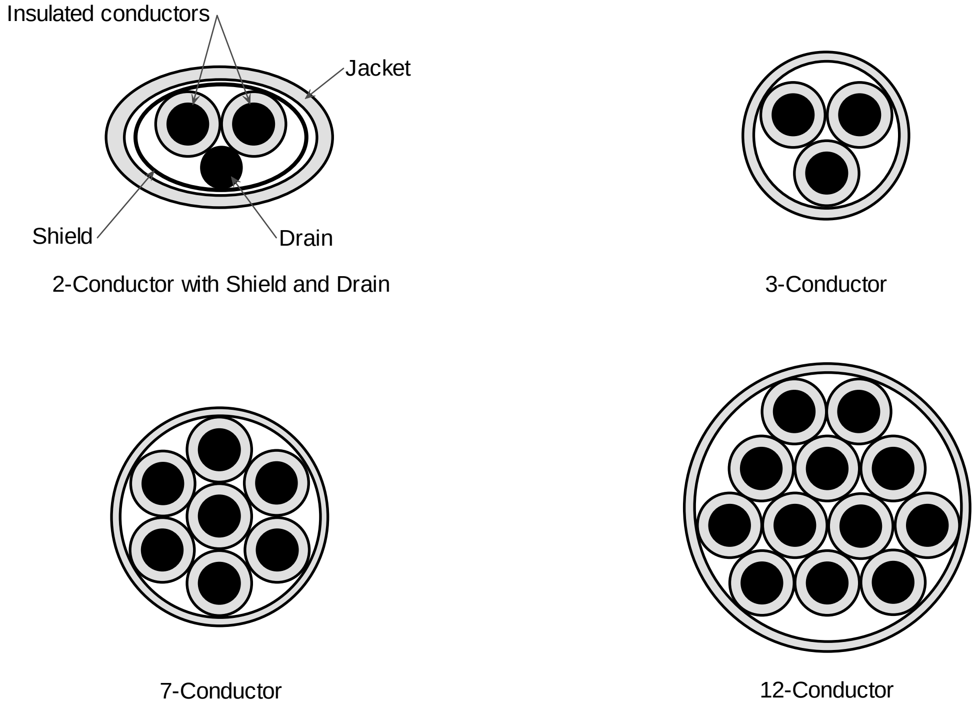
[7] Note that communication cables are similar to instrument cables and are not separately identified. Similarly, indication functions are typically performed by the corresponding control cable and are not separately identified.

[8] This study is not concerned with fiber optic cables.



2-Conductor with Shield and Drain

3-Conductor

7-Conductor

12-Conductor

Figure 2-1. Illustration of common multiconductor cable arrangements.

where stray electromagnetic or radio frequency interference (EMI/RFI) may be a concern. These cables are also used commonly in communications systems. Figure 2-1 also illustrates a simple two-conductor with shield and drain arrangement. The drain is an uninsulated conductor run along with the insulated conductors and would typically be grounded.

Power cables may be single-conductor or multiconductor. One very common power cable configuration is a triplex cable - a cable with three, spiral wound, individually insulated conductors and typically no overall jacket. The triplex cable will come off the cable reel as a single unit with the conductors forming a mutual spiral pattern that will retain their relative proximity even after being installed in a raceway. The triplex cable may also include an uninsulated ground conductor. Triplex cables are especially common in three-phase power supply systems. Groups of single conductor cables may also be used in such cases. For single-phase light power applications use of either two- or three-conductor cables is common. For single-phase three-conductor applications, one conductor would typically be grounded.

Control and instrument cables are generally of a multiconductor design. Control cables will typically range from 3 to 12 conductors, although in theory any number of conductors may be encountered in a given application. For instrument cables, the number of conductors is potentially very large (50 or more) whereas control cables will rarely exceed about 12 conductors.

A cable’s size is generally expressed using the total conductor count and the American Wire Gage (AWG) of the individual conductors (note that a higher AWG number indicates a smaller conductor diameter). Hence, a “3/C 12AWG” cable is a three-conductor 12 gage cable. Power cables will typically range from relatively small 12 AWG cables (equivalent to cables used in residential applications for household power circuits) up through very large cables whose conductor’s diameter can easily exceed 2.5 cm (1"). For power cables, the size selection is generally based on either the required current carrying capacity (ampacity) or maximum voltage drop allowed in a specific application. Control cables are generally of a smaller gage, commonly ranging from 16 AWG up through 10 AWG. Instrumentation cables are generally of 16 AWG or smaller, although cables as large as 12 AWG may be used.

Voltage ratings (i.e., the maximum allowable voltage for a cable) will also vary with the application. Instrument circuits generally use low voltages (50 volts or less) and the cables may be rated accordingly. Control circuits are commonly encountered in the 120-250 volt range and commonly used cables rated for 600 V. Power circuits encountered within the plant generally range from 120 to 4160 volts, with power circuits associated with off-site power ranging up to 15 kV or higher. Many power cables will also be rated for 600 V, although in general any circuit using a voltage of greater than 480 V will use a cable with a higher voltage rating.

Cables are generally routed through the plant horizontally in raceways (generally trays or conduits) with vertical runs used as required between different elevations in the plant. The cables are generally segregated by type (power, control, and instrument) but cables of various voltages and functions can be found together in the same raceway for some plants (generally older plants). High-voltage power cables are typically routed by themselves and may use “maintained spacing” due to ampacity concerns. For most cables, random placement within the tray is common (that is, the cables are simply laid into the tray in a, more or less, random way).

2.2 Cable Failure Modes

Recall that per the definitions in Section 1.4, cable failure implies that one or more conductors in the cable can no longer provide adequate electrical integrity and continuity such that proper circuit operation is assured. As discussed in Section 1.4, the cable failure modes of interest are:

- loss of conductor continuity,
- conductor to external ground short circuit,
- conductor to conductor short circuit (including hot shorts and shorts to ground if one or more conductor is grounded), and
- loss of insulation resistance (primarily of interest for instrument circuits).

It is recognized that this terminology may appear somewhat cumbersome. For example, it may not appear necessary to distinguish between conductor to external ground and conductor to conductor shorts that involve a grounded conductor. In the context of the circuit fault behavior, the two failure modes would have the same impact. However, one objective of this study is to assess the relative likelihood of the various failure modes given the existing data. While exceptions exist, far and away the most common approach is to test a cable in a non-circuit-specific mode (i.e., the cable is not wired in such a way as to represent any particular control or power circuit). As a result, the mode of cable failure reported is most commonly conductor to external ground shorts versus conductor to conductor shorts. Hence, in the interpretation and application of the test data, these are typically the only distinctions possible. This leads one to a need for additional analysis tools and methods to further characterize the conductor to conductor short circuits in particular. The impact of such shorts will depend on the nature of the conductors assumed to be involved. Special cases include a conductor to conductor short that involves one or more conductors that are grounded by design, and hot shorts. However, these behaviors, and their associated likelihood, can only be assessed in the context of a specific circuit and a specific cable wiring configuration. This topic is taken up further in Section 5.

It is important to note that, as discussed above, a cable may have any number of conductors. In considering the failure of a cable it is possible for more than one conductor failure mode to be active at a given time. For example, one set of three conductors may be shorted together (possibly creating a conductor-to-conductor hot short) while a fourth conductor has shorted to an external ground.

Note that conductor shorts may be manifested in the form of a low-impedance short (often referred to as a “bolted-” or “dead-short”) or as a high-impedance short. These two modes of shorting are distinguished for the following reasons:

- A high-impedance short may allow power to pass from one conductor to another (or to ground) even between circuits with dissimilar voltages whereas a low-impedance short between circuits of dissimilar voltage or between a circuit and ground will in many cases trip circuit protection features (fuses or breakers) in one or both circuits.

- A single low-impedance short in a power circuit with proper selectivity would trip the lowest level of upstream circuit protection whereas multiple high-impedance faults may trip a higher level circuit protection feature (if proper circuit protection coordination is not provided[9]) leading to loss of a higher level electrical bus.

- High-impedance shorts in an instrumentation circuit may lead to a biased indication that might not be detected by operators whereas a low-impedance short would likely result in a more easily detectable loss of indication (i.e., at the extreme high or low end of the scale or an off-scale reading).

A description of the potential circuit fault modes resulting from each of the cable failure modes is presented in Section 3.2.

2.3 Review of Experiments on Fire-Induced Cable Failures

This section summarizes the state of knowledge available from the cable fire performance testing over the past three decades. A great deal of research on cable fires was performed during that time period. The results of this work were reviewed with the objective of determining what is known about cable failure behavior and the factors that can affect the potential for different conductor failure modes during a fire including their relative importance. A more detailed description of the review findings is provided in Appendices A and D. This section of the report focuses on the question of factors that may influence the

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[9] Breaker coordination and selectivity is discussed further in Sections 3 and 4.

failure mode likelihood. The analysis of the data in terms of the relative likelihoods indicated is deferred to Section 5.

The effort was initiated by performing a general search of the public literature for any documents relating to cable fire testing, cable damage, cable functionality, and cable failure. Of the citations that were returned, 45 reports and papers (totaling more than two thousand pages) were identified that included some discussion of fire-induced cable failures. Of these, 26 were found to contain unique information or data on cable failures. The remaining documents were found to be either subsidiary documents that repeated data already available from the other 26, or included only high-level discussions (no data). The identified reports and papers are listed in Appendix A. For the 26 reports found to contain unique data, the Appendix is presented in the form of an annotated bibliography. The other 19 documents identified in the literature review are not reviewed in detail, but are identified without elaboration.

From the standpoint of cable failure mode likelihood estimation, the available information in these reports is sparse. This is because the bulk of fire-related cable research has focused on one of two areas:

- Most large-scale cable tests were designed to examine the flammability and fire behavior of cables. Topics include propagation of cable fires in and between cable trays and the effectiveness of various fire protection features in mitigating cable fire growth behavior. In a minority of these tests electrical performance of a small sample of cables was monitored, but this was rarely a primary test objective. Even in those cases where electrical function was monitored, only a small subset of these tests explicitly sought information on cable failure modes.

- A second class of cable tests has sought to determine the failure thresholds of the cables. These are typically small-scale tests where cables are exposed to simulated fire conditions. Typical tests use either radiant heating lamps or an air-oven to create the exposure. The time to failure for exposed cables is commonly monitored. The failure behavior is commonly characterized based on the heat flux or atmospheric temperature in the test chamber and the time of exposure to these conditions. Thresholds are typically expressed as a minimum temperature or heat flux leading to failure.

One unique series of cable fire tests specifically designed to explore cable failure modes and effects has recently been completed. These tests were conducted at Omega Point Laboratories (OPL) facilities in Elmendorf, Texas under the sponsorship of the Electric Power Research Institute (EPRI) and the Nuclear Energy Institute (NEI) [13]. SNL also participated in these tests under the sponsorship of the USNRC. The EPRI/NEI tests focused on a prototypical motor-operated valve (MOV) control circuit and the potential for spurious actuation of the circuit upon failure of the cables. SNL implemented a supplemental cable monitoring circuit through which the mode of cable failure could be explicitly determined based on conductor-to-conductor and conductor-to-ground insulation resistance (IR) [14]. A brief discussion of the USNRC/SNL results from these tests is provided in Section 5 and in Appendix A. Appendix D discusses the results from the EPRI/NEI MOV circuit.

One objective of the literature review was to identify those factors that may influence the likelihood that any given cable failure mode might be observed. An initial listing of factors based on the judgement of the authors was developed. The identified reports associated with fire-induced cable failure were then reviewed for information that would shed light on the identified factors, or that might indicate additional factors that need to be considered. Upon completion of the literature review, an expanded list of factors was developed, and the potential importance of each factor was assessed. These results have been incorporated into the discussion presented in Section 2.5 below.

2.4 Cable Damage During the Browns Ferry Fire

A second potential source of information on fire-induced cable failure behavior is actual fire experience. However, fire experience is relatively limited, and fire reports rarely focus on details of cable failures or the resulting circuit faults. The most significant exception to this observation is the 1975 Browns Ferry fire [15].

This fire damaged more than 1600 cables routed in 117 conduits and 26 cable trays. Various studies of that incident have noted that the fire resulted in spurious initiation of components, spurious control room annunciation, spurious indicator light behavior, and loss of many safety-related systems. Examples of the component and system behavior observed during the fire as described in the USNRC report on the fire [16] are briefly discussed below.

After notification of the fire was received in the control room, alarms occurred on the Unit 1 control panel that contains the controls and instrumentation for much of the emergency core cooling systems (ECCS). Comparison between the indications by the operators revealed discrepancies. For example, one panel indicated all the ECCS pumps were operating but the reactor parameter instruments indicated that the parameters were normal and did not cause actuation of the ECCS. This is a clear indication that spurious operation of these systems, or at the very least spurious indications of operation, occurred due to fire-induced cable hot shorts. In fact, it appears that several spurious actuations of the ECCS occurred. In addition, many other spurious control room alarms occurred including a reactor low level auto blow-down permissive and alarms from various other shutdown panels. The fire also resulted in shorts to ground or open circuits that failed several power sources that significantly affected Unit 1. This included a 120 Vac preferred power source which resulted in loss of all neutron monitoring instruments; two 250 VDC boards which failed 7 of 11 relief valves (the air supply to the remaining 4 valves was also lost due to loss of power to a solenoid valve in the airline) and the Reactor Core Isolation Cooling and the High Pressure Coolant Injection systems (both due to loss of power to the steam line isolation valves); and several 480 V boards that resulted in complete failure of the Core Spray, Residual Heat Removal and Standby Liquid Control systems. Loss of power to several 4 kV shutdown boards occurred, requiring actuation of the emergency diesel generators. The Unit 2 impacts from the fire were substantially fewer.

For Unit 1 during the fire, indicating lights in the control room for valve and pump control switches were alternately glowing brightly, dimming, and going out. Smoke was observed coming from at least one of the control room panels. The fire also damaged cables containing the conductors leading from various power distribution panels to indicator lights which inform the operator of the status of the plant's electric power system. Due to the configuration of the circuits containing these lights, the fire damage to these conductors actually led to the unavailability of multiple redundant components. The impact of the circuit design was discussed in the USNRC report on the fire [16]:

> "*The light circuits were thought to be isolated from the power sources and safety circuits by series resistors. These resistors were ineffective because the circuit designers did not consider the types of short circuits that actually occurred during the fire. When the cable insulation had burned away, the resulting short circuits among the wires in the trays fed power backwards from the lights toward*

> *the power and control panels in spite of the series resistors, causing breaker trip coils to remain energized thereby keeping breakers open. Tripping the breakers removed power from safety equipment and made normal breaker control impossible. This was discovered during the fire; some power and control circuits were restored by physically disconnecting the light circuits at the control or power panel, then replacing blown fuses and realigning tripped breakers."*

The above failures occurred because the indicating light circuits were not recognized as potential failure sources for safety equipment, and thus, their associated cables were not separated by division nor segregated from non-safety cables. Appendix R [5] requires that circuits such as these must be designated as "associated circuits" which are required to meet the same separation criteria as safety circuits, or they must be isolated from the safety circuits (physically and electrically).

A separate review of certain of the occurrences observed during the Browns Ferry fire was performed as part of this study. The goal of this effort was to gain additional insights into what factors may be important to fire-induced circuit faults and to assess whether or not the purported spurious equipment operations and instrument/control signals could be explained through analysis of the impacted circuits. The effort is documented in Appendix C. Three specific occurrences were examined in detail:

- the occurrence of the ECCS annunciator alarms,
- the reported spurious operation of the ECCS pumps, and
- the indicating light behavior (described above).

Several conclusions were reached from this independent review as discussed immediately below; however, the review was unable to reach definitive conclusions regarding whether or not specific spurious actuations did in fact occur during the fire. In large part, this residual uncertainty arises because (1) the quality of the information available is less than ideal, (2) there may be more than one explanation for the cited behavior, and (3) some of the purported spurious actuations were not verified as actual operations at the time of the fire (i.e., they may have been spurious indications of an operation rather than an actual operation).

The analysis of the annunciator and pump control circuits did consider the potential failure modes for the identified fire-affected cables and conductors as provided on available system and cable routing drawings (obtained from the USNRC Public Document Room). For those occurrences noted during the Browns Ferry-1 fire that were pursued in the analysis, it was found that the alarms and apparent spurious component operations can be explained based on the circuit analysis results. That is, the analysis was able to identify cable failures that would have produced the cited circuit fault occurrences that were pursued in the analysis (not all of the individual occurrences noted during the event were pursued here). However, it is not possible to eliminate all other potential failures as valid alternative explanations of the observed behaviors.

One question asked in the analysis was whether or not a single hot short could have caused both the spurious alarms and spurious ECCS activation. If this is possible, then the event might not provide evidence of multiple hot shorts as has been purported in past reviews. The results of this study do not support the single hot short theory. That is, the study finds that multiple hot shorts were almost certainly required to cause the various behaviors noted during the fire. For example, shorts in one of the automatic blow-down system logic circuits could explain some of the alarms but not all. In addition, the two RHR and two CS pumps are not automatically started by the relays associated with the blow-down system; hence, spurious operations attributed to these systems must have involved additional cable failures. The only other identified possibility is that multiple conductor-to-conductor shorts occurring concurrently caused all four pumps to start. By a process of elimination, the multiple hot short theory appears to be the most plausible explanation.

In summary, from an electrical standpoint, the events reportedly observed during the Browns Ferry fire can be explained through analysis using the available documentation. The results support the theory that multiple hot shorts and spurious actuations did occur during the fire. However, to show that the postulated faults are, in fact, the only possible explanation would require additional drawings and information that were not available to this study. It is likely that even given open access to all of the plant records, some residual uncertainty in the findings would be inevitable. At the least, questions regarding the as-designed versus as-built plant configurations will always remain unanswerable, as will the uncertainty associated with whether certain systems actually did operate spuriously or only indicated a spurious operation.[10]

2.5 Factors Influencing Cable Failure Mode Likelihood

A range of factors may impact the conditional probability that, given a fire-induced cable failure, a particular mode of failure might be observed. Various factors may also influence the timing of potential faults being observed and the timing of fault mode transitions (e.g., hot short transition to a short to ground). This section discusses the results of an effort to identify and characterize these factors based on current knowledge.

This effort was broadly inclusive of potential influence factors. That is, even factors perceived or known to have a weak influence were identified and evaluated. While there may be good reason to ultimately dismiss several factors from final consideration of a fault mode probability analysis, it is appropriate to identify them and provide an explicit basis for their ultimate exclusion. The objective of the current study is limited to identifying these factors and assessing the current state of knowledge regarding each.

As noted above, the initial listing of factors was based on the knowledge of the authors coupled to early results of the literature and event review tasks as described in Sections 2.3 and 2.4 respectively. The event and literature reviews then continued, seeking information relevant to the identified factors and to identify other factors of potential importance. The results are summarized in Table 2-1. It must be acknowledged at the outset that the literature and event reviews have provided relatively few clear insights into the factors of influence. The data sources are collectively too diverse in design and approach for significant comparison of a given factor between test programs. Taken individually the available sources are generally too limited in scope to provide definitive insights across a broad range of potential factors. As a result, the discussion of influence factors and their potential importance remains heavily reliant on the judgement of the authors. Those cases where explicit data or experience leads to specific knowledge of a given factor's importance are few, but are identified in the table.

The identified factors can be roughly categorized as falling into one of four broad groups; namely, factors associated with the cable's physical properties and configuration, factors associated with the routing of the cable, factors associated with the electrical function of the circuit, and factors associated with the fire

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[10] These specific issues were identified as potential points of uncertainty by current Browns Ferry plant personnel during early discussions of SNL's plans to pursue the circuit faults noted during the 1975 Browns Ferry fire as a part of this program.

exposure conditions. Within each of these broad groups, a number of individual factors have been identified. The identified factors are as follows:

Cable physical properties and configuration factors:
- insulation/jacket composition
- number of conductors in a multiconductor cable
- armoring
- shielding of conductor pairs
- presence of an uninsulated ground conductor or drain wire
- aging condition
- cable size
- cable qualification status

Routing factors:
- cable tray type
- conduits (as compared to cable trays)
- overall raceway fill
- maintained spacing installations
- protective coatings
- raceway orientation
- bundling of cables

Electrical function factors:
- circuit function (i.e., instrument, power, control)
- cable ampacity load for power cables
- circuit voltage
- circuit-to-cable wiring configuration

Fire exposure condition factors:
- exposure mode (flame impingement, thermal radiation, convection)
- exposure intensity and duration
- application of suppressants
- relative fire elevation

Table 2-1 discusses each of the influence factors identified to date including the current evidence available regarding each of the factors from both experiments and actual experience. A preliminary ranking of the potential importance of each factor is made based on the available evidence and judgement. Note that in this context, the importance ranking is limited to the potential influence on the failure mode likelihood given cable failure. Those factors that have been shown to be of primary importance to the failure mode likelihood are ranked as “significant” influence factors. Those factors that have been shown to have only a very weak influence on failure mode likelihood are ranked as “weak” influence factors. Influence factors for which there is little or no direct evidence are ranked as either “likely significant” or “likely weak” reflecting the authors’ perception of the likely final ranking of each.

Table 2-1. Cable failure modes: matrix of influencing factors.

Factor:		May influence failure mode likelihood because:	Evidence	Ranking
Cable Physical factors:				
	Insulation properties	The two dominant types of insulation are thermoset and thermoplastic. The insulation material is known to substantially impact the vulnerability threshold (e.g., failure temperature) with thermoplastic cables failing at much lower temperatures than thermoset cables. Recent testing also indicates that material type influences certain aspects of the failure mode behavior and, in particular, the likelihood of spurious operations. Tests recently performed by industry [13] in which the USNRC participated [14] provide direct evidence of these effects. For intra-cable conductor-to-conductor shorting (as apposed to shorts to an external ground) the two materials perform similarly. However, inter-cable conductor-to-conductor shorts were found to be more likely for thermoplastic cables than for thermoset cables. This latter effect may also be related to the jacket material type (see discussion below). This recent experimental evidence is considered strong. It appears that the melting behavior of an overheated thermoplastic (as compared to the charring/decomposition behavior of an overheated thermoset) may allow conductors of separate cables to come into contact more easily. Special consideration may also be appropriate for cases where there is a mixture of cable insulation types present in a common raceway. For example, cable-to-cable material variations within a tray or conduit could impact the likelihood of cable-to-cable shorts versus shorts to ground if certain cables (e.g., thermoset cables) are degrading more quickly than others (e.g., thermoplastic cables). Such effects have not been experimentally investigated. Most tests have been performed using only a single type of cable in a given test (i.e., all the cables in a given test would typically be of the same type if not identical).	Good	Weak for intra-cable behavior, Moderate for inter-cable behavior.
	Jacket properties	The jacket material and thickness may influence the cable failure mode behaviors. Jackets are generally considered sacrificial and are not intended to perform any electrical function. Hence, damage to jackets during installation is not considered problematic. Also, jackets tend to age and degrade more quickly than insulation materials. Nonetheless, a robust and intact jacket may delay the onset of short circuits outside of a multiconductor cable. This may make internal cable failure modes (intra-cable conductor-to-conductor shorts) more likely at the expense of external failure modes (inter-cable conductor to conductor or shorts to external grounds). As noted above, thermoplastics melt and thermosets do not. Also, thermoplastics degrade at much lower	Poor	Likely weak for intra-cable; Likely moderate for inter-cable

Table 2-1 (cont). Cable failure modes: matrix of influencing factors.

	Factor:	May influence failure mode likelihood because:	Evidence	Ranking
		temperatures than do thermosets. Hence, cables with a thermoplastic jacket may be more likely to see inter-cable conductor-to-conductor shorts. The available experimental evidence does appear to bear out this effect (as described immediately above). One might also presume that cables with a thermoset jacket may be more likely to experience intra-cable conductor-to-conductor shorts. However, the limited experimental evidence does support this supposition. The experimental evidence specific to jacket material effects remains poor. Most tests are performed with cables that have jacket and insulation materials of the same type (e.g., both are thermoplastic or both are thermoset). Hence, it is difficult to separate insulation and jacket behaviors. Overall, the ranking is assigned as the same as was noted above with regard to insulation material based on the available weak evidence.		
	Number of Conductors	The number of conductors will certainly influence the likelihood that a specific pair (or set) of conductors within a cable might short together. This particular issue is discussed under the factor "circuit-to-cable wiring configuration" below. (Note that cables with greater than three conductors will generally be instrument and control cables rather than power cables.) However, it does not appear that the total conductor count has a significant impact on the cable failure mode likelihood in and of itself (i.e., that a given cable would experience conductor-to-conductor versus conductor-to-external ground shorts first). There is no single test program that provides substantive direct evidence to support this conclusion. Rather, this conclusion is based on comparison of early tests that were dominated by 3/C cables and more recent tests dominated by 7/C and 9/C cables.	Fair	Likely Weak with regard to initial cable failure mode
	Armoring	For an armored (metal jacketed) cable, cable-to-cable shorting without a short to ground would be considered highly unlikely, if not impossible. Armoring will also increase the likelihood of conductor-to-ground(armor) shorts at the expense of non-grounded intra-cable conductor-to-conductor shorts. In effect, the armor represents a readily accessible ground plane (the armor is typically grounded). The ready availability of a strong ground plane would tend to increase the likelihood of ground shorts involving the armor. Note that the conductors are commonly wrapped, as a group, with a mylar spiral-wound sheath before application of the armor. Hence, intra-cable conductor-to-conductor shorts are still possible. Experimental evidence regarding armored cables is available, in particular, from testing by IRSN in France (see Appendix A for details) and by recent industry testing [13]. In the IRSN program several samples of various armored cables were tested. Most showed evidence of the initial failures involving one	Good	Significant (armored cable conductors are more likely to short to grounded armor than to each other)

Table 2-1 (cont). Cable failure modes: matrix of influencing factors.

Factor:	May influence failure mode likelihood because:	Evidence	Ranking
	conductor and the armor, and relatively few showed conductor-to-conductor shorts independent of the armor. In the recent industry tests [13], eight armored cables were tested with seven observed cable failures. Only one of the seven failures led to a spurious actuation, and this one case may be suspect because it involved a cable whose minimum bend radius was violated in the installation. Companion IR measurements conducted through USNRC/SNL participation in these tests [14] were inconclusive.		
Shield wraps	Shield wraps may be encountered in multiconductor instrument cables. Typically, conductor pairs may be wrapped in a foil or metal braided shield to prevent interference from stray EM or RF signals. The shield is generally grounded. For this type of cable, the shield will increase the likelihood of ground shorts and substantially decrease the possibility of intra-cable conductor-to-conductor shorts. Cable-to-cable shorts or short between conductors within the shield and conductors outside the shield without a concurrent ground short would be virtually eliminated. Some experimental evidence to support this supposition is available. In testing by USNRC/SNL [17] one of the cables tested was a two-conductor with shield and drain control cable. In 38 of 40 failures, the initial failure mode was conductor-to-shield/drain shorting. In just 2 of 40 cases was the initial fault mode conductor-to-conductor shorting.	Good	Significant (intra-cable conductor-to-conductor shorts less likely than shorts to grounded shield)
Drain wires	A drain wire is an uninsulated conductor within a multiconductor cable. Drain wires are commonly grounded and are often encountered in conjunction with shield wraps. The arguments regarding drain wires parallels that associated with shield wraps, as does the experimental evidence.	Good	Significant
Cable age	As cables age the insulation and jacket materials become more brittle. Different materials age at different rates. The physical aging of cable materials is well characterized. The impact of aging on general electrical properties is also well known. However, cable aging studies are generally based on simple pass-fail conductor IR thresholds that do not consider cable failure mode. While a number of studies on cable aging are available [e.g., 18,19] the impact of aging on the relative likelihood of various failure modes has not been examined in any such study known to the authors. The stiffening of an originally flexible cable may make certain modes of failure less likely. In particular, inter-cable shorts may be less likely because the cables will be less inclined to move; hence, less inclined to come into contact. Cable-to-raceway shorts to ground may also be reduced somewhat for the same reasons. However, for this to have some overall impact on likelihood would require a corresponding	Very limited	Likely weak

Table 2-1 (cont). Cable failure modes: matrix of influencing factors.

Factor:	May influence failure mode likelihood because:	Evidence	Ranking
	increase in the conductor-to-conductor hot short likelihood. It is not clear that a mechanism for such behavior exists. Experimental evidence regarding aging effects on fire-induced cable failure modes is relatively poor. Fire damage testing of aged and unaged cables [17] revealed little impact on failure thresholds, but the tests did not directly explore failure mode effects. The early insulation degradation behavior of the aged and unaged samples did show some changes, but whether these changes are significant for failure mode likelihood is not clear.		
Cable size (wire gauge)	The available evidence relating to cable size and failure mode is currently weak. Nominally, there is no indication that cable size substantially impacts the likelihood of conductor-to-conductor versus conductor-to-ground shorts, in particular, when considering intra-cable shorts. However, note that the overall size of a cable and the size (or wire gauge) of the conductors will impact the rate of cable heating, and hence, the timing of failure onset. In cases where all of the collocated cables are of similar size, multiple cables will likely experience failures over a relatively short period of time. In raceways that contain mixed (large and small) cables, smaller small cables are likely to degrade more quickly than large cables and substantial differences in time of failure may be observed. Because cables tend to short to ground eventually, the probability of an inter-cable interaction between a large and small cable may be substantially smaller than the probability of the same failure mode for cables of like size.	Poor	Likely significant only when cable sizes vary within a raceway

Table 2-1 (cont). Cable failure modes: matrix of influencing factors.

Factor:	May influence failure mode likelihood because:	Evidence	Ranking
Cable qualification status	Cable qualification status (rated or un-rated) in this context refers specifically to the cable's status with regard to all aspects of the IEEE-383 qualification standard [14] (both flame spread and harsh environments). An IEEE-383 rated cable is, in general, more robust than an un-rated cable. Given this, the qualification status will likely influence the timing of failure onset for any given fire scenario. In most respects, the issue of qualified versus unqualified parallels that presented above regarding insulation type. Most qualified cable will be of the thermoset family, and most unqualified cables will be of the thermoplastic family. It is expected that the thermoset versus thermoplastic factor is predominant. Use of qualification status as an influence factor is not recommended. Rather, use insulation type.	n/a	Use insulation type as an alternate criterion
Cable Routing and Installation Factors			
Cable tray type	There are variations on the cable tray configuration that may be important. In particular, the use of solid bottom trays versus open bottom trays, and trays with or without rungs will likely impact the potential for ground shorts to be observed. In these cases, competing effects may need to be considered. For example, the rungs of a ladder type tray represent pressure points for the cables that contact the rungs. The highly localized supporting force may make failures near the rungs more probable, and indeed, may make ground shorts to the rung themselves more probable. In contrast, a solid bottom tray without rungs has a far more substantial ground plane, but will also support the cables more evenly. It may be observed that a solid bottom tray is more like a conduit in this regard than a ladder tray, although this remains to be seen. There is little or no evidence to support an assessment of the importance of cable tray type as a failure mode influence factor. All of the tests identified involving cable trays have involved ladder trays. Some evidence regarding conduits was identified, as discussed immediately below, that may be relevant to the question for solid bottom trays without rungs in particular.	Very poor	Likely significant

Table 2-1 (cont). Cable failure modes: matrix of influencing factors.

Factor:	May influence failure mode likelihood because:	Evidence	Ranking
Conduits	It is expected that conduits would present unique cable failure behaviors as compared to cable trays, particularly the most commonly used ladder type trays. However, there are competing effects that need to be considered. The conduit itself represents a prevalent ground plane. However, the conduit also supports the cables evenly along their entire length eliminating the discrete localized loading forces associated with a ladder tray. One clear effect is that the presence of the conduit will virtually eliminate the possibility that the cables inside the conduit might short to cables outside the conduit without a concurrent short to ground. The experimental evidence is inconclusive regarding conduits. In one test series [21] several cables in conduits were functionally monitored during large scale tests, and three failures were observed. One failure involved conductors shorting to the conduit. The second failure involved an intermittent conductor-to-conduit short that later healed and in the end an intra-cable conductor-to-conductor short was detected. The third failure involved an intra-cable conductor-to-conductor hot short. The recent industry tests [13] involved a small number of failure cases (8) involving cables in conduits. Given the limited data, conduits and cable trays experienced nearly the same percentage of cable failures leading to spurious operations of the MOV circuits (25% versus 30% respectively). The companion USNRC/SNL IR measurements [14] indicated a tendency for conductors to short first to the conduit rather than to each other. The data are somewhat contradictory, and no firm conclusions regarding the role of conduits in the likelihood of spurious operation given cable failure can be drawn. However, nominal indications are that the spurious actuation likelihood given cable failure is likely similar.	Fair but not consistent	Low - Moderate

Table 2-1 (cont). Cable failure modes: matrix of influencing factors.

Factor:	May influence failure mode likelihood because:	Evidence	Ranking
Air Drops	Air drops are unsupported lengths of cable, often where the cable leaves an overhead tray or conduit and drops down to a panel or electrical component. (This discussion assumes an unarmored cable. Armored cable air drops should be no different from armored cables in a tray.) Air drops may be quite short (on the order of one foot or so) or may be several feet in length. This length is likely to be a significant factor in determining the failure mode likelihoods. Very short air drops will likely expose the entire length of the drop including the point of exit from the tray/conduit (and entry into the panel/component). The weight of the air drop is supported at the raceway exit point. This exit/loading point is a likely location for a short to occur if this portion of the cable is significantly stressed due to the fire exposure. With a longer air drop, the exit/load point will be under a greater load, but may not be the point of failure. If the fire exposure is most severe near the bottom of the air drop, then failure may not occur at the exit/loading point. If, instead, failure occurs along the unsupported length of a cable, then the failure is almost certain to involve conductor-to-conductor shorting given the absence of an external ground plane. For bundled air drops, the possibility of cable-to-cable hot shorts would also likely increase substantially under these conditions. Many of the small scale tests performed to date have, in effect, simulated air drop conditions in that cables are isolated electrically and thermally from the support structures [e.g., 17,22]. These tests clearly show that in the absence of ready access to a ground plane, sustained conductor-to-conductor shorts are the dominant failure mode with a probability approaching 1.0. The only exceptions would be cables with grounded shield/drain arrangements and armored cables (two cases where routing is likely unimportant as discussed above). No experiments where the exit/support point was directly threatened by fire were identified. One study [23] did investigate airdrop loading effects, but the results provide no useful insights in this context because only post-test measurements of conductor-to-conductor insulation resistance were taken and shorts to the support were not monitored at all. Overall, there is substantial evidence to suggest that the likelihood of conductor-to-conductor hot shorts in an air drop approaches 1.0 provided the exit/support point is not threatened by the fire. If the support point is substantially threatened then the effect may be reversed and shorts to ground may become predominant. Air drops appear to hold the potential for complex behavior.	Good for some aspects, very poor for others	Significant

Table 2-1 (cont). Cable failure modes: matrix of influencing factors.

Factor:	May influence failure mode likelihood because:	Evidence	Ranking
Raceway loading	A cable tray or conduit may contain only one cable, or may contain quite a large number of cables. This is likely to be a very important factor in determining the likelihood that various failure modes might be observed. In particular, in a very sparsely loaded cable tray, the likelihood of cable-to-cable shorts would be substantially reduced, unless the cables are bundled (see next item). For cable loads that exceed a single layer of cables, the physical loading on the bottom cables increases and the proximity of the upper cables to ground diminishes. Hence, the lower cables may be more likely to short to ground, and the upper cables less likely to short to ground. There is some substantial experimental evidence available to support these suppositions in the specific case of ladder cable trays. In many of the tray tests performed there was a substantial load of cables. For example, in the early SNL/USNRC tests [23] cable trays were loaded with nearly 100 passes of a single length of cable (one length of cable making several passes through the tray). The contact points between the cable and the tray were under a considerable load. During the tests many such loading points for, in effect, one length of cable were exposed to the fire. In the majority of cases, a cable-to-tray ground short was the first fault mode observed. In hindsight, these early tests may present a distorted picture of the conductor-to-tray short likelihood because of the non-representative cable routing configuration. Other tests that have used only one cable or a single layer of individual cables have indicated a higher probability of conductor-to-conductor shorts as the initial failure mode. The recent industry tests [13] provide additional evidence. The SNL/USNRC IR data [14] is inconclusive about the effect of raceway loading on the likelihood of a particular failure mode. However, the EPRI/NEI MOV circuit data (see Appendix D) indicate that cables in contact with the tray experienced proportionally fewer spurious actuations (on the order of 1 actuation to 2 fuse blow failures). Cables in other than the bottom row experienced a substantially higher likelihood of device actuations (on the order of 5 actuations to 3 fuse blow failures). Ultimately, because the actual location of a cable may not be known, this will likely be treated as a randomizing factor.	Good	Significant

Table 2-1 (cont). Cable failure modes: matrix of influencing factors.

Factor:	May influence failure mode likelihood because:	Evidence	Ranking
Maintained Spacing	“Maintained spacing” is a cable installation practice that may be encountered in higher voltage power cables in cable trays. With maintained spacing, cables are physically separated within a tray and are tied in place using metal or, more commonly, nylon ties. This practice allows for higher cable ampacity limits than would be allowed in a random fill cable tray. This practice would substantially decrease the likelihood of cable-to-cable shorts. Even in the case of plastic ties that are likely to melt during a fire, the cable is tied along its entire length, and the cable-to-cable spacing would reduce the likelihood of cable-to-cable shorts even if the cables shift somewhat as the ties release. The fact that the cables are individually tied to the tray at regular intervals may also increase the likelihood of ground shorts. However, nylon ties will likely release well before the cable insulation fails, and the effect should be minimal. There is no experimental or experience-based evidence regarding this factor.	None	Likely Weak for intra-cable behavior; Likely Significant for inter-cable shorting
Protective coatings	A protective coating is generally a mastic material sprayed directly onto the cables in a cable tray or air drop. While the coatings will result in some delay in cable heating during a fire, they are not designed to prevent thermal damage. Rather, coatings are primarily intended to reduce cable flammability and minimize fire growth potential. There is some evidence regarding cable coating provided in early SNL/USNRC tests [24]. However, the data are limited to reports of the relative time to shorting with and without coatings and no failure mode information is available. No evidence directly relevant to the failure mode was identified. Fire retardant protective coatings may have some impact on failure mode because thermal heating is delayed and cables may be subjected to a “slow cook” rather than a “fast burn” exposure. However, the coatings are applied only after installation of the cables so there is no impact on raceway contact. It would appear likely that protective coatings would have a limited impact on failure mode. It may be appropriate to treat this factor by adjusting the nominal fire intensity influence factor as a surrogate. That is, if the impact of fire intensity on failure mode can be established, then a protective coating might be treated by choosing a modified fire intensity modification factor to reflect a less severe but longer fire exposure (e.g., the slow cook versus the fast burn).	None	Likely weak

Table 2-1 (cont). Cable failure modes: matrix of influencing factors.

Factor:		May influence failure mode likelihood because:	Evidence	Ranking
	Raceway orientation	The orientation of a raceway may also influence the likelihood of certain failure modes. In particular, for a horizontal raceway gravity acts as a "motive force" that will ultimately drive all of the conductors to ground on the support structure (i.e., the tray or conduit) assuming the damage progresses far enough. However, in a vertical orientation it is actually possible (albeit unlikely) that a completely bare conductor will simply hang in air and not experience any shorts provided its insulation remains intact at its upper and lower ends. While this is an extreme example, it does illustrate that failure mode might be impacted by orientation. A vertical orientation for conduits may increase the likelihood of conductor-to-conductor shorts within a multiconductor, and decrease the likelihood of ground shorts. In the case of a vertical cable tray, the cables will likely be strapped to the trays using some type of cable ties. This practice might mitigate the potential differences for cable trays, however, nylon wire ties are most commonly employed and these ties will likely melt well before the cable insulation fails. Hence, wire ties may not be a significant factor in this behavior, particularly for the more robust thermoset cables. Overall, the loss of the localized loading force at the rungs (and transfer of that force to the top of the vertical run) may reduce the likelihood of cable-to-tray ground shorts depending, especially given that most fires will first expose the lower sections rather than the upper sections. Cable failures have been observed in vertical cable trays. In one such test [25] the one failure observed was a conductor-to-conductor short. However, this may have been influenced by the test configuration and is considered unreliable. The recent industry tests [13] included two tests with vertical trays that experienced a total of five cable bundle failures. Of the five bundles that failed, two experienced spurious circuit actuations. Given the small number of cases, the relative likelihood of device actuations was similar to that seen for cables in horizontal trays.	Fair	Likely weak

Table 2-1 (cont). Cable failure modes: matrix of influencing factors.

Factor:		May influence failure mode likelihood because:	Evidence	Ranking
	Bundling of cables	When cables are installed, they may be bundled into groups for the convenience of the installers (i.e., groups of cables may be tied together using wire or nylon ties). This may occur in trays, but is more common in a conduit (cables are often bundled to ease the pulling operation) and air drop applications. The bundling of cables should increase the likelihood of cable-to-cable shorts. In effect the bundling makes the cable group appear more like a larger multiconductor cable than like several individual cables. The most recent cable tray tests [13,14] did involve bundled cables. Typically, three single-conductor cables were bundled to one 7-conductor cable using fiberglass tape. A significant number of cable to cable interactions were observed. However, because equivalent cable arrangements without the actual bundling of cables were not tested, the relative impact of this factor cannot be directly assessed.	Limited	Likely significant
Basic circuit factors				
	Circuit function / type	The function of the circuit (instrument, control, power) will certainly influence the nature of the circuit faults that might be observed. The circuit function will also determine the type of cable failure that will be of primary interest. Hence it is recommended that circuit function be treated as a primary factor in the selection of base cases rather than as a failure mode likelihood modifier (see Section 5.3 for further discussion).	Good	Significant - treat as primary factor

Table 2-1 (cont). Cable failure modes: matrix of influencing factors.

Factor:	May influence failure mode likelihood because:	Evidence	Ranking
Current loading for power cables	The issue of current loading is of interest primarily in the case of power cables. This may be a minor consideration for some control cables that must carry a power load continuously to maintain a circuit in a specific operational mode (e.g., a solenoid-operated valve). The cable conductors currently employed retain some electrical resistance. Hence, any cable carrying an electrical current is subject to some level of resistance heating along the entire length of the cable. The intensity of the current imposed on a cable as a fraction of the maximum allowable current load (or ampacity limit) is the most significant factor influencing a cable's normal operating temperatures. The maximum available current (along with voltage) also determines the potential energy content that might be released in a short circuit. Hence, two factors may be of interest deriving from base ampacity. Failures may occur more quickly for cables loaded to near their ampacity limits than for lightly loaded cables because the more heavily loaded cables will be operating at higher temperatures than their neighbors. In the typical case, cable loads will vary substantially between cables in a given raceway. The more heavily loaded cables will likely fail first, and this may increase the probability of cable-to-cable hot shorts to the more heavily loaded cables. If cable failure times are substantially different, then inter-cable hot shorting behavior may be far less likely. A second consideration is that cables with high potential energy available (current and voltage combined) may not be able to sustain a short circuit, especially a short to ground, for any substantial time period. Rather, once the insulation does break down, shorts will result in a highly localized energy discharge that may well melt (or vaporize) the conductor at the point of contact breaking the short. This behavior will also likely lead to a series of intermittent shorts ultimately followed by an open circuit fault (either breaking of the conductor or opening of over-current protection). The only open circuit conductor failure noted in the experiments and incidents reviewed here involved high energy cables (current carrying potential on the order of 50 A or more) [e.g., 26].	Good for some aspects	Significant in particular for open circuit likelihood

Table 2-1 (cont). Cable failure modes: matrix of influencing factors.

Factor:	May influence failure mode likelihood because:	Evidence	Ranking
Circuit Voltage	The role of circuit voltage is expected to be similar to that of the base current load as discussed immediately above. The principal difference is that the imposed current load contributes to cable self-heating whereas the impressed voltage does not. As with current load, the most significant effect with respect to impressed voltage will be the impact of high voltages on potential cable failure behavior. The impressed conductor voltage is one factor in determining the available energy that might be discharged in a short-circuit situation. With a high voltage cable (where the exact definition of 'high' in this context has not yet been clearly defined) the likelihood of loss of continuity failures increases substantially. In particular, high voltage cables may experience a series of short-lived shorts to ground followed ultimately by a loss of conductor continuity (as discussed in the text). For such cables, a sustained low impedance short to ground will not likely be maintained for any substantial period. Another factor that has not yet been explored is shorting between circuits operating at different nominal voltages. Many cable raceways contain cables with a mix of applied voltages. For example, could a high impedance inter-cable conductor-to-conductor hot short involving an energized cable of higher voltage shorting to a normally de-energized cable of lower voltage allow for the spurious actuation of the lower voltage circuit? This possibility has never been explored experimentally, and the event experience does not offer sufficient detail to assess this potential. Note also that voltage is linked to circuit function. Most instrument cables will operate at 50V or less. Most control cables will operate at either 120 VAC or 125 VDC. Most cables with voltages in excess of 120 VAC or 250V DC will be power cables. Cable insulation thickness is typically determined based on the dielectric voltage withstand properties of the insulation, and hence, on the rated voltage of the cable. In this case, it is reasonable to presume that all cables are energized well within their rated voltage as this is a fundamental consideration in the cable selection and design process.	Good	Significant

Table 2-1 (cont). Cable failure modes: matrix of influencing factors.

Factor:		May influence failure mode likelihood because:	Evidence	Ranking
	Circuit-to-cable wiring configuration	This factor refers to the specific pattern by which conductors in a multiconductor cable are connected to their associated circuit (e.g., which conductor supplies the motive power to the control circuit, and what is the physical proximity between this conductor and the conductor that is energized to transmit the actuation signal to the control device). The conductors in a multiconductor cable will maintain the same positions relative to each other throughout the cable's length. Hence, the wiring configuration would be an important influence factor in the overall circuit analysis problem. However, the wiring configuration is ultimately found to be a factor influencing circuit fault mode likelihoods given a conductor-to-conductor cable failure rather than cable failure mode likelihood. Experimental evidence [14] strongly suggests that conductor-to-conductor interactions are most likely to occur first between adjacent conductors. It is also noted that cables with more than six conductors will have at least one conductor that is fully surrounded by sibling conductors. For such cables the available evidence[14] shows that conductors in the outer ring tend to fail before interior or embedded conductors presumably because the outer conductors heat up more quickly than the embedded conductors. Hence, if the wiring configuration is known, this could be used to refine estimates of the circuit fault mode likelihood. However, in the context of cable failure mode, the specific wiring configuration may not generally influence the cable failure mode likelihood. That is, the wiring configuration would not be expected to significantly impact the likelihood of conductor-to-conductor versus conductor-to-external ground failure modes. It is recommended that this factor be considered primarily in the assessment of circuit fault mode likelihoods given a cable failure mode rather than as a factor significant to the cable fault mode in and of itself. If, as is more likely, the conductor wiring configuration is not known, then this factor will act as a randomizing variable adding to uncertainty.	Good	Weak re. cable failure mode in and of itself (Significant re. circuit fault mode likelihood given conductor-to-conductor cable failures)
Fire/exposure factors				
	Exposure Mode	There are at least four possible fire exposure modes. These are (in nominally decreasing order of severity): direct flame impingement; convective exposure in the plume or ceiling jet but outside the flame zone; convective exposure in the hot gas layer; and direct radiative heating (radiative heating intensity is a strong function of fire intensity and proximity). Direct flame impingement would involve very rapid and severe localized cable damage. Convective and radiative heating modes would raise cable temperatures more slowly and likely expose a longer section of the cable. It is not clear how differences in the exposure	Poor	Likely significant

Table 2-1 (cont). Cable failure modes: matrix of influencing factors.

Factor:		May influence failure mode likelihood because:	Evidence	Ranking
		mode might impact cable failure modes. There are competing effects that may be relevant. For larger fires that expose a substantial length of a cable to direct flame impingement, the rapid and severe degradation will likely increase the likelihood of ground shorts and may make sustained hot shorts highly unlikely. For some circuits, those involving latching relays, the impact may not be significant because even a momentary hot short may lock in a spurious actuation. However, for other circuits, such as a MOV circuit, hot shorts would likely be short-lived and may not be sustained long enough to reposition equipment. Convective heating will heat cables more slowly than direct flame impingement. This may enhance the opportunities for sustained conductor-to-conductor shorts. The recent industry tests [13] involved primarily convective exposures (either in the hot gas layer or fire plume outside the flame zone). Hence, only very limited information on the relative impact on failure mode likelihoods can be gleaned from these tests. The plume and hot layer exposures nominally showed similar results, although it appears that a somewhat higher proportion of device actuations were observed for the hot layer exposures compared to the plume exposures. Again, this may indicate that the "slow cook" is more likely to lead to sustained conductor-to-conductor shorts than is a "fast burn." Other large scale tests have involved various exposure modes, but it is difficult to discern from the available information what mode was active at the time of failure (or just prior to failure). That is, one cannot tell if the cables were exposed to direct flaming when they failed, or if they were only in the fire plume. This is the case for the ANI/UL tests [27], for example. Many small scale tests simulate convective heating conditions (e.g., those performed by SNL) while others use a radiative heating mode (e.g., tests conducted by Factory Mutual Research Corp. (FMRC)). Unfortunately, in both cases these tests also tend to isolate the cable sample from potential ground faults and intra-cable conductor-to-conductor failures are the only possible failure mode. Hence, little or no information on cable failure mode is provided. No known test program has directly investigated fire exposure mode effects beyond the plume/hot layer investigations of the recent industry tests. Hence, the evidence available to assess the impact of fire exposure mode on failure mode remains poor.		

Table 2-1 (cont). Cable failure modes: matrix of influencing factors.

Factor:	May influence failure mode likelihood because:	Evidence	Ranking
Exposure duration/ intensity	As noted above, the fire exposure mode does impact the expected time to damage. However, beyond the exposure mode, the exposure intensity will also impact time to damage. As noted above, this may have some influence on the initial failure mode, and will almost certainly influence the timing of failure mode transitions (e.g., the duration of a hot short). Hence, the exposure duration and intensity may have an influence on the failure mode likelihood estimates. Most of the tests where exposure intensity and duration were explicitly controlled are small-scale tests, and these tests typically sought information on cable failure thresholds providing little data on failure mode. In most large-scale tests, the exposure intensity is not controlled and difficult to characterize relative to the time of failure. In the recent industry tests [13] the exposure intensity was varied over a modest range, but this effect is inextricably linked to the plume versus hot layer exposure mode so that separate effects cannot be assessed. Also, most of the recent industry hot layer exposure tests involved hot layer temperatures that hovered very near the failure threshold leading to extended fire damage times (e.g., over one hour in many cases). This was in part due to the use of a burn room made from uninsulated steel plate. This led to a very high rate of heat loss from the walls of the test room and therefore lower hot layer temperatures than might generally be anticipated. The room conditions would not be typical of, for example, a concrete enclosure in terms of the fire intensity / hot layer temperature relationship. Overall, the experimental evidence regarding this influence factor is very poor.	Poor	Likely Significant with regard to failure mode transition times
Relative fire elevation	The relative elevation of the fire as compared to the cables of concern may have a substantial impact on the likelihood that certain modes of failure might occur. However, this will largely be due to the impact of the relative elevation on the exposure mode observed (e.g., is the cable in the flame zone or above the flame zone in the fire plume). Some secondary effects beyond this are, however, possible. In general, fires heat cables from below. That is, the fire is most likely to occur at a level below the cables of interest rather than above the cables. Hence, the lower surfaces are subjected to the most significant heating. In this situation the likelihood of ground shorts would be increased because the cables are supported by the conduit/tray from below and that support structure would be grounded. In contrast, if the fire exposes a heavily loaded cable tray from above, the likelihood of a ground short may be substantially reduced in favor of hot shorts. This is because the top cables will almost certainly short first, and there is no readily accessible ground plane available to these cables. There is no experimental evidence associated with this factor since all of the identified fire tests involved	None	Likely significant for a very limited set of fire scenarios and ultimately of little interest

Table 2-1 (cont). Cable failure modes: matrix of influencing factors.

Factor:		May influence failure mode likelihood because:	Evidence	Ranking
		exposure fires below the raceways/trays. Ultimately, while the factor may be significant, it may not be relevant to the most commonly postulated fire scenarios because most fires will be exposing cables from below. It may be possible to use the exposure mode can be used as a surrogate for relative elevation for these scenarios.		
	Application of suppressants	The application of suppressants, and in particular water, may impact failure mode likelihoods in several ways. Suppressants will cool the exposed cables and this may "freeze" a given damage state into place, or cause "healing" of cable shorts. The healing effect has been observed in various tests [28], where some substantial insulation resistance is recovered upon cooling even though a short circuit may have occurred during the fire exposure. Water applied to a degraded cable may sharply aggravate shorting behavior creating a number of both high and low impedance shorts where none previously existed. A hose stream will also cause physical movement of the cables which might enhance the likelihood of cable-to-cable shorts (this has been noted as a factor in at least one fire incident in Armenia [29]). There is very little experimental evidence associated with suppressants and cable shorting. Only one known cable damage test series has involved both suppressants and monitoring of cable functionality [13]. In most of these tests, a 60-second water spray was applied following extinguishment of the gas burner pilot fire. However, in most cases the cables had either already failed blowing all of the fuses in the test circuits, or they had not displayed any significant evidence of cable degradation (in general, if the USNRC/SNL IR measurements indicated substantial cable degradation, the test would be continued to cable failure). For such cases there was little potential for a spurious actuation given the sprays. Nonetheless, in one case a spurious device actuation was observed upon activation of the water spray. Note that no additional damage or degradation was detected in the corresponding SNL/NRC IR measurements. Water spray applied near the time of failure can cause additional hot shorts and actuations. However, the tests are inconclusive with regard to the likelihood that such effects might be observed. Clearly, the timing of spray application relative to the degradation state of the cables is critical. This may minimize the general importance of this factor.	Poor	May be significant but highly dependent on timing issues

3 CIRCUIT FAULT MODES

The effect of a fire-induced cable or conductor failure on a circuit is dependent upon many factors including the type of circuit (i.e., power, control, or instrumentation), the type of cable conductor failure (i.e., open circuit, short to ground, or hot short), the purpose served by the conductor in the circuit, and the availability and location of certain circuit features relative to the conductor failure. In turn, these fire-induced circuit faults can result in initiation of accidents, failure of required systems for mitigating these accidents, and spurious operation of components that can worsen the situation. This section discusses the possible circuit fault modes and their impacts on components required to prevent or mitigate an accident. Circuit design features that can affect the potential for fire-induced component failures are also discussed. These circuit features were identified through a review of actual circuit designs, discussions with personnel who perform circuit analysis, a review of existing reports pertaining to circuit analysis, and NRC Information Notices concerning actual and potential circuit faults.

3.1 Description of Circuit Fault Modes

There are different potential power, control, and instrumentation circuit fault modes that can occur as a result of each type of fire-induced conductor fault. In turn, the circuit fault modes can have variable impacts on the operation of the different components used in nuclear power plants. These impacts can be dependent upon many factors including the circuit design. This section identifies the general impact of each type of cable/conductor failure mode on power, control, and instrument circuits. The section also discusses the resulting impact on component operation and circuit design features that may affect the circuit fault mode.

3.1.1 Loss of Conductor Continuity

A loss of conductor continuity involving a power cable will result in an open circuit fault condition and the loss of power to components. In effect, the loss of continuity mimics opening of current limiting protective devices such as fuses and breakers. The following circuit fault effects may be of interest:

- For operating components requiring motive power such as pumps, air compressors, and fans, the loss of power will result in loss of the component function. In turn, the loss of the component function can degrade reactor operating conditions leading to a reactor trip or result in failure of a required accident mitigating system.

- For standby components, loss of power will prevent the component from starting and operating as required.

- Some components require constant power to maintain their position (e.g., some solenoid valves or relays that are normally energized). An open circuit in the associated power circuit for these components will result in a change in the component position that, depending upon the component function, can have adverse effects on system operation. For example, loss of power to a solenoid-operated valve can result in opening of a flow diversion path or, alternatively, closing a desired/required flow path, either one of which could fail a system.

- For components that only require power intermittently to provide their function (e.g., motor-operated valves), the loss of power will leave these components in their initial state, but will prevent the component from functioning if required for accident mitigation. Manual operator actions may be able to overcome such faults.

- Open circuits in electrical distribution cables can result in loss of power to multiple components. Hence, power distribution cables represent important targets to consider in fire assessments.

The impact of a loss of conductor continuity in a control circuit cable is dependent upon where it occurs in the control circuit. Again, the loss of continuity introduces an open circuit fault condition. Potential circuit fault responses include the following examples:

- An open circuit in the portion of the circuit controlling power to remotely operated breakers, relays, and motor contactors that must be closed for power to reach the component are likely to be of the most concern. Such failures/faults would generally render such systems inoperable, although local manual actions might be possible to overcome the fault.

- Open circuits in the portion of the control circuit used to shut off a component or change its position will eliminate this capability. Such components would continue to run, but again, might be secured through local manual actions.

- For components where a continuous control signal is required to maintain the circuit status or position (e.g., a solenoid-operated valve (SOV)) an open circuit would cause the system to change state and would render the system unavailable for further operation.

- Open circuits in the indicating portions of a control circuit could lead to loss of status indication which could influence operator actions in a negative manner.

It is important to note that the various individual conductors for a given component control circuit are generally routed via the same multiconductor cable. Thus, if a loss of continuity is experienced by one conductor, the remaining conductors in that same cable would likely experience similar failures. This would lead to the circuit experiencing some combination of the fault modes listed above, depending on the nature of the circuit. For example, a SOV might reposition, lose remote operability, and suffer a loss of indication.

Circuit fault effects on instrument systems are not so clear cut as for power and control circuits. Instrument sensors typically convert process variable values to an electric signal (e.g., voltage/current) for transmission–via conductors–to a remote readout or display. Depending on the type of sensor, an open circuit condition would likely lead to a complete loss of indication. Such faults would likely be easily diagnosed as circuit faults by operators (rather than operators being misled by a false signal). Digital instrument circuits present unique challenges that have not been explicitly addressed in this study. However, a loss of continuity failure for such circuits would lead to a loss of the signal that would likely be obvious to operators and might be diagnosed by on-line control software.

No circuit design features that would reduce the potential of a fire-induced loss of continuity cable failures were identified. However, the available evidence indicates that the impressed voltage on a cable will impact the potential for an open circuit. There is some evidence that loss of continuity failures are possible for lower voltage cables, but only as the result of a prolonged fire exposure. In all such cases, the cables experienced shorts to ground well before the loss of continuity failure. No case was identified where a loss of continuity was the first mode of cable failure observed. Hence, such failures may not be a significant concern for instrument and control cables, at least in the context of the initial failure mode.

Higher voltages may lead to a higher likelihood of loss of continuity cable failures, an observation relevant primarily to power circuits. Even in these cases, the only experimental evidence indicates that loss of continuity is typically observed only after repeated short-duration shorts to ground. Again, for power circuits the loss of continuity failure mimics the effects of opening of circuit protection devices which typically results from over-current due to either shorts to ground or phase-to-phase shorting. Hence, here again, for power circuits the loss of continuity failure may be of secondary concern at most.

3.1.2 Shorts to Ground

In this discussion it is assumed that a short to ground may involve either a conductor-to-external ground short (e.g., the raceway) or a conductor-to-conductor short that involves a grounded conductor. As noted above, the distinction between these two failure modes has been made for mechanistic reasons in order to tailor the failure mode likelihood analysis process to the available experimental data. Once a short to ground has formed, its impact on the circuit will be the same, regardless of the source of the ground.

The impact of shorts to ground in power and control circuits is dependent upon whether or not the circuit is grounded, and where in the circuit the failure occurs. Some example cases are as follows:

- In a grounded circuit, a short to ground involving a grounded portion of a circuit will have no impact since the circuit is already grounded. However, a short to ground involving one of the ungrounded power phases will divert power from the circuit. A high impedance short could result in a sustained power flow, whereas a low impedance short would typically trip circuit over-current protection devices leading to an open circuit fault condition.

- In an ungrounded circuit, a short to ground involving either a non-energized conductor or any one phase of the power supply circuit would have no effect on the circuit.

- Ungrounded circuits introduce a potential unique concern related to multiple shorts to ground. If, for example, one phase of the power supply circuit shorts to ground, this would ‘float up’ the ground potential to the voltage of the shorted conductor. A subsequent short to ground involving another conductor could then energize that second conductor. In effect, multiple shorts to ground can mimic a hot short.

- If two phases of an ungrounded power circuit both short to ground concurrently, the effect is the same as a phase-to-phase short on that circuit and likely the over-current protection for the circuit would trip.

- A particular issue of potential concern is multiple high-impedance shorts involving power circuit cables. As noted above, a high-impedance short may cause a power drain from the circuit. If the impedance of the short is of the right magnitude, the fault current could be significant, but insufficient to trip the nearest upstream protective devices. Should several power cables form concurrent high-impedance shorts, then the combined fault current for the multiple cables might trip a higher-level circuit protection device leading to loss of multiple power busses. This is discussed further in Section 3.2.1.

- Another potential concern unique to power circuits is the potential random failure of the circuit protection device. Such failures can result in opening of circuit protection devices upstream and loss of power to multiple components required for accident mitigation. The nominal probability of a circuit breaker failing to open when required is approximately 1E-3 per demand [30]. However, manual actions to remotely open a failed breaker and then re-close the upstream breaker would reduce the risk significance of such a scenario.

One circuit design feature that can influence the impact of a short to ground, in particular for power circuits, is breaker coordination. Breaker coordination assures that the circuit breaker immediately upstream of a short to ground or (phase to phase short) trips before any breakers upstream of that breaker. A lack of breaker coordination can result in a short to ground in one component circuit resulting in loss of power to multiple components through opening of upstream breakers feeding power supplies. In most nuclear power plants, breaker coordination is assured for higher voltage power circuits (i.e., greater than 480 VAC). There is no general assurance of breaker coordination for lower voltage circuits, except when specifically required by Appendix R compliance. A review of the plant-specific circuit design practice is required to determine the level of breaker coordination provided at a given plant.

In the case of an instrument circuit, a short to ground may generate no impact, faulty indications, or a complete loss of signal depending on the nature of the circuit. Here again, multiple shorts to ground on an ungrounded instrument loop can mimic conductor-to-conductor shorts for that same circuit (see discussion in Section 3.1.3). High-impedance shorts may result in a misleading or biased instrument reading whereas a low impedance short would typically result in a complete loss of the signal often leading to an off-scale instrument reading.

3.1.3 Conductor-to-Conductor Shorts Including Hot Shorts

Conductor-to-conductor shorts can create complex circuit faults depending on the conductor combinations involved. Of particular interest are hot shorts because hot shorts can cause spurious operations. The potential circuit faults are, in this case, different for power, control, and instrument circuits. Examples related to power circuits are as follows:

- Most of the primary components in a nuclear power plant (e.g., MOVs, motors, pumps, fans, etc.) are powered by three-phase AC power systems (the exception being the limited set of DC powered equipment relied upon during station blackout conditions). For such components, concurrent hot shorts on all 3-phases of an AC power source are generally required to activate the component (it may be appropriate to verify that hot shorts on two phases are insufficient to operate such components). As indicated in Section 5.1, these types of hot shorts are considered to have low probability and are not considered in most fire assessments (Appendix R or PRA analyses). The one exception is that such failures are considered for high/low pressure interfacing valves in the typical Appendix R safe shutdown analysis. For such equipment, it appears far more likely that a spurious operation would result from the failure of a control cable that from failure of power cables.

- A conductor-to-conductor short between circuits of different voltage can result in the application of destructive voltages to the lower voltage circuit. This is possible where mixed voltage cables are routed in the same cable trays. Such failures would typically result in non-recoverable failure of the lower voltage circuit.

- Conductor-to-conductor shorts between phases of a common power supply would typically lead to opening of circuit protection features for that circuit. Also, see discussion in Section 3.1.2 regarding multiple high-impedance shorts and the random failure of circuit protection features.

The impact of conductor-to-conductor shorts in control circuits is dependent on several factors. One important factor is whether or not the circuit is grounded. (Note that in the U.S. nuclear power industry, grounded control circuits are more common than ungrounded control circuits.) The following examples illustrate this point:

- For grounded control circuits, any energized conductor might represent the power source conductor in a hot short, regardless of which circuit supplies the power.

- For ungrounded control circuits, two cases might lead to a spurious actuation:
    - One case requires that two hot shorts form concurrently - one involving a positive side source conductor and a positive side target conductor, and the second involving a negative side source conductor from the same power supply circuit shorting to the corresponding negative side target conductor for the same control circuit. This case is often referred to as the ‘smart short’ scenario.
    - In the second case, the energizing source conductor must be powered from the same power source as the target control circuit (e.g., the same control power transformer or battery). In this case, a single hot short to the proper conductor could cause spurious actuation.

- A conductor-to-conductor short on an ungrounded DC control circuit could also result in opening a circuit protection device (i.e., a fuse or circuit breaker) if a positive conductor shorts to a negative conductor from the same DC source (or vice versa).

- Multiple shorts to ground on ungrounded DC circuits from the same battery (or on ungrounded AC circuits from the same transformer) may have the same functional effect as a hot short as discussed in Section 3.1.2.

Other control circuit effects are also possible beyond those associated with spurious operation. Other examples include the following:

- Conductor-to-conductor shorts may lead to misleading indications should the short involve those conductors associated with the indication functions. This might involve loss of indication or contradictory indications.

- Some conductor-to-conductor shorts may have no impact on the control system, or may only impact the control system only if an attempt is made to operate the system.

These and other circuit fault effects are discussed in detail in Section 5 and in Appendices B and C.

For control circuits, the potential for hot shorts leading to spurious operation is a primary concern. While a short to ground or open circuit would typically render a system unavailable (due for example to a loss of the control function or loss of the power source), a hot short might lead to spurious actuations, misleading signals, and unrecoverable losses of plant equipment as noted above. For example, a hot short in a control circuit may result in opening a closed MOV or energizing a solenoid-operated valve (SOV). Note that a conductor-to-conductor hot short may not be capable of causing a spurious opening of a valve if insufficient voltage is available from the energized source. An example of this is provided in the SOV circuit analysis in Section 4.2.2.

The location of the hot short within a control circuit can also be an important factor. For example, the issue addressed in IN 92-18 [31] indicates that hot shorts can occur in MOV control circuits upstream of the valve limit switches and torque switches. If there is no thermal overload protection for the valve (which is the case for many MOVs), a sustained hot short can drive a MOV beyond its intended limits causing unrecoverable mechanical damage. Any mechanical damage may also prevent an operator from manually operating the valve using a handwheel.

Other open contacts, beyond limit switches, in a control circuit can also affect the potential for or impact of a hot short. Examples of open contacts in a control circuit include the main control switch, permissive signal and actuation contacts. Hot shorts in conductors located upstream of these open contacts will not result in actuation of the component. One circuit design that is sometimes used involves ‘double breaks.’ The term double breaks refers to the use of open contacts (either control switch or actuation contacts) at both ends of the actuation leg of the component control circuit. This unique arrangement prevents any hot short on conductors located between these contact sets from causing an inadvertent operation. Note that the evaluation of the hot short potential in these circuits must consider the potential that the permissive or actuation signal is present at the same time as occurrence of the hot short. In fact, the potential for a hot short in the actuation signal circuit should be evaluated since it may have the potential for inadvertently actuating multiple components.

Instrumentation circuits might also suffer degradation due to conductor-to-conductor shorting and the resulting systems effects might be unique. The following provide illustrative examples:

- Various cable failure modes might render the instrumentation system unavailable. However, a high-impedance short (loss of insulation resistance without a dead short) between conductors of a low-voltage, current-driven instrumentation signal wire might result in signal bias, producing misleading indications. Instrument cables exposed to fire will likely experience a progressive reduction in insulation resistance (IR) between separate signal conductors (or between the signal conductors and ground). As the IR, the effect on the signal accuracy will increase in magnitude until the insulation is damaged to the point it no longer provides a barrier to electrical conduction, i.e., a low-impedance short forms. Substantial IR degradation can lead to a biased instrument reading. The direction of the bias can be easily determined by analysis of the circuit. However, such circuit faults may be difficult for operators to diagnose. Recent experimental data [14] suggests that thermoset cables may be more susceptible to such behavior than thermoplastic cables. The thermoplastic materials showed sharp transitions from an operable condition to low-impedance shorts and loss of the signal.

Thermoset cables showed a prolonged period of substantial IR degradation and the sustained transmission of a biased signal prior to the onset of low impedance shorting and loss of the signal.

- Another, related concern is the potential that biased instrument readings might cause spurious operation of a pump or valve if the instrument reading governs the switching of auto-start (automatic initiation) control circuits.

- A third area of concern is instrumentation circuits that are tied to component start/stop logic. For example, some components (such as pumps) are dependent on the operation of lubrication systems. Hence, there is commonly a permissive tie to, for example, an oil pressure instrument reading. Should the instrument circuit cables fail in such a manner as to indicate a loss of oil pressure (despite the fact that the oil pressure is actually acceptable) the pump may trip or fail to start on demand.

Experimental and anecdotal experience relating to conductor-to-conductor shorts in general, and hot shorts in particular, indicates that given a sufficiently severe and prolonged fire exposure, the affected conductors will eventually short to ground. That is, conductor-to-conductor shorts will likely transition to shorts to ground eventually provided the fire continues to burn. The timing of the ground fault transition cannot, however, be clearly established and is a strong function of the fire exposure intensity and duration. In tests, the transition times ranged from seconds to several minutes, and in some cases (e.g., where the fire was extinguished) transitions to ground shorts were never observed. In some cases, the effect of the hot short may not be reversed even if a ground short transition is observed. An example is a circuit where the command signal is locked into the circuit (e.g., by the use of a latching relay) and another signal is needed to reverse the action (e.g., energizing a MOV via a locking relay). In other cases, the effect of the hot short will be mitigated by the transition to a short to ground. The best example of this is a SOV which may open or close upon experiencing a hot short but would revert back to the default position when the solenoid is de-energized.

3.2 Associated Circuit Concerns

An important part of the assessment of fire effects on circuits is related to the issue of associated circuits. The issue of associated circuits is generally addressed in Appendix R assessments but is also pertinent to fire PRAs in that it addresses the potential that cables of required accident mitigation systems may share the same physical location or electrical bus as nonessential systems. Fire damage to these nonessential circuits may negatively impact the operation of required mitigating systems whether they are Appendix R or non-Appendix R systems. To credit any system modeled in a fire PRA, the issue of associated circuits should be addressed for that system.

The definition of associated circuits includes any circuit (safety related or non-safety related) whose fire-induced damage could prevent operation or cause mal-operation of required mitigating systems or components. These circuits may be found to be associated with circuits of required systems through any of the following configurations each of which is discussed in the subsections that follow:

- Circuits that share a common power supply with circuits for mitigating equipment,
- Circuits that share a common enclosure (e.g., cable tray or conduit) with cables required for operation of mitigating equipment, or

- Circuits of equipment whose spurious operation or mal-operation may adversely affect mitigating systems (e.g., open a flow diversion path sufficient to compromise the safety function).

3.2.1 Circuits That Share a Common Power Supply

It is not uncommon in nuclear power plant design to include nonessential equipment on the same electrical bus as safety-related equipment. This raises a concern that a fire that causes a short in these nonessential cables can affect safety-related equipment by causing a fault current of sufficient magnitude to trip a circuit protection device upstream of the affected circuit resulting in loss of power to the safety-related equipment. This may result in a fire in one compartment directly failing equipment for one safety-related train and indirectly failing equipment for the other train through fire-induced shorts on nonessential equipment cables. Protection against this type of failure is generally provided for Appendix R safe shutdown equipment by ensuring proper coordination of all circuit protection devices (e.g., circuit breakers or fuses) associated with a power supply required for the safe shutdown equipment. In a properly coordinated power circuit, fire-initiated faults are isolated by the protective device located nearest the fault thus preventing the fault current from propagating and causing the tripping of a protective device upstream of a bus supplying power to the safe shutdown equipment. Another common method of providing protection against this concern is to include operator actions in fire procedures to shed nonessential loads from potentially affected power supplies and/or include directions in the procedures to attempt to restore the operability of tripped power supplies by first shedding nonessential loads and then reloading required loads. Such actions could be credited in a fire PRA provided sufficient procedural guidance and time are available.

Perhaps the most extreme example of this approach is the so-called self-induced station blackout (SISBO) procedure. This approach to overcoming hot shorts and spurious actuations calls for isolation of all normal and emergency sources of AC power (off-site power and the emergency generators), shedding of all nonessential loads and selective restoration of desired accident mitigation loads. (To the knowledge of the authors, no plant has ever attempted to implement such procedures under actual fire conditions.)

A unique concern related to common power supplies are multiple high-impedance faults. High-impedance faults on cables may involve arcing faults rather than direct contact, or may be associated with severe, but not total, degradation of insulation resistance. High impedance faults may not generate fault currents sufficient to trip the first level circuit protection features (i.e., fuses or breakers). Multiple high-impedance faults on circuits powered by the same bus may result in a cumulative fault current sufficient to trip a higher level, or upstream, bus supply circuit protection feature. This would cause a loss of power to the entire electrical bus. Protection against multiple high-impedance faults involves proper coordination of breakers.

It is not possible to tell whether or not multiple high impedance faults have ever been a factor in an actual fire. Indeed, in any post-fire investigation it would be difficult to determine this with any certainty. In fire testing, it has been observed that cables may display a progressive breakdown behavior in which insulation resistance degrades over some time period (typically seconds to minutes) followed ultimately by a “bolted” or low impedance short (see Appendix A for further discussion). Hence, the potential for multiple high impedance faults would appear real, at least in theory. The unique configuration which must be achieved would imply a low likelihood of this scenario developing. Each of the high impedance faults must develop concurrently, each fault must be of sufficient impedance so as to not trip the first upstream fuse or breaker, and yet the combination of fault currents on multiple cables must be sufficient to trip the second (or third) upstream fuse or breaker. It is not possible to estimate the probability of occurrence for such scenarios based on current knowledge. Historically, the probability of high-impedance faults has been assumed to be low. To the authors' knowledge no fire PRA has considered this failure mode.

3.2.2 Circuits That Share a Common Enclosure

It is not unusual for cables of nonessential equipment to share a common enclosure (e.g., cable trays, conduits, or panels) with cables of required accident mitigating systems. Circuits that share enclosures present several concerns. First, a fire-initiated cable failure could cause an over-current that results in a secondary fire ignition, potentially in a different part of the plant. For this scenario to occur, the cables would have to be inadequately protected (i.e., improperly sized fuses or circuit breakers) or would have to short to another power supply cable in such a manner so as to bypass the existing circuit protection (for example excessive fault currents on a grounded conductor). Furthermore, the heat generated by the over-current would have to cause ignition of the cable jacket. It is not clear if such scenarios are risk significant or have been considered in fire PRAs. One method for addressing this concern in an Appendix R assessment is to verify the adequacy of electrical protection provided for nonessential cables that share a common enclosure with safe shutdown equipment. The electrical protection must be such that the nonessential cable insulation will not ignite in the presence of a low-impedance fault. An alternative approach to providing protection against this failure is to provide steps in the fire procedures to isolate the nonessential circuit by removing the associated fuses or tripping the associated breakers. Such actions can be credited in a fire PRA.

A second concern is that a shared enclosure can provide a combustible pathway (via fire spread along the cables) for a fire to propagate outside the immediate area where the fire originated. Of particular concern is that a common raceway may connect two raceways containing redundant trains of equipment. This would provide a pathway for a single fire to fail cables associated with multiple trains of safe shutdown equipment. This concern is usually addressed for Appendix R safe shutdown equipment by ensuring that suitable flame-spread mitigating features such as fire stops or cable coatings are installed in safe shutdown cable trays to prevent fire propagation. In addition, proper sealing of electrical penetrations is also required to prevent propagation through fire barriers. Modeling of fire growth in current fire PRAs is generally simplistic and does not always include analysis of fire propagation through a common raceway.

3.2.3 Spurious Operation of Associated Equipment

Cables that are not related to the circuits for accident mitigating equipment can be damaged by postulated fires. However, the damage to some of these cables may result in spurious operation of equipment that would prevent the proper performance of required mitigating systems. A common method for addressing this potential in Appendix R assessments is to identify all components related to each required safe shutdown system whose inadvertent operation would prevent the system from performing its function. The cables for such components are then generally provided with the same fire protection features (i.e., separation or fire wraps) as the safe shutdown equipment to ensure that a fire does not disable both trains of safe shutdown equipment. A common alternative method for dealing with spurious actuations is to include steps in fire procedures for defeating the spurious operations. These steps include opening circuit breakers for such components and manually positioning valves.

Correct modeling in a fire PRA requires that all components that can adversely affect operation of a system be included in the evaluation. Most fire PRAs utilize internal event PRA models which may not have included random spurious operation of components due to their low probability of occurrence. For a fire PRA, these events must be reconsidered since fires present a mechanism for their occurrence. This will likely require modification of the plant response model to suit the needs of the fire analysis.

4 CIRCUIT ANALYSIS PROCESS FOR FIRE RISK ASSESSMENT

This section describes a process for inclusion of more detailed methods of circuit analysis into a fire risk assessment than has been typical of past PRAs. The process begins with the area and scenario screening routinely performed as part of current PRAs. Circuit analysis is required to obtain realistic core damage frequencies for unscreened fire scenarios involving cables. The process can include the circuit analysis performed to meet 10 CFR 50 Appendix R requirements but, as discussed in Section 4.1, must consider the limitations of those analyses when used in a PRA. Additional qualitative circuit analysis is required if non-Appendix R equipment is credited in the PRA. One method for performing this additional circuit analysis is presented in Section 4.2 of this report.

4.1 Circuit Analysis Process Description

A proposed process for including circuit analysis into a fire PRA is shown in Figure 4-1. The process strives to minimize the amount of circuit analysis that is performed through a series of screening steps. The output of the process is a quantitative assessment of fire-induced cable failures for risk-significant scenarios.

Since circuit analysis is a time-consuming process, screening methods can and should be used to appropriately limit the scope of the circuit analysis. This screening can be performed as within the context of current fire PRA practice. A typical fire PRA preliminary screening analysis involves two screening passes, one qualitative and one quantitative. In both preliminary screening steps, all essential components, including those with cables known to be located in a fire compartment[11] are assumed to fail due to any fire that can occur in the compartment. It is also common to assume that mitigating components fail as well unless it can be verified that no cables required for the operation of those components are located in the compartment.

In the initial qualitative screening, the analysis typically looks only for two possibilities; namely, the presence (and therefore the potential loss) of any PRA modeled components, and for the potential that a fire might lead to a demand for safe shutdown. If neither is true for the compartment, the compartment is screened out from further analysis. The initial quantitative screening step typically adds consideration of two quantitative factors; namely, the compartment fire frequency and the conditional core damage probability (CCDP) given loss of all components in the compartment. Should the product of these two factors fall below a predefined screening threshold, then the compartment is screened out from further analysis. Two changes to this initial screening process are anticipated to accommodate advanced circuit analysis.

First, most components/circuits will have more than one potential fault mode, and only some of these fault modes may be detrimental to the plant. The significance of a particular circuit fault may also be dependent on the nature of the operational demands anticipated (e.g., spurious opening of a pilot-operated relief valve when not required versus failure of the same valve to open when required). The PRA screening process must

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[11] This discussion assumes the screening of fire compartments which are presumably not identical to the fire areas defined for Appendix R purposes. Defining what constitutes a valid compartment in the context of a fire PRA is recognized as a point of potential debate, but is beyond the scope of this study.

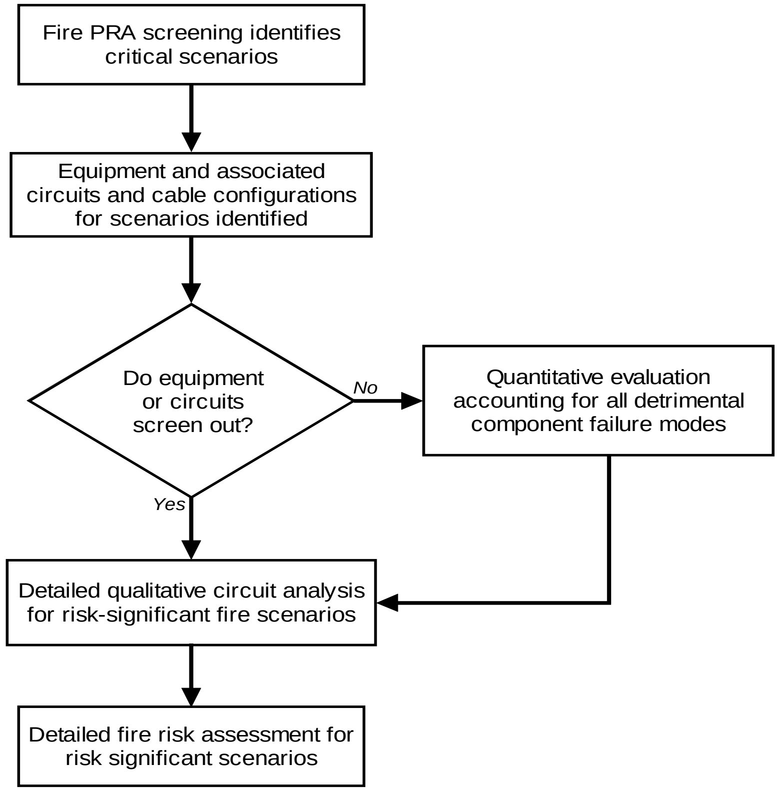


Figure 4-1. Circuit analysis process for fire risk assessment.

consider all possible detrimental component and system faults that could occur as a result of fire-induced cable failures (including multiple hot shorts) in the fire area. This will primarily impact the calculation of the screening CCDP in the quantitative screening analysis.

Second, some component and system faults that can be induced by cable failures during a fire are not typically included in PRA models. Hence, the internal events plant response model may need to be modified to capture the additional component failure modes relevant to fire-induced cable failures. These may include failures that arise through associated circuit issues (see Section 3.2 for a detailed discussion of these issues). Examples of this include the spurious closure of a valve that results in the dead heading of a pump and a short to ground in a cable for a nonessential component that leads to the loss of power to essential equipment. Spurious valve failures are not typically included in PRA models since the random probability of spurious valve closure is small compared to the failure probability for the pump itself. However, fires have the potential to increase the probability of spurious valve operation. This change has the potential to impact both the qualitative and quantitative screening steps. Qualitative screening may be impacted because the analysis may expand the list of PRA modeled components somewhat. Quantitative screening may be impacted because the screening CCDP should correctly reflect the worst-case combination of circuit faults.

The PRA screening process should assume failure of components that can cause plant scrams or require plant shutdowns, components required to operate for accident mitigation, components that can cause failure of a mitigating system (e.g., through spurious opening of valves that cause a flow diversion or the draining of supply tanks), and instrumentation where a fire can cause spurious actuations. In addition to direct effects on mitigating components and systems, the potential risk significance of instrumentation conductor faults that can potentially influence operator actions must also be addressed.

Given these insights, some level of circuit analysis is required to perform the preliminary screening analysis. In some PRA approaches, only Appendix R equipment is credited in the initial screening. Since some level of circuit analysis has been performed for this equipment, it can be used in the screening process. However, the limitations of the Appendix R circuit analysis must be understood and compensated for in the screening process. The limitations of a typical Appendix R circuit analysis process are addressed in Section 4.2.1.

The possible component failures leading to a reactor scram are also not typically included explicitly in PRA models. If fire areas are screened based on the lack of a mechanism for the fire to cause a plant scram, then the potential for fire-induced failures resulting in a reactor scram must be determined through a circuit analysis. This can be a difficult process since many balance-of-plant related circuits would have to be identified and examined. It may be more prudent not to qualitatively screen fire areas based only on the lack of a potential scram mechanism, particularly since there may be a reasonable probability that a manual plant scram would be performed as a result of any significant fire. This decision will involve a balancing act between the desire to appropriately focus the scope of the analysis and the desire to avoid premature screening of a potentially important compartment.

The result of the fire PRA initial qualitative screening process is the identification of fire compartments that contain components whose failure can directly initiate plant transients, where a fire might indirectly cause a demand for safe shutdown, or where a fire might cause the loss of components required to mitigate a plant transient. The quantitative screening analysis identifies those compartments that have a nominal potential to introduce risk-significant fire scenarios. Equivalently, the preliminary screening analysis screens out those compartments that do not meet these criteria. The balance of the fire PRA focuses on the identification and analysis of fire scenarios in the retained compartments. (Note that compartments screened out are reexamined in the analysis of multi-compartment fire scenarios as potential sources of fire that might threaten an adjacent compartment.)

For the retained, or unscreened, fire compartments an analysis is performed of specific fire scenarios involving specific fire sources and equipment damage states. Additional screening of fire compartments may occur, but in general, screening is always performed on the basis of the compartment fire risk contribution rather than on the basis of the risk contribution of any individual fire scenario. Some basis for the screening of fire scenarios may be practicable, but care must be taken to avoid excessive truncation error. That is, one can always redefine fire scenarios to reduce the risk contribution of an individual scenario. Care must be taken to ensure that the screening process cannot be manipulated (either intentionally or unintentionally) such that risk-significant compartments are improperly screened.

The analysis of each fire scenario requires that the cables damaged in the fire scenario, and components served by those cables, be identified. The analysis includes the potential for fire growth and the potential for fire-induced damage to additional cables and components before suppression can occur. The timing, effectiveness, and reliability of fire suppression activities are also assessed. The output of this analysis is typically a set of fire scenarios, each of which induces a particular plant damage state with some quantitative frequency. A given fire scenario would typically be presumed to lead to alternate damage states based on uncertainty in various parameters such as fire intensity, fire spread rate, and fire suppression time. For example, intervention in a fire within ten minutes might prevent damage to a particular cable tray, and the analysis might continue with two sub-scenarios, one involving loss of the tray for fires lasting longer than ten minutes, and a second assuming survival of the tray for fires lasting less than 10 minutes. Each sub-scenario would represent a unique plant damage state and potentially unique plant safe shutdown challenges.

If non-Appendix R equipment (i.e., equipment not credited in the Appendix R safe shutdown analysis) is credited at this point in a fire PRA, then additional circuit analysis of that equipment may be required to identify the possible component and system faults that can occur in each of the identified fire scenarios. This includes the evaluation of associated circuit issues pertaining to the non-Appendix R equipment.

Alternatively, an additional level of fire compartment screening can be performed where only Appendix R equipment is credited. The results of this screening process would be the identification of fire compartments with low risk-significance based on a conservative model of the available plant systems (i.e., only the Appendix R equipment is credited). In such an analysis it is important to consider the components that might cause the failure or mal-operation of the credited safe shutdown equipment, i.e., the associated circuits. A review of the Appendix R safe shutdown and associated circuits analyses is appropriate to ensure completeness in the PRA context. For example, the Appendix R analyses may not postulate multiple concurrent spurious operations, and some components may have been eliminated from the required safe shutdown equipment list and/or from the associated circuits equipment list on this basis. In the fire PRA screening process, such considerations should be included, and this may require close examination of the Appendix R safe shutdown analysis bases.

If a fire compartment is shown to have a potentially significant risk contribution when crediting only the Appendix R equipment, a second pass could be made where non-Appendix R equipment is credited for accident mitigation where justified. An analysis of the circuits for any non-Appendix R equipment in the fire compartment, including evaluation of associated circuit issues, is required to fully justify the operation of this equipment.

The level of circuit analysis required to support the evaluation of specific fire scenarios may be adjusted to suit the objectives of the analysis, the level of refinement desired to meet those objectives, and the risk significance of the fire compartment under analysis. For example, it is anticipated that an initial pass at risk quantification would be made assuming worst-case circuit faults for those circuits damaged in a specific fire scenario without consideration of the likelihood of those faults. Summing all scenarios for a compartment would yield a refined screening estimate of the compartment risk contribution. Compartments that fall below the quantitative screening threshold given such assumptions would not warrant further refinement. Compartments that do not fall below the screening threshold may warrant additional analysis, and in particular, additional circuit analysis.

For compartments that remain unscreened, it is likely that certain key circuit faults will be driving the risk estimates more strongly than others. This would be determined from an examination of the plant response model and the exploration of the changes in CCDP that result from assuming that alternate circuit fault modes are observed. If the key circuit faults involve a particular fault mode or combination of fault modes, such as one or more spurious operations, then a refined analysis that utilizes a quantitative estimate of the conditional probability of that particular set of fault modes is possible. Additional detail can also be pursued in the circuit analysis to support such refinements. One method that can be used to perform the additional circuit analysis is discussed in Section 4.2.

Section 4.2 focuses on a qualitative circuit analysis method that can identify potentially important cable failure modes, circuit fault, and functional impact effects. The approach can identify what faults are possible as a result of different failure modes for the cables involved in each fire scenario, and can identify those failure/fault modes with the most significant functional impact on the plant systems. The results of the qualitative analysis could ultimately be extended to provide quantitative failure/fault mode likelihood estimates given a method for quantifying the conditional probability that specific cable failure and circuit fault modes would occur. This subject is taken up in Section 5. Using established probabilities for each fire-induced cable failure mode and knowledge of the circuits, the unscreened compartments can be requantified to obtain refined estimates of the fire risk.

4.2 Qualitative Circuit Analysis Methodology

Qualitative circuit analysis refers to the process of identifying the circuit fault modes that can occur due to the presence of different fire-induced cable or conductor failures. The discussion is limited to qualitative methods in that the issue of failure/fault mode likelihood estimation is not addressed. This topic is taken up in Section 5. Two approaches that can be used in a circuit analysis performed to support a fire PRA are described in this section. The first is the approach typically used in the safe shutdown circuit analysis performed to meet Appendix R requirements. This method includes several underlying assumptions that should be considered when using an existing Appendix R circuit analysis to support a fire PRA. The second is the use of Failure Modes and Effects Criticality Analysis (FMECA) which allows for a systematic analysis of cable failure modes and their associated circuit fault modes, as well as a qualitative assessment of the importance of each failure/fault mode in the context of plant systems functional impact. The FMECA requires a significant effort but results in additional insights useful in a fire PRA.

4.2.1 Appendix R Circuit Analysis Process

The safe shutdown evaluation performed by most nuclear power plants to meet the requirements of 10 CFR 50 Appendix R includes circuit analysis of the safe shutdown equipment including associated circuits. As indicated in the previous section, the results of this circuit analysis can be utilized in a fire risk assessment. However, a critical factor in this utilization is an understanding of the assumptions and limitations of an Appendix R circuit analysis. This section describes one common Appendix R circuit analysis approach.

The most critical limitation of an Appendix R circuit analysis as applied to a PRA is the fact that not all the components credited in a PRA model are credited in the Appendix R safe shutdown analysis. Thus, a large portion of the equipment modeled in a PRA will not have been subjected to circuit analysis. To determine how this equipment may respond to cable damage in specific fire scenarios, additional circuit analysis may be needed. The FMECA circuit analysis method discussed in Section 4.2.2 or some alternative method can be used to meet this end. As suggested in Section 3.2, the circuit analysis performed for this non-Appendix R equipment should include consideration of associated circuit issues.

An Appendix R circuit analysis is performed for all components with electrical interfaces required for safe shutdown. Safe shutdown equipment is generally listed on a Safe Shutdown Equipment List (SSEL). The SSEL generally excludes mechanical devices such as manual valves, tanks, heat exchangers, and pressure relief valves. The SSEL list may or may not include a comprehensive listing of valves in flow paths that can result in a flow diversion. For example, some flow diversion paths require that multiple valves in series must open, or involve multiple small lines in parallel whose total flow can result in a significant flow diversion. Such paths may not be included in the Appendix R analysis if the analysis excludes consideration of multiple concurrent spurious actuations. Hence, a review of the Appendix R SSEL is appropriate to identify exclusions that may prove important to the quantification of fire risk. For each component on the SSEL, all associated cables are reviewed to determine if their failure can prevent the component from performing its required safe shutdown function. This review includes consideration of the worst case fault mode, including spurious operation.

Appendix R circuit analyses generally assume that the control switches, position switches, and some relay contacts in the control circuits for safe shutdown components are in their normal operating position. However, other relay contacts, and in particular those related to automatic actuation and permissive logic, are often (conservatively) assumed to be in their permissive position. This assumption results in the circuit configuration that is most susceptible to spurious actuation of the component and may not be desirable for use in a PRA since it can result in conservative results. Alternatively, an Appendix R analysis may have chosen to analyze the circuits associated with the actuation or permissive logic and thus included the associated cables in the safe shutdown circuit analysis. Note that when actuation logic, such as a Safety Injection Signal, is included in the Appendix R circuit analysis, typically only cables associated with the master actuation relays are included (master actuation relays are energized or de-energized when the required number of instrumentation signals is obtained; the relays then actuate emergency equipment such as the ECCS pumps and valves). The analysis would not typically include each leg of the initiating logic circuit due to the redundancy in the signals and their fail-safe design. This is generally consistent with the level of instrumentation modeling currently performed in most PRAs.

The Appendix R circuit analyses generally do not consider whether the fire-induced circuit damage will also provide some sort of erroneous component indication (e.g., a spurious valve “open” light) that may result in an operator taking an unsafe action. Indications that may affect the operators’ response should be considered in the PRA. However, instruments necessary for safe shutdown are included on the SSEL and fire impacts on the instrument circuits are considered. In general, instruments exposed to a fire are assumed in Appendix R analyses to fail. While instrument fluid boundaries are assumed to remain intact, sensing lines exposed to a fire are considered to have the potential for causing erratic or false indication. Instrument cables generally operate at low signal levels and thus have grounded metal shields to prevent signal interference. In Appendix R analyses, such instrument cables are not considered to be susceptible to hot shorts since they are assumed to short to ground via the shield. However, in addition to shorts to ground, instrument circuits are assumed to be susceptible to short circuits between conductors within the shield or to loss of continuity failures. The review of experimental data on cable failures performed in this study tends to support these assumptions (see Section 5.2 for further discussion). However, there is still a small potential for hot shorts in instrumentation cables that may have to be considered in the PRA.

Because there is uncertainty as to which cable failure mode will occur, Appendix R circuit analyses assume the cable failure that results in the worst component failure mode. This includes multiple loss of continuity failures, multiple shorts to ground, and hot shorts. However, some nuclear power plant licensees have interpreted the guidance in GL 86-10 [6] as inferring that the analysis need not consider multiple concurrent hot shorts, except for components that are part of a high/low pressure boundary interface. For high/low pressure boundary interfaces, multiple hot shorts are assumed to occur concurrently. Following the guidance provided in GL 86-10 [6] for three-phase AC circuits, the probability of getting a hot short on all three phases in the proper sequence to cause spurious operation of a motor is considered sufficiently low and is not evaluated in an Appendix R analysis. As mentioned above, the exception is for three-phase power cables for components in high/low pressure interfaces (including hot shorts impacting multiple valves in series). GL 86-10 also indicates that in ungrounded DC circuits, multiple hot shorts involving concurrent cable-to-cable proper polarity faults (i.e., positive-to-positive concurrent with negative-to-negative hot shorts) also are of low probability and can be generally ignored except for any cases involving high/low pressure interfaces. With the exception of assuming only one hot short at a time, the above assumptions are not unreasonable. In reality, multiple hot shorts can be induced by a fire in a relatively short time as demonstrated by the Browns Ferry fire and some of the experimental data reviewed for this report. To realistically evaluate the risk from fires, the potential for different hot shorts occurring both concurrently and at different time intervals needs to be assessed.

According to the guidance in GL 86-10, hot shorts are considered to exist until action has been taken to isolate the affected circuit from the fire area, or other actions are taken to negate the effects of the spurious actuation. The potential for the affected cables eventually shorting to ground or opening due to the fire is not considered. The duration of a hot short is generally only important for components that require continuous energizing of a relay, contactor, or solenoid for the spurious operation of the component. A typical example is a solenoid-operated valve. Thus, assuming a sustained hot short is generally a conservative assumption for those types of components. However, most components such as motor-operated valves and pumps only require a hot short long enough for the component to actuate or change position. Thus, the Appendix R assumption is not limiting for these types of components. The available evidence suggests a wide range of potential hot short durations ranging from momentary (less than one second) to several minutes or more. The potential for a sustained hot short has been demonstrated in both experiments and experience.

Electrical coordination of fuses and breakers in nuclear power plants (i.e., breaker coordination) is typically assured for high voltage circuits (i.e., greater than 480 V). For lower AC voltages and DC circuits, breaker coordination exists for the Appendix R related electrical distribution but may not exist for the non-Appendix R electrical distribution. Lack of breaker coordination can result in loss of power to multiple equipment in other circuits powered by the same source when a component with a circuit fault trips an upstream breaker prior to tripping the breaker for that component. Appendix R assessments do not account for failure of circuit breakers to open when required. Failure of the circuit breakers when challenged by fire-induced shorts to ground should be considered in fire PRAs. For example, generic breaker reliability data [e.g., 30] may be applied in a fire analysis to assess the likelihood that the first circuit breaker in line might not actuate on the failure of a power cable. This would lead to the loss of the upstream breaker (i.e., the higher level bus) and the equipment powered from that breaker. This additional equipment loss could then be propagated through the systems model to quantify the risk contribution. Operator actions to restore the upstream breaker could also be modeled if directed by a procedure and if sufficient time is available.

4.2.2 Failure Modes and Effects Criticality Analysis

The possible circuit faults resulting from different cable failure modes can be systematically examined and documented using a FMECA approach [4] applied to circuit designs used at existing nuclear power plants. The FMECA process can be used to identify possible circuit faults resulting not only from hot shorts but also from different failure modes of cables, including loss of conductor continuity, shorts to ground, and high impedance shorts to power or ground. Examples of potential circuit faults arising from fire-induced cable failures include low currents to signal processors, spurious energizing of a relay, and loss of power to portions of a control circuit. The FMECA process also identifies the corresponding functional impacts resulting from the identified cable failures. Examples of functional impacts resulting from the cable failures include complete loss of function, an incorrect instrumentation reading, spurious activation of a component, and the inability to change the state of a component. The FMECA process also indicates when the circuit fault can result in different component behaviors that are dependent upon the system design. For example, an air-operated valve can be designed either to fail open or closed when the power to the controlling solenoid valve is lost. Thus, the parameters affecting whether a fire results in either energizing or de-energizing a SOV have to be examined.

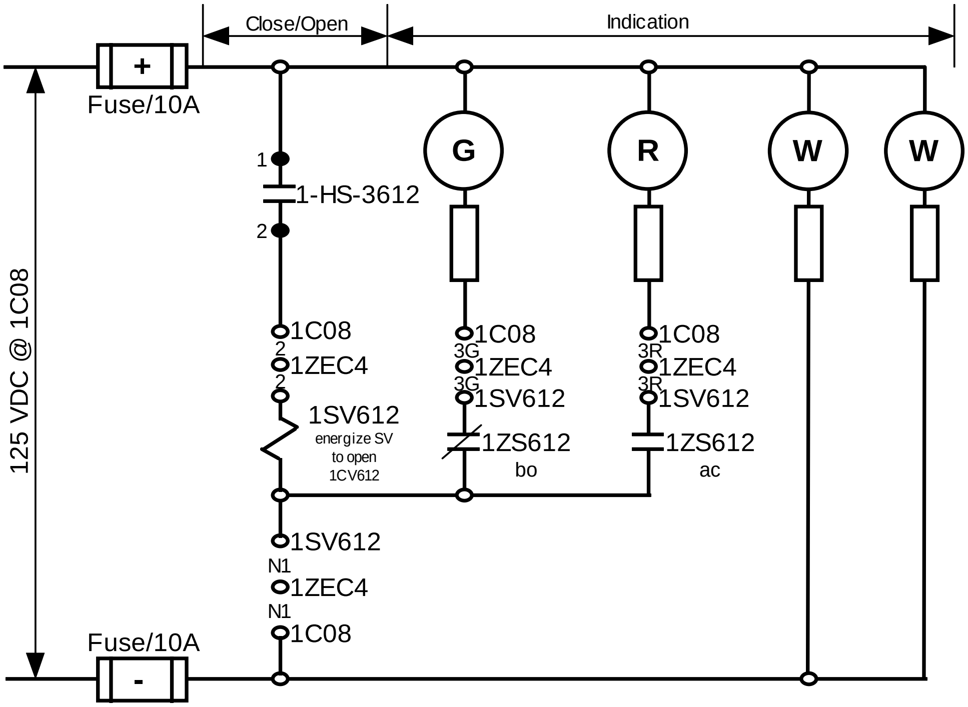
The timing of the cable or conductor failure, including the time of onset and duration of the fault, can affect the significance of a given circuit fault. Thus, timing factors are included in the FMECA. For example, a hot short in a MOV control circuit could result in the valve changing state and staying in that state even after the cable shorts to ground. On the other hand, a hot short in a SOV control circuit would only result in the valve being in a changed state for the period that the hot short exists.

The final characteristic of the FMECA process is the assignment of a criticality ranking to each circuit fault mode identified. The criticality ranking provides a qualitative measure of the severity of the functional impact associated with each circuit fault mode. The utility of the criticality ranking is that it provides a means to categorize the possible circuit faults according to the impact on the component, the duration of the fault, and the potential for identifying the existence of the fault and taking appropriate recovery actions.

To illustrate the insights that can be obtained from a circuit FMECA, an FMECA for a simple SOV control circuit, shown in Figure 4-2, is summarized in Table 4-1. The FMECA addresses all possible cable failures for the SOV control circuit (i.e., loss of continuity, short to ground, and inter- and intra-cable conductor-to-conductor shorts including hot shorts). A criticality ranking for each failure mode is provided in Table 4-1. The definitions for the criticality rankings are provided in Table 4-2. Table 4-2 also provides a summary of the number of conductor faults for the circuit for each criticality ranking.

The following assumptions were used in performing the example SOV FMECA:

- The FMECA investigated cable failure modes only; equipment and components are assumed to remain intact.
- The locations of cable failures are between the boundaries of the control panel(s) and controlled component(s).
- The analysis was limited to three cable failure modes: loss of continuity, short to ground, and conductor-to-conductor shorts including hot shorts. In this particular analysis, hot short effects from both positive and negative DC power sources were evaluated.
- The direct current power source was assumed to be isolated from ground (i.e., it's an ungrounded DC source).
- The valve is assumed normally de-energized and closed, and it was assumed that operation of the valve to mitigate the accident scenario may be desired.
- All conductors in the SOV circuit are in the same cable.



Scheme 1CV612

Figure 4-2. Example solenoid-operated valve (SOV) control circuit.

Table 4-1. FMECA for SOV.

Item	Identification	Description	Failure Modes	Effects	Criticality
1	Conductor 2	Positive DC power lead	1) Loss of continuity	- Valve inoperable	5
			2) Short to ground	- None	0
			3) Hot short to +125 Vdc source	- Valve opens	9
			4) Hot short to -125 Vdc source	- Valve inoperable (+ fuse will blow when HS contacts 1-2 are closed), loss of CLOSED indication	7
2	Conductor N1	Negative DC power lead	1) Loss of continuity	- Valve inoperable & loss of CLOSED indication (power indication available)	8
			2) Short to ground	- None	0
			3) Hot short to +125 Vdc source	- Fuse blows, valve inoperable & loss of CLOSED and power indications	8
			4) Hot short to -125 Vdc source	- None	0
3	Conductor 3G	Valve CLOSED status indication	1) Loss of continuity	- Valve operable, loss of CLOSED status indic.	2
			2) Short to ground	- None	0
			3) Hot short to +125 Vdc source	- Fuse blows, valve inoperable & loss of CLOSED and power indications	8
			4) Hot short to -125 Vdc source	- False CLOSED indication when valve is opened	3
4	Conductor 3R	Valve OPEN status indication	1) Loss of continuity	- No OPEN status indication when valve is opened	1
			2) Short to ground	- None	0
			3) Hot short to +125 Vdc source	- Undetected loss of OPEN indication (+ fuse will blow when valve position contact “ac” is closed resulting in valve inoperability)	7
			4) Hot short to -125 Vdc source	- False OPEN indication	4

Table 4-1 (cont). FMECA for SOV.

Item	Identification	Description	Failure Modes	Effects	Criticality
5	Conductor 2	Positive DC power lead	1) Shorts to 3R 2) Shorts to 3G 3) Shorts to N1	- None - insufficient voltage to energize the solenoid - Fuse will blow when HS is closed, valve inoperable - Fuse will blow when HS is closed, valve inoperable	0 7 7
6	Conductor N1	Negative DC power lead	1) Shorts to 3R 2) Shorts to 3G	- OPEN indication lights, valve still Closed - CLOSED indication will stay on when valve is opened	4 3
7	Conductor 3G	Valve CLOSED status indication	1) Shorts to 3R	- OPEN indication lights, valve still Closed, both indication lights remain on	4
8	Conductor 2	Positive DC power lead	1) Shorts to 3R & 3G 2) Shorts to 3R & N1 3)Shorts to 3G & N1	- OPEN indication lights, fuse will blow when HS is closed, valve inoperable - OPEN indication lights, fuse will blow when HS is closed, valve inoperable - Fuse will blow when HS is closed, valve inoperable	6 6 7
9	Conductor N1	Negative DC power lead	1) Shorts to 3R & 3G	- OPEN indication lights, valve still closed, both indication lights remain on, CLOSED indication will stay on when valve is opened	4
10	Conductor 2	Positive DC power lead	1) Shorts to 3R & 3G & N1	- OPEN indication lights, fuse will blow when HS is closed, valve inoperable	6

Table 4-2. Conductor fault criticality ranking.

Criticality Ranking	Description	Number of Conductor Faults in SOV Example	
		Internal Conductors	External Conductors*
0	No effect on valve operability or position and power indication	5	n
1	Valve operable, loss of valve position indication if valve position changed when fault is present	1	0
2	Valve operable, loss of valve position or power indication	1	0
3	Valve operable, spurious valve position indication if valve position changed when fault is present	1	n
4	Valve operable, spurious valve position indication for duration of conductor fault	3	n
5	Valve inoperable, position and power indication functions	1	0
6	Spurious position indication, valve and position/power indication failures if valve position changed when conductor fault is present	3	0
7	Valve and position/power indication failures if valve position changed when conductor fault is present	3	m+n
8	Valve inoperable and position and power indication failure	1	2m
9	Spurious valve operation for duration of conductor fault, position and power indication functions	0	m

* n = number of –125 Vdc conductors in cable tray
m = number of +125 Vdc conductors in cable tray

A review of Table 4-2 provides the following insights relative to the SOV circuit analysis:

- Many of the identified conductor failure modes result in the inability to open the SOV.
- Only faults involving inter-cable hot shorts would lead to spurious opening of the SOV; intra-cable conductor-to-conductor shorts cannot cause spurious operation in and of themselves.
- Many of the identified conductor failure modes would result in some indication prior to attempts to open the valve.
- Some of the identified conductor failure modes would result in some indication after attempts are made to open the SOV.
- Some of the conductor failure modes would not provide indication at any time.
- Many of the identified circuit faults are dependent on the duration of the postulated hot short.

Additional FMECAs were performed for a typical MOV and pump control circuits, a temperature instrumentation circuit, and an auxiliary relay circuit. For these FMECAs, the circuit faults resulting from all combinations of intra- and inter-cable conductor-to-conductor shorts including hot shorts, loss of continuity failures, and shorts to ground were evaluated. The results of these FMECAs are presented in Appendix B. The benefit of the FMECA method is illustrated by some of the significant insights obtained from utilization of this approach in this study. The following examples illustrate the insights gained in each of the circuit FMECAs.

Solenoid-Operated Valve:

Of the 27 SOV circuit fault scenarios studied in the FMECA, two cases were identified where the OPEN and CLOSED indicating lights remain lit no matter what the valve position is. This would provide conflicting information to the operators on the position of the valve.

Motor-Operated Valve:

Several unusual findings resulted from the MOV control circuit FMECA. They include the following cases identified from the 280 circuit fault scenarios generated in the FMECA:

- Twenty-six scenarios were identified where spurious valve closure would occur, but the motor continues to drive the valve closed until the overloads open, or the circuit breaker trips. This will likely result in damage to the valve which will preclude manual opening of the valve. This is the scenario identified in IN 92-18 [31].
- Twenty-eight scenarios were identified where the valve motor would drive the (open) valve in the OPEN direction until the overloads open, or the circuit breaker trips. This occurrence may result in damage to the valve causing leakage through the valve body.
- Three cases were identified where the valve would spuriously reopen after it has been closed by use of the hand switch. Such an occurrence would require additional operator actions to disconnect power to the valve and manually close the valve.
- Twenty-six scenarios caused both directional control contact coils to be energized simultaneously leading to a phase-to-phase short on the 480 Vac power supply. This would open the circuit breaker rendering the valve inoperable (manual closure of the valve would be required).

Pump Motor Control Circuit:

Ninety-three circuit fault scenarios were studied in the pump motor circuit FMECA. Two types of unusual effects were identified:

- Five scenarios were identified where the trip coil is always energized causing the circuit breaker for the pump motor's power supply to trip immediately when it is closed (i.e., when an operator tries to start the pump).
- Seven scenarios were identified where both the circuit breaker close circuit and trip coil are energized causing the pump to spuriously start and trip repeatedly. Cycling the circuit breaker may cause it to fail if this condition is allowed to continue beyond a few cycles.

Auxiliary Relay Circuit:

> Of the 301 separate circuit fault scenarios identified in the FMECA for the auxiliary relay circuit, 226 of them (75%) caused inadvertent actuation of the logic circuit. Hot shorts in this type of circuit can potentially lead to undesired actuation of multiple components.

As mentioned previously, the FMECAs performed in this study examined the circuit faults produced by all combinations of internal conductor-to-conductor shorts. An example of the results from the MOV control circuit FMECA is provided in Table 4-3. This table shows that the number of conductors shorting together can be important in determining the potential for a particular circuit fault mode. Of particular interest is the ability of the FMECA process to identify specific conductors that would mitigate a specific component fault. For example, the data in Table 4-3 clearly show that the potential for spurious valve operation decreases as the number of conductors shorting together increases above six. This would be particularly useful if the cable behavior during a fire is such that multiple conductors short together. In fact, the review of experimental data performed in this study indicates that for multiconductor cables, shorting of multiple conductors can be expected with a significant probability. Indeed, it is possible to see more than one group of conductors forming mutual shorts, and for the members of the various shorting groups to change over time. Clearly, the conductor shorting behavior is complex. This is illustrated by the following example:

> The recent USNRC/SNL IR tests [14] included the observation and diagnosis of failures in ten cable bundles. For the multiconductor cable in each of these bundles, four out ten initially failed by internal conductor-to-conductor shorts (failure was defined to be less than 100-ohms resistance between the conductors). All four of these cases involved seven-conductor cables. In two of these four cases, three of the seven conductors shorted together for 26 and 100 seconds, respectively, before shorting to ground. In a third case, two conductors shorted together for approximately 24 seconds before going to ground. In the fourth case, there was a progression of internal conductors shorting together in separate groups with the groups coalescing until, finally, all seven conductors were shorted together for about 100 seconds before the group shorted to ground.

Overall, the available data indicates that internal conductor-to-conductor shorts can be sustained for a considerable period of time before the affected conductors short to an external ground and that the shorting behavior is complex.

A specific example of how the shorting of an additional conductor to other conductors can mitigate a specific component fault condition is evident in SOV FMECA provided in Table 4-1. Item eight in the table, shows the effect when conductor 2 shorts to conductors 3G and N1. The effect is that the fuse will blow when the hand switch is closed to energize the valve, thus rendering the valve inoperable. By adding the 3R conductor to this 3-conductor fault, now making it a 4-conductor fault, the effect is to provide the operator indication that something is wrong with the circuit by virtue of the fact that both the OPEN and CLOSED indicating lights are illuminated. The operator could therefore investigate the cause of the conflicting indication lights and perhaps avoid the impending valve failure.

The timing of additional conductor involvement in existing shorts can be important dependent upon the component. For the MOV, a hot short of two or more conductors that causes spurious valve operation only has to last as long as it takes for the valve to open. Thus, the shorting of additional conductors that would mitigate the spurious valve operation would have to occur before the valve completely opens (typically within one minute). The involvement of a ground conductor sometime after the valve has begun to change position will result in the control circuit fuse opening, stopping the valve at its current position, preventing further operation of the valve, and eliminating indication of the valve status. For the SOV example given in the previous paragraph, there may be sufficient time for involvement of conductor 3R in the existing short involving conductors 2, 3G, and N1 before the operator needs to actuate the valve.

The potential for mitigation effects from the involvement of certain conductors in a conductor-to-conductor short identified in the FMECA process suggests that this insight might be used to enhance other circuit analysis techniques. For example, one method for identifying hot short effects is the “hot probe” method. In this method, a circuit is reviewed to see if a spurious actuation would occur if some arbitrary energized source (internal or external to the circuit) were to contact any single conductor in the circuit. This method could be expanded to assess wether or not another “cold” conductor, for example a grounded conductor, would mitigate the effects of the hot short. Such an enhancement might expand the level of insights gained without substantially adding to the analysis burden.

Table 4-3. **FMECA summary results for the MOV control circuit.**

Criticality Rank	Definition	Open ckt	Sht-gnd	External Shorts	2/c shorts	3/c shorts	4/c shorts	5/c shorts	6/c shorts	7/c shorts	8/c shorts	TOTAL
0	No effect on valve operability or position and power indication		2	4	6	4						16
1	Valve operable, loss of valve position indication if valve position changed when fault is present	2										2
2	Valve operable, loss of valve position or power indication	2										2
3	Valve operable, spurious valve position indication if valve position changed when fault is present				1		1					2
4	Valve operable, spurious valve position indication for duration of conductor fault	2		4	3	6	4	1				20
5	Valve inoperable, position and power indication functions			1	3	8	5	1				18
6	Spurious position indication, valve and position/power indication failures if valve position changed when conductor fault is present					1	7	10	5	1		24
7	Valve and position/power indication failures if valve position changed when conductor fault is present	4	4		6	7	2	1				24
8	Valve inoperable and position and power indication failure	1	5	1	4	20	41	38	22	7	1	140
9	Spurious valve operation for duration of conductor fault, position and power indication functions			1	5	10	10	5	1			32
Totals		11	11	11	28	56	70	56	28	8	1	280

5 ESTIMATING CABLE FAILURE MODE LIKELIHOODS

In order to evaluate the risk from fire-induced cable failures, it is necessary to establish the probability of the different conductor failure modes. This includes the potential for loss of conductor continuity, shorts to external ground, and conductor to conductor shorts including both single and multiple hot shorts. The probability for each of these failure modes can be dependent upon a number of factors related to the fire, the cable type, the cable layout, and the circuit design. This section discusses probabilities for fire-induced conductor failure modes that have been used in past fire PRAs. Available experimental data and the evidence it provides regarding the conditional probability of various cable failure modes being observed given cable failure is summarized. Finally, a framework for developing failure mode probabilities for specific types of cables under specific sets of plant and fire conditions is proposed.

5.1 Current Estimates of Cable Failure Mode Probabilities

Currently, the conditional probability for a hot short given fire damage to a cable utilized in most fire PRAs was published in NUREG/CR-2258 [2]. The authors of this report used empirical data from the Browns Ferry fire and information from three cable test programs[12] that were available at the time to generate a single distribution for the probability of a hot short for a multiconductor cable. However, in reviewing this study it is important to note that the authors define a hot short as a conductor-to-conductor short leading to spurious actuation. Hence, the "hot short" probability as defined in NUREG/CR-2258 actually includes both the probability of a conductor-to-conductor hot short, and the probability that the short involves the right combination of conductors to induce the spurious actuation.

Using the limited information available, the authors concluded that there is a "significant frequency (on the order of 0.1 or larger) that wires in a multiconductor cable would contact one another before touching the grounded tray." However, the authors also indicated that since a spurious actuation (a hot short in their own terms) requires that specific conductors contact each other, the probability must be lower and must depend on the relative position of the conductors. For a multiconductor cable that contains both of the conductors required for a hot short/spurious actuation to occur, the authors of NUREG/CR-2258 judged that the probability of a hot short is less than 0.2. Their state of knowledge on hot shorts leading to spurious operation was expressed as a log-normal distribution with the 5th and 95th percentile at 0.01 and 0.2, respectively. The resulting mean probability is 6.8E-2. Although the authors stated that the probability of a hot short should be larger for a two-conductor cable than it would be for a cable with more conductors, no attempt was made to establish different probabilities as a function of the number of conductors. In addition, this report did not address the probability of a hot short between conductors in different cables nor did it attempt to establish the probability of multiple hot shorts.

A review of the fire assessments in the Individual Plant Examinations of External Events (IPEEE) indicates that when the potential for hot shorts leading to spurious operation was treated, one of two methods was applied. In one method, the worst case conductor failure mode was assumed to occur as a result of the fire.

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[12] Note that Appendix A includes a review of all three of the reports cited in NUREG/CR-2258 (see the first three citations in Section A.2.3).

That is, if a spurious opening of a valve was the worst possible consequence of cable failure, then that failure mode was assumed to occur with a probability of 1.0 given cable failure. Under the second method, a conditional probability for the occurrence of a hot short leading to spurious component operation was assumed. The assigned probability was typically either 6.8E-2, the mean value from NUREG/CR-2258, or an arbitrarily assumed value of 0.1. The potential for multiple hot shorts was often calculated by assuming that each hot short was conditionally independent given fire damage to the cables of interest. Thus, the probability for hot shorts leading to spurious operation of two components was calculated in some assessments as 6.8E-2 x 6.8E-2 or 4.6E-3.

The potential for concurrent hot shorts on all three phases of an AC power circuit is generally accepted to have a low probability. Similarly, the potential for concurrent proper polarity hot shorts on both conductors for ungrounded DC circuits is also generally accepted as having a low probability. For this reason, both of these types of hot shorts are not generally considered in Appendix R or fire risk assessments except for the analysis of high/low pressure interface components. To the knowledge of the authors, no fire PRA to date has explicitly included the consideration of such shorts.

The authors of NUREG/CR-2258 state that open circuits are the dominant conductor failure mode during a fire. Note that the definition of an open circuit in NUREG/CR-2258 includes both physical discontinuities in the conductor and opening of circuit protection features due to a short-to-ground. That is, the definition encompasses both loss of conductor continuity cable failures and open circuit faults as those terms are used in the current report. The probability that cable failure would initially result in an open circuit fault was established as the complement of the probability for a hot short leading to spurious actuation; that is, a distribution with 5th and 95th percentile of 0.8 and 0.99, respectively, and a mean probability of 0.932.

The duration of a hot short/spurious actuation was also addressed in NUREG/CR-2258. One factor was the opinion that hot shorts eventually become open circuit faults due to the further deterioration of cable insulating materials under the continued presence of a fire. A second factor was the observation that spurious actuation signals during the Browns Ferry fire occurred during the first half hour. Hence, the transition time from hot short/spurious actuation to open circuit was expressed as normally distributed with 5th and 95th percentile of 5 and 35 minutes, respectively. Hot short duration was apparently not addressed in any of the IPEEE fire assessments. Appendix R assessments will generally assume that hot shorts remain active until actions are taken to clear them. It would appear that, in effect, the same assumption was used in those IPEEE assessments that included spurious actuations.

High-impedance faults are not generally considered explicitly in fire PRAs. The lack of modeling of high-impedance faults may be due to two factors: (1) circuit breaker designs and coordination schemes may have eliminated their potential at a given plant and (2) their potential has historically been considered a low probability event in the U.S. partially because of the quality of the design of power supply systems. Appendix R assessments review the potential for multiple high-impedance faults in the safe shutdown paths and, if the potential for adverse consequences is identified, licensees will typically resolve the vulnerability in some physical or procedural manner. For example, the resolution may include inclusion of steps in the fire procedures to trip all non-safe shutdown power circuits in a compartment containing a fire. Alternatively, the potential might be addressed through plant design through fuse/breaker coordination. Multiple high-impedance fault analyses are generally limited to Appendix R equipment and their associated circuits and on higher voltage (480 V and above) power supplies. Thus, their potential occurrence in other (non-Appendix R) equipment modeled in the PRA will likely not have been considered in the Appendix R analysis. The lack of modeling of multiple high-impedance faults in fire PRAs is at least partially due to the perceived low probability of such events. No known estimate for the probability of a high-impedance fault has been identified during this study.

In order to trip a higher level breaker, there must be concurrent, high-impedance faults, of the proper quality, on multiple conductors, connected to the same power supply to result in loss of a higher level electrical bus. Each of the individual conductor shorts must fit within a narrow range of impedance. That is, each conductor must have fault current magnitudes that won't trip the load breaker for each of the individual faulted circuits, but collectively, result in a fault current sufficient to cause the higher level supply breaker feeding all of the faulted circuits to open. If the impedance is too low, then the nearest upstream fuse or breaker will trip. If the impedance is too high, then the sum of the combined fault currents will not be sufficient to trip the fuse or breaker further upstream in the circuit.

While a more detailed analysis would require consideration of circuit voltage, it can safely be assumed that the conductor short circuit impedance would need to fall within, at the most, a specific order of magnitude range of insulation resistance. One order of magnitude is not a very wide band in the overall context of cable performance where insulation resistance values in the hundreds of megohms are commonly encountered. IR changes of an order of magnitude may be associated with only very modest temperature differences (on the order of 20-30°C based on typical cable equipment qualification results). It appears unlikely that a fire exposure would cause such uniform heating of multiple power cables even if the cables are co-located in a common raceway.

Finally, a high-impedance fault has the potential to quickly degrade to a low-impedance fault condition (e.g., by actually contacting a grounded conductor or structure such as a cable tray). Such shorts may result in a fault current sufficient to open the load breaker. This would eliminate the contribution of that particular circuit to the fault current on the upstream breaker. Such faults are also seen to be intermittent in many cases. That is, a short forms, but excess current causes part of the conductor to melt or vaporize breaking the connection. This process may repeat several times until the conductor ultimately loses continuity. In such cases, each individual pulse of fault current is of very short duration.

Overall, it would appear reasonable to assume that, from a PRA perspective, multiple high impedance faults that might lead to tripping of an upstream breaker are very low frequency events. Hence, one might reasonably argue that neglecting such faults in a fire PRA is unlikely to miss significant fire vulnerabilities. This is particularly true given that the deterministic Appendix R analyses have ensured that measures have been taken to address such faults if they have the potential to impact those systems credited in Appendix R safe shutdown analysis.

5.2 Experimental Data Related to Conductor Failure Modes

As indicated in Section 2.3, reports on fire-related cable experiments were reviewed in order to identify parameters that may affect the likelihood of different conductor failure modes being observed during a fire and to estimate, to the extent possible, the relative likelihood of the different cable failure modes (i.e., shorts to ground, conductor-to-conductor shorts, and open circuits). This data does not include failures identified during post-test examinations. Data from post-test examinations does not necessarily reflect the failure modes that could have occurred during the test. This is primarily due to the fact that "healing" (the recovery of substantial insulation resistance) of shorts between conductors and between conductors and cable trays can occur after extinguishment of a fire or removal of a heat source [28].

Measured data directly relevant to quantifying the relative probability of different fire-induced cable failure modes was obtained from twelve reports, including two documenting the recently completed NEI/EPRI tests [13] and USNRC participation in those tests [14]. A detailed discussion of the tests and their results is provided in Appendices A and D. These recent tests involved the variation of several test parameters, and any analysis of the data must consider and allow for these variations. One of the most significant variations, which is discussed in detail in Appendix D, was the use of control power transformers (CPTs) in the second half of the test program. In the U.S., CPTs are often used to supply power to a control circuit, in particular for MOVs. The CPT will place a hard limit on the total power available to the circuit (the product of current and voltage). Hence, as the current flow increases beyond a certain point, the voltage begins to degrade below the nominal line voltage. If the voltage drops below the minimum pickup voltage for the actuation device, then no spurious actuations can occur. The data show a significantly reduced rate of spurious actuations for tests where the CPTs were used as compared to those without CPTs. This illustrates the importance of the circuit design in the quantitative assessment of failure modes and likelihood analysis. This factor underlies all of the results for the MOV circuits tested by NEI and should be considered in any future application of these results. For the purposes of the discussion presented in this section, this factor is not explicitly treated because the focus is placed on other aspects of the data. Appendix D provides an explicit discussion of the observed behaviors in this regard.

The data are grouped and discussed here according to the type of cables tested. Three cable types that are of primary interest and have been found to present unique behaviors were identified as follows:

- Multiconductor cables (without shield, drain wires, or armor),
- Armored multiconductor cables (without shields and drain wires), and
- Multiconductor cables with shield and drain wires.

For cables with a shield and drain wire, the shield and drain represent a ground plane within the cable which will significantly affect the potential for a short to ground versus a conductor-to-conductor short. Similarly, the armor in armored cable is also typically grounded and thus also affects the relative potential for different cable failure modes. Even if the armor is not grounded, its presence presents a greater surface area for conductors to short to a tray or conduit than does the surface area presented by just the conductor. In addition to reviewing the data for the relative likelihood of each cable failure mode, the data was also reviewed in an attempt to establish a distribution for the duration of a conductor-to-conductor hot short. Finally, available data on cable-to-cable hot shorts is discussed.

It must be acknowledged that only limited success was achieved in meeting the goal of establishing failure mode probability values. Additional analysis of the most recent industry and USNRC/SNL tests may well yield additional insights in this regard. Unfortunately, due to the timing of the tests and other activities, further analysis proved to be beyond the scope allowed for the completion of this study. Some analysis has been performed as described below, but this analysis has not exhausted the potential inherent in this data set. Additional analysis is recommended.

It is also worth noting that EPRI convened an expert panel to assess the results of the NEI circuit fault modes and effects tests. The final report on this activity has been published [36]. This report includes estimates of the spurious actuation likelihood given the design and wiring of the test circuit for various cable type and installation configurations based primarily on the NEI test data, but including to some extent the corresponding data gathered by the USNRC and SNL. The expert panel report is licensed EPRI material; hence, the findings of the expert panel cannot be directly cited here.

5.2.1 Multiconductor Cable Data

The data obtained for multiconductor cables without shield and drain wires and without armor is shown in Table 5-1. As indicated, the available data is dominated by a single report [27] from Underwriter's Laboratories (UL) which represents 161 of the 186 data points available. All of the UL tests involved seven-conductor cables. In many regards, this particular data set is considered one of the best of the available sources. The data appears to be of high quality. There are 98 tests involving eight cable types (including types typical of both qualified and unqualified cables), three fire exposure intensities, and both vertical and horizontal trays were used. Each horizontal tray test involved a stack of four cable trays each of which was monitored for circuit integrity. Only two shortcomings to the data set were identified. First, while eight cable types were tested and are described in the report, the results are obscured such that individual results cannot be tied to a specific cable type. Second, in evaluating the mode of failure for the UL tests, all reported shorts to ground have been counted as shorts to the tray. In reality these may also be conductor-to-conductor shorts since one of the seven conductors was grounded along with the cable tray. The grounded conductor was always the conductor at the center of the cable. See Figure 2-1 for an illustration of a typical seven-conductor cable. Note that IR measurements from recent testing [14] indicate that the center or core conductor of a seven-conductor cable does tend to fail later than the outer conductors. Hence, shorts to ground in the UL tests were likely dominated by shorts to the raceway.

Of the remaining sources, the majority of the data is from tests performed by SNL under USNRC sponsorship. The method for measuring electrical integrity in the tests reported in NUREG/CR-0833 [32] was not provided. Although both conductor-to-conductor and conductor-to-tray shorts are reported for the same cable, the lack of knowledge of the electrical integrity measurement method presents uncertainty in the interpretation of the results. Of primary concern was the fact that conductor-to-conductor shorts were recorded after conductor-to-tray shorts occurred. Normally it would be expected that low impedance shorts to a cable tray would mask any subsequent conductor-to-conductor shorts because all conductors would then be grounded. It is possible that what is being reported is a scenario where one conductor shorted to the tray and the remaining two conductors later shorted together. Given the timing between the different faults that occurred in some of these cases, this appears unlikely.

Other, additional data was obtained from the Sandia IR measurements [14] made during the EPRI/NEI cable tests [13]. These measurements made it relatively simple to determine the time that cable failure occurred and its failure mode. Transitions in failure mode are also characterized to a similar level of detail. A variety of cable types and designs were included in these tests. Note that the EPRI/NEI results are not explicitly included in this particular discussion. The EPRI/NEI results are based on the response of a surrogate MOV circuit to cable failure. Circuit faults are characterized as either spurious actuations or fuse blows (e.g., an open circuit fault generally caused by a conductor-to-ground short). One conductor in each of the EPRI/NEI multiconductor cables was typically grounded. Hence, it is not always possible to tell whether a fuse blow resulted from a conductor-to-external ground failure, or from a conductor-to-conductor failure that happened to involve the shorted conductor. Further, there were some potential modes of conductor to conductor and conductor to external ground failure that would not be detected by the EPRI/NEI circuit monitoring scheme. This makes integration of these results with the other experiments problematic. The EPRI/NEI test results are discussed in detail in Appendix D, and are summarized separately below.

Table 5-1 shows that for multiconductor cables, initial faults involving conductor-to-conductor shorts are of high likelihood. When considering individual data sets, the conditional hot short probability ranges from approximately 0.3 to 0.8 depending on the test set considered. Note that the UL data set actually falls at the upper end of this range. For the data set taken as a whole the hot short probability is approximately 0.7 where, again, this result is dominated by the UL data set. In all of the cited tests, the remaining failed cables all experienced shorts to ground as the initial fault mode. There was not a single case of a loss of continuity cable failure in any of the reports referenced in Table 5-1 (nor in the EPRI/NEI tests). The only test where loss of continuity failures have been observed involved the testing of high voltage cables by LLNL [35] and occurred only after repeated high-intensity shorts to ground. These tests are discussed further in Section 5.2.4 below.

Both the UL tests and the more recent EPRI/NEI tests provide some nominal indication of the potential for multiple hot shorts and spurious actuations. In the other tests reviewed, there was typically only a single length of instrumented cable in each test. In the UL horizontal tray tests there were four trays exposed during each test. Most of these tests did record conductor-to-conductor shorts as the initial failure mode in multiple trays. There was, however, only one instrumented cable in each tray, and the tray loadings were quite sparse. Also, given the overall high likelihood of conductor-to-conductor failures demonstrated by the UL tests, in hindsight, the occurrence of multiple conductor-to-conductor shorts in a single test would be expected.

The EPRI/NEI tests confirm the observation that multiple hot-short-induced spurious actuations are possible, if not likely. Actuations of multiple actuators in a single test were observed, and in several cases, a single actuator experienced repeated distinct actuations through the course of a given test before fuse blows deactivated the circuit. As many as four actuations were observed to impact one single actuator. Most tests involved four surrogate MOV control circuits, although in some tests one would be located in a conduit while the other three were in a cable tray. Each MOV had two potential actuation targets, one to represent the valve opening circuit, and the second the valve closing circuit. Counting each individual spurious actuation, including multiple actuations on a single device, 52 total actuations are reported in the EPRI/NEI tests.

Focusing only on the cable tray tests, cable bundle failures were observed in a total of 12 tests. The number of bundles that failed in a given test ranged from one to all four. In nine of the tests, at least three of the four cable bundles failed. Among these nine tests, six experienced spurious operations on multiple circuits. Note that the companion USNRC/SNL measurements typically involved only one cable bundle, but the overall results are similar with conductor-to-conductor shorts representing the dominant initial failure mode.

Table 5-1. Measured data on multiconductor cable failure modes.

Reference	Type of Cable[1]	Size (AWG)	Number of Conductors	Number of Failures [2]			Comments
				Shorts to Tray or Conduit	Conductor-Conductor Shorts	Loss of Conti-nuity	
NUREG/CR-0833 (Reference 32)	Qualified (XLPE/XLPE)	12	3	6/6	0/6	0/6	It is not known how the cables were instrumented to measure electrical integrity. The data shows that conductor-to-conductor shorts occurred after shorts to the tray for 11 of the cables.
	Unqualified (PVC/PVC)	Unknown	3	6/6	0/6	0/6	
NUREG/CR-3192 (Reference 33)	Unqualified (PE/PVC)	12	3	4/7	3/7	0/7	Some of the cables included a grounded conductor. Thus, for the unqualified cables, three of the shorts to ground could have been to grounded conductors.
	Qualified (XLPO/XLPO)	12	3	0/1	1/1	0/1	
NUREG/CR-0596 (Reference 25)	Unqualified (PE/PVC)	12	3	0/1	1/1	0/1	Multiple cables were used but the same colored conductors in the different cables were electrically connected. Thus the configuration has to be treated as containing only one cable. Cables were on vertical tray
NUREG/CR-6776 (Reference 14)	Thermoset						Four cables were tested while run in conduit (c); in the case of the three cables they were bundled together in the conduit and were monitored during the same test. Failure was defined to be insulation resistance <100 ohms between separate conductors or between conductor and ground.
	(XLPE/Neoprene)	14	7	0/1	1/1	0/1	
	(EPR/Hypalon)	14	7	½	½	0/2	
	(EPR/Hypalon)	14	5 (c)	1/1	0/1	0/1	
	(EPR/Hypalon)	14	3 (c)	3/3	0/3	0/3	
	Thermoplastic (Tefzel)	14	7	0/2	2/2	0/2	
EPRI NP-1881 (Reference 21)	Qualified (EPR/Hypalon)	9	7	0/1	1/1	0/1	Both cables were in ungrounded conduits. The cables were also connected to an ungrounded power source.
	Unqualified (PE/PVC)	12	3	1/2	1/2	0/2	

Table 5-1 (cont). Measured data on multiconductor cable failure modes.

Reference	Type of Cable[1]	Size (AWG)	Number of Conductors	Number of Failures [2]			Comments
				Shorts to Tray or Conduit	Conductor-Conductor Shorts	Loss of Conti-nuity	
ENS-IN-99-00412 (Reference 34)	Unknown	16	2	0/1	1/1	0/1	Conductor-to-conductor short followed by short to another cable with both cables shorting to the tray soon thereafter.
UL File NC555 (Reference 27)	Various (eight types tested but results are obscured)	12	7	11/43 V 24/118 H ________ 35/161	32/43 V 94/118 H ________ 126/161	0/161	Both vertical (V) and horizontal (H) trays were tested using three exposure fire intensities. Shorts to ground are ambiguous since one conductor was grounded to the tray. All ground shorts are counted as tray shorts.
Total				57/195	138/195	0/195	Note that the UL tests included cables that would nominally be typical of both qualified and unqualified types, but the results have been obscured such that the results cannot be tied to individual cable types.
Qualified cable total				6/8	2/8	0/8	
Unqualified cable total				11/16	5/16	0/16	

[1] Qualified versus unqualified refers to whether the cable meets the flame test requirements of IEEE-383-1974. The designators in parentheses present the following information (jacket material/insulation material). The following abbreviations are used for insulation jacket material:
PE - polyethylene; XLPE - cross-linked polyethylene; PVC - polyvinyl chloride; XLPO - cross-linked polyolefin; EPR - ethylene propylene rubber; Hypalon - chlorosulfonated polyethylene (or CSPE)

[2] The first electrical failure mode is identified in these columns. Different failure modes occurred later for cables in some of the tests. Cables samples that did not fail during testing are excluded from the count.

The data presented in Table 5-1 only address the potential for conductor-to-conductor shorts. It does not directly address the potential for a hot short leading to spurious actuation. Spurious actuation may, for example, require that two specific conductors within a cable to short together. In fact the data reviewed in this study suggests that for three-conductor cables, if two conductors short together, it is likely that the third conductor will short to the other two. (Note that the UL tests provide no insights in this area because of the way circuit integrity was measured.) The data shows that, in many cases (approximately 40%), all three shorted simultaneously. In other cases (approximately 50%), the data showed that the interval before the third conductor became involved ranged from approximately 10 to 200 seconds. Only a small fraction of the conductor-to-conductor shorts in three-conductor cables involved just two conductors (approximately 10%).

In the recent USNRC/SNL IR measurements [14] complex conductor-to-conductor shorting behaviors were observed. Shorts between as few as two conductors were observed, but shorts involving larger groups of conductors, up to and including all seven conductors, also occurred. In some cases two or more separate groups of shorting conductors would form concurrently. For example, a given test might see a short circuit involving one pair of conductors and a concurrent short involving a separate group of three conductors.

The data supporting these observations are summarized in Table 5-2(a) as related to three-conductor cables. Note that a sensitivity evaluation is included where the data from NUREG/CR-5546 [23] is excluded. These tests were terminated soon after a conductor-to-conductor short was identified which thus eliminated the opportunity for the third conductor to short to the other two in some tests. These observations indicate that, if the shorting of a specific conductor to other conductors within the same cable might mitigate a hot short (e.g., a grounded conductor), then this may be an important consideration in determining both the likelihood and duration of a potential spurious actuation.

The recently completed EPRI/NEI tests included four distinct wiring configurations. Each configuration included the same basic set of circuit/conductor functions; namely, two energized ‘source’ conductors (powered through a single fuse), one spare conductor (not connected into the MOV circuit), two non-energized ‘target’ conductors each capable of generating a spurious operation if energized by a hot short, and one grounded conductor that would mitigate the potential for a spurious actuation should either of the two source conductors short to it. However, the manner in which specific functions were assigned to specific conductors in a given sample cable was varied. This changed the relative proximity of conductors serving specific circuit functions within the cable. The wiring configuration was found to be an important factor. It was observed that the outer ring of conductors tended to fail first and the one centrally located, or embedded, conductor was less likely to be involved in the initial shorting patterns. It was also observed that conductors tended to short to nearest-neighbor conductors first. These results were confirmed by the USNRC/SNL IR measurements [14]. Additional analysis of these tests may reveal additional insights.

There is very little data in the earlier reports reviewed here that can be used to characterize the likelihood that specific conductors might short together, and in particular, for cables with more than three conductors. The IR and MOV circuit data from the most recent tests [13,14] may offer this potential, but the analysis of this data set in the context of a mechanistic failure mode model fell beyond the available scope for this study. The available data shows that the conductor shorting behavior is neither simple nor static.

Table 5-2(a). Measured data on number of conductors involved in conductor-to-conductor shorts in three-conductor cables.

Reference	Type of Cable[1]	Size (AWG)	Number of Conductors Shorting			Delay Time (sec)	Comments
			Two	Three			
				Simultaneous	Delayed		
NUREG/CR-5546 (Reference 23)	Qualified (XLPE/Neoprene)	12	5/42	18/42	19/42	10 to 200	These tests were instrumented to detect only conductor-to-conductor shorts. The tests were terminated soon after shorts were detected. Because of the early termination, it is uncertain whether the third conductor would have shorted to the other two.
	Qualified (EPR/Hypalon)	16	7/40	13/40	20/40	10 to 60	
NUREG/CR-4638 (Reference 25)	Unqualified (PE/PVC)	12	0/3	2/3	1/3	60	These tests were configured to detect only conductor-to-conductor shorts. These tests did not have thermocouples embedded in the jacket like the other tests reported in this reference.
	Qualified (XLPE/XLPE)	12	0/3	1/3	2/3	50	
EPRI NP-1881 (Reference 21)	Armored	Unknown	0/2	0/2	2/2	60	The cables were connected to an ungrounded power source. The conduit was also ungrounded.
	Unqualified (PE/PVC)	12	0/1	0/1	1/1	60	
Total			12/91 (0/9)	34/91 (3/9)	45/91 (6/9)		Values shown in parentheses exclude data from NUREG/CR-5546.

[1] Qualified versus unqualified refers to whether the cable meets the flame test requirements of IEEE-383-1974. The designators in parentheses present the following information (jacket material/insulation material). The following abbreviations are used for insulation jacket material:
PE - polyethylene; XLPE - cross-linked polyethylene; PVC - polyvinyl chloride; EPR - ethylene propylene rubber; Hypalon - chlorosulfonated polyethylene

Table 5-2(b). Measured data on number of conductors involved in conductor-to-conductor shorts in seven-conductor cables.

Reference	Type of Cable[1]	Size (AWG)	Number of Conductors Shorting					Delay Time (sec)	Comments
			Two	Three		Four	Seven		
				Simultaneous	Delayed	Delayed	Delayed		
NUREG/CR-6776 (Reference 14)	Thermoset (XLPE/Neoprene)	12	0/1	1/1	0/1	0/1	0/1		These cables were instrumented to measure insulation resistance (IR) during the EPRI-NEI cable tests. In each case a short was defined as an IR of less than 100 ohms.
	(EPR/Hypalon)	12	0/1	0/1	0/1	0/1	1/1	54 to 130	
	Thermoplastic (Tefzel)	12	2/4	1/4	0/4	1/4	0/4	160	
Total			2/6	2/6	0/6	1/6	1/6		

[1] The designators in parentheses present the following information (jacket material/insulation material). The following abbreviations are used for insulation jacket material: PE - polyethylene; XLPE - cross-linked polyethylene; PVC - polyvinyl chloride; EPR - ethylene propylene rubber; Hypalon - chlorosulfonated polyethylene.

For example, the shorting together of individual conductors was monitored by the Sandia IR measurement system [14] during the EPRI-NEI cable tests [13]. In one test, the IR measurements indicate that two conductors shorted together first and were later joined by two more conductors while, concurrently, three of the remaining conductors generated their own short circuit. In another run, three conductors shorted together without any other interaction and remained in that condition for about three minutes. As a final example, there was a case where shorted pairs of conductors formed and progressively joined one to another until at one point there was a seven-conductor short circuit formed. Table 5-2(b) shows the results from the IR measurements conducted during the EPRI/NEI cable tests regarding the progression of conductor-to-conductor shorting events in the ten-conductor cable bundles tested. Note that in one case, all seven conductors in the central seven-conductor cable shorted together without influence from either an external ground or one of the three single-conductors bundled with it. The tests show that continued exposure of the cable to a fire will eventually result in all of the failed conductors shorting together and eventually to ground(see Appendix A and Figure A-2). However, no conclusions have yet been reached on the relative probability of certain combinations of conductor shorts in a given multiconductor cable.

The majority of the test reports reviewed provided little information on the duration of the conductor-to-conductor shorts. While the majority of these tests reported the time of the initial conductor-to-conductor short, most did not provide information on the duration of the short before the conductors shorted to ground. For example, in the UL tests, the instrumentation was able to detect the onset of a phase-to-phase (or conductor-to-conductor) short following a phase-to-ground short (interpreted here as conductor-to-tray), but not vise-versa. That is, because of the test design, once a phase-to-phase short occurred the ground faults were no longer detectable. Hence, there is no data on the duration of the phase-to-phase shorts observed in these tests.

Of the earlier tests, only EPRI NP-1881 [21] and a French test report [34] provided some information pertaining to the duration of conductor-to-conductor shorts. These early tests did not provide sufficient data for statistical analysis. These two earlier test reports cite short durations from less than one second (a momentary short) to several minutes. The most recent industry tests also provide duration information based both on the EPRI/NEI MOV response data [13] and on the USNRC/SNL IR data [14]. These data have not yet been subject to a rigorous statistical analysis. However, in general, the duration of conductor-to-conductor shorts, and similarly hot shorts (based on the MOV circuits) was wide ranging.

The IR measurements showed conductor-to-conductor shorts that lasted from 24 seconds to about 5.5 minutes before shorts to ground were detected. For the EPRI/NEI MOV circuits, the spurious actuation durations ranged from momentary (less than one second), to a maximum of 10 minutes. Note that in all cases where actuations were observed, the pilot exposure fire continued to burn throughout the short transition period. A more rigorous analysis of this data would likely yield additional insights, but unfortunately fell beyond the available scope for this study. Such an analysis would need to consider the many factors varied in the test program from test to test as discussed further in Appendix D.

Section 3.1 above discussed the potential impact of cable failure modes on instrumentation cables. In six of the recent EPRI-NEI fire tests, a separate current loop circuit was also included and monitored using the USNRC/SNL IR measurement system. These results are discussed in detail in Reference 14. The current loop consisted of an ungrounded DC current source providing the loop with a nominal 15 milliamp signal. This signal was monitored by a voltmeter across a 250-ohm resistor. The expected output range was 1-5

VDC for loop currents in the range of 4-20 milliamps. At 15 mA the initial reading was 3.75 Volts, or approximately 69% of full scale. Failure was defined as a significant change in the voltage level being read across the resistor.

In all six cases the instrumentation cable failed at some point during the test. All the failures in the current loop circuit were by means of a reduction in the output voltage reading. Since the loop was supplied by an ungrounded source, this loss of the signal indicated either conductor-to-conductor interaction or both conductors shorting to a common ground (such as the grounded shield wrap). Thermoplastic instrument cables tended to fail catastrophically to an output of zero volts. In contrast, the thermoset cables showed some degree of signal degradation prior to the loss of the output signal. This difference in behavior could be important in the analysis of operator response. The catastrophic loss of an instrument reading would be easily detected as a failure. However, the progressive degradation of an instrument reading might not be easily diagnosed. The direction of the reading bias is easily predicted by circuit analysis.

5.2.2 Armored Cable

Two of the early tests programs reviewed in this study involved armored cables. In addition, the most recent cooperative tests by EPRI/NEI and the USNRC/SNL also involved two tests with armored cables. As previously discussed, the presence of armor can influence the relative likelihood of a short to ground versus a conductor-to-conductor short. For this reason, the test data involving armored cables were reviewed separately from other cable data.

The identified data from the early tests is provided in Table 5-3. As indicated in Table 5-3, a large fraction (approximately 60%) of the cables in these tests initially shorted to the armor. Two of these cables in an ungrounded circuit experienced conductor-to-conductor shorts while simultaneously shorting to ungrounded armor. Three of the cables experiencing conductor-to-conductor shorts later shorted to the armor. The time period between the conductor-to-conductor shorts and conductor-to-armor shorts in these tests were 1, 10, and 14 minutes. Note that the two three-phase power cables that experienced conductor-to-conductor shorts tripped their circuit breaker on phase-current differential and thus a subsequent short to the armor was not measured even though it could have happened.

Table 5-3 includes a sensitivity test where this power cable is assumed not to short to the armor. Overall, the fraction of conductor shorts involving the armor is high, ranging from 0.8 to 1.0. None of the cables in this data set experienced a loss of conductor continuity as the initial cable failure mode.

From the most recent tests, two armored cables were monitored with the prototype IR measuring system. However, one of the two armored cables did not exhibit any failures (IR <100 ohms) between conductors or to ground. In the second instance, the IR measuring system had been mis-wired so that no definitive determination of failure mode could be made. There are some indications of failures (very low total IR values) occurring during the test, but the mode is not discernable. For the EPRI/NEI portions of the test, eight armored cables were tested, and seven of the eight cables failed. In only one case was a spurious operation observed, and this one case involved a cable whose minimum bend radius was violated during the installation in the test tray. Hence, this result is suspect.

Table 5-3. Measured data on armored cable failure modes.

Reference	Type of Cable[1]	Size (AWG)	Number of Conductors	Number of Occurrences [2]			Measured Shorts to the Armor[3]	Comments
				Shorts to Armor	Conductor-to-Conductor Shorts	Loss of Continuity		
EPRI NP-1881 (Reference 21)	Unknown	Unknown	3	2/2	2/2	0/2	2/2	All conductors shorted together and to the armor at the same time. The circuit and armor were not grounded.
EF.30.15.R/96.442 (Reference 26)	Power	10	3	3/3	0/3	0/3	3/3	The 16 AWG control cables had conductor-to-conductor shorts involving all seven conductors and transitioned to shorts to ground. The 6 AWG cables were three-phase power cables that tripped the circuit breaker upon experiencing a conductor-to-conductor short. The armor was grounded in all three types of cables and all shorts to ground are likely to have been to the armor.
	Power	6	3	1/3	2/3	0/3	1/3 (1/1)	
	Control	16	7	0/3	3/3	0/3	3/3	
Total				6/11	7/11	0/11	9/11 (9/9)	Value shown in parentheses excludes two cables that tripped the circuit breaker before shorting to the armor could occur.

[1] Whether the cable was qualified or unqualified and the type of jacket/insulation material used in the cable was not specified in the reports.

[2] The first electrical failure mode is identified in these columns.

[3] Includes all shorts to the armor either during the initial cable failure or after transitioning from a conductor-to-conductor short to a short to the armor.

A second factor is that in the second test, which accounts for four of the seven failures, CPTs were used which limit the total power available to the control circuit. As noted in Section 5.2 above, the CPTs had a fairly profound impact on the number of spurious actuations observed. Hence, one cannot extrapolate these results directly to an alternate circuit that does not have CPTs.

Overall, while the data are sparse, they do appear to indicate a lower likelihood of spurious actuations for armored cables. It is not, however, possible to estimate the relative likelihood either directly for armored cables, nor for armored cables as compared to a general multiconductor cable.

5.2.3 Shielded Cables with Drain Wires

One series of tests [17] identified in the review used a two-conductor cable with a shield and drain wire. The cables in these tests were not instrumented for conductor-to-tray shorts. However, the data can be used to help establish the potential for conductor-to-conductor shorts between the insulated conductor versus conductor-to-drain shorts for these cable types. Although the drain wire was not grounded in the test, it is common practice to ground drain wires when these cables are used in nuclear power plants. Thus, any shorts to the drain wire recorded in these tests could be inferred as shorts to ground. A review of the data shows that the majority (38 out of 40) of the initial shorts occurred between the drain wire and another energized conductor. This is attributed to the lack of insulation around the drain wire that makes it the preferential target for a short compared to a second insulated conductor. In most of the tests (33 out of 40), all three conductors eventually shorted together and may have for the other tests if they had continued longer (for the two tests that did not initially include the drain wire in the short, all three conductors did short together). However, there was some time delay in many of the tests before all three conductors shorted together. This time delay ranged from 10 to 50 seconds. Thus, the duration of a hot short in this type of wire may be very short. As with the other test data, no open circuits were recorded in these tests.

5.2.4 Inter-Cable Shorting Behaviors

The reviewed data contained very little information on cable-to-cable failures. For the earlier test reports, only two were instrumented to specifically identify the occurrence of cable-to-cable shorts. The tests performed by Lawrence Livermore National Laboratories [35] were specifically instrumented to detect cable-to-cable shorts, cable-to-tray shorts, and loss of continuity failures. However, the test configuration (specifically the high ampacity used in the circuits and the lack of circuit protection) resulted in highly volatile behavior that made it impossible to differentiate when shorts to the tray versus shorts between cables occurred. One significant insight from this report is that high ampacity circuits may result in energetic but brief shorts to other cables or to ground that may not trip circuit breakers. Thus, sustained hot shorts involving high ampacity sources are not likely. In addition, it is noted that this was the only test to record a loss of continuity cable failure. The loss of continuity failures occurred after the occurrence of many shorts between cables and the tray. The occurrence of loss of continuity failures in these tests and not in any of the others reviewed in this study indicates that loss of continuity failures will most likely occur in situations where the energy content carried by the cables is high (i.e., high voltage or current). Further discussion of these tests is provided in Appendix A.

The second early test that contains information on cable-to-cable shorts is the French test performed in cooperation with NEI [34]. This test involved one two-conductor ‘source’ cable surrounded by seven ‘target’ cables. The results of this single test show that a conductor-to-conductor short occurred first in the energized source cable at approximately 8 minutes. This cable then shorted to a target cable approximately 40 seconds later. Both cables then shorted to the grounded cable tray approximately 20 seconds later. (Note that this interpretation differs from that in the original test report. The original test report does acknowledge the conductor-to-conductor hot short, but does not conclude that a cable-to-cable short occurred prior to the target cables shorting to ground.)

The only other test set to provide information on cable-to-cable failures is the recently completed industry tests performed in cooperation with the USNRC [13,14]. In these tests the typical cable bundle targets consisted of one seven-conductor (7/C) cable bundled with three single-conductor (1/C) cables. The four cables were tied together using fiberglass tape, and each bundle was connected to one of the four MOV circuits in each test. The target bundles were placed in separate locations within the cable tray, and there was little or no chance for interactions between bundles. The tests did experience inter-cable hot short induced spurious actuations in at least four cases. Inter-cable conductor-to-conductor shorts were also detected in some cases by the companion IR system. In one of the four spurious actuation cases, two separate cable-to-cable (1-conductor cable to the 7-conductor cable) interactions occurred. The tests also included one case where a source conductor in the 7/C cable hot-shorted to a 1/C target conductor causing a spurious actuation. However, the test configuration was rather contrived and atypical of actual installations. Hence, the applicability of the results to actual applications is suspect.

One insight obtained from these tests that is considered robust is that the thermoplastic cables showed a greater tendency toward inter-cable interactions than did the thermoset cables. In post-test examinations, the differences in behavior were quite evident. The thermoplastic cable bundles typically fused into a single mass of shorted conductors and re-solidified plastic. It was sometimes difficult to tell clearly which conductors had originally been the single versus multiconductor cables except in that the single conductor cables were of a larger size. In contrast, the thermoset cables were typically left as conductors surrounded by charred or burned insulation, but with a greater distinction evident between the single-conductor and seven-conductor cables.

In conclusion, there is insufficient data in the reviewed reports to establish the relative likelihood that given cable failures, inter-cable hot shorts might develop. The data do indicate that inter-cable interactions are less likely than intra-cable interactions, and perhaps substantially less likely, especially for thermoset cables. The most recent tests provide some limited insights but limitations to the test design make it difficult to justify reliance on the results to statistically estimate the likelihood of such interactions.

5.3 A Proposed Framework for Failure Mode Likelihood Estimation

As discussed in other sections of this report, the available data for estimating the relative likelihood of one particular mode of cable failure given a cable failure is sparse. This is a potential weakness of the proposed circuit analysis methods. Without some reasonably concise and reliable data and/or an accepted method for estimating the relative likelihood of a given failure mode, risk estimates obtained using the improved methods will retain large uncertainty. Unfortunately, many questions remain unanswered regarding these distributions.

For example, many previous studies assume a mean spurious actuation probability of 0.068 per cable failure based on the probability distribution from NUREG/CR-2258 (see Section 5.1 above). It is interesting to note that the current review has found that this probability estimate is roughly consistent with test data for one specific type of cable, a 2-conductor 16 AWG instrument/control cable with a metallic shield wrap and drain conductor. That is, available data nominally indicate a mean relative probability of 0.05 that the two insulated conductors will initially short to each other without first (or simultaneously) shorting to the shield/drain based on 2 such occurrences out of 40 observed failures during testing. If a hot short between the two conductors in such a cable can lead to a spurious actuation, then the two values are quite comparable. However, this review has also found evidence to support a higher mean conditional probability of hot shorts and/or spurious actuations occurring in a multiconductor cable than the value implied in NUREG/CR-2258.

NUREG/CR-2258 cited that the hot short probability for a multiconductor cable was “on the order of 0.1 or larger.” The current review has found that the conditional likelihood that the initial failure mode of a multiconductor cable will be intra-cable conductor-to-conductor shorting is on the order of at least 0.7 to 0.8 (i.e., given failure of a general multiconductor cable this is the conditional probability that the initial failure mode will be a non-grounded conductor-to-conductor short circuit). For some configurations, e.g., air drops, the likelihood approaches unity.

This still leaves open the question of the likelihood that the hot short that forms will lead to a spurious actuation. The recently completed industry testing involving a surrogate MOV control circuit demonstrated a relatively high likelihood of spurious actuation for the tested circuit. Depending on how the data are parsed, for some test configurations nearly 70% of cable failures led to spurious actuations. Other test configurations showed substantially lower spurious actuation likelihoods and a number of factors were found to be important to the likelihood estimation process. Overall, it is quite clear that the question of hot-short probability is more complex than can be reflected in any single probability distribution.

As a second example, consider that in estimating the probability of multiple spurious actuations, it is common practice to simply multiply the conditional probability of one spurious actuation (e.g., 0.068) the appropriate number of times. There is currently no evidence to indicate whether or not this practice is reasonable. It assumes that the two spurious actuations are totally independent events, and this may not be correct depending in particular on how the hot short probability is established in the first place. If the hot short or spurious actuation probability is established in such a way that all of the potential dependency questions are properly accounted for, then it may well be appropriate to assume failure independence of one cable versus another. Indeed, an approach that directly addresses any dependency issues and thereby allows the resulting failure mode probabilities to be treated as independent event probabilities would be the preferred long-term approach. However, the question of independence remains a point of debate that has not been fully resolved, and cannot be resolved by this study. Assuming that any given failure mode conditional probability value is actually independent remains a questionable practice.

As a third example, consider that cases have been put forward where a potential concern arises only if a hot short between two specific conductors of a multiconductor cable can be postulated with some significant likelihood. This type of insight may be gained from the FMECA approach; that is, the FMECA may reveal that an undesired impact might occur only if two specific conductors in a multiconductor cable hot-short. However, if the two subsequently short to one (or perhaps more) of the other cable conductors, then the undesired impact may be self-mitigating.[13] In certain plant applications simple combinatorial models have been proposed to estimate the likelihood that any two out of ‘n’ conductors might short together. Again, this review has identified no specific experimental evidence to either support or refute this model with the possible exception of the recently completed industry/USNRC cooperative tests [13,14]. These data hold the potential to support the further development of such combinatorial models, but as noted above, such analyses could not be undertaken as a part of the current study due to issues of timing and scope limitations.

Combinatorial models assume, in effect, that the internal failure process and/or the circuit wiring and conductor selection are fully random. One can speculate on reasons why such a model would not be appropriate. One would be the fact that electrical wiring practices are not generally based on random selection of conductors. In a multiconductor cable it is general practice to select conductors routed adjacent to each other for associated wiring connections rather than to simply select conductors at random. Furthermore, most cables are rigidly structured with conductors routed in very carefully arranged patterns that will be maintained along the cable’s entire length. Hence, the proximity of one conductor to another remains fixed along the cable’s length. The experimental evidence also shows that initial failures are more likely to involve conductors that are in close proximity within the cable than conductors that are remote from each other (interaction with remote conductors may still occur if the fire damage progresses). The data also show that shorts are most likely to occur first in conductors near the outer surface of the cable, likely because the fire exposure heats the cable from the outside-in (self ignited fires not being a concern for I&C cables). Hence, the treatment of specific pair shorting as a totally random process may be poorly founded.

A more structured framework for estimating failure mode likelihoods will ultimately be needed to support refinements and uncertainty reductions for the improved circuit analysis methods proposed here. The subsections that follow discuss a potential framework for such assessments.

5.3.1 Likelihood Estimation Framework

The ultimate objective being pursued here is to establish a method that would allow an analyst to predict the relative likelihood of a given failure mode for a specific cable under a specific set of plant and fire conditions. The method would need to provide a structured approach to establishing these probabilities for a range of potential applications. The method should ideally be kept simple and should be readily repeatable by different analysts.

To address this need, a framework is proposed for future developments in the area of failure mode likelihood estimation. This framework builds on a concept of “base cases” and “modifying factors.” In very general terms, the base cases would reflect a set of nominal or generic applications that are then adjusted using the modifying factors to reflect the specifics of a given fire scenario analysis. Ideally, the base cases would be sufficiently varied so as to inherently encompass the most significant influence factors. The modifiers would then provide for only minor adjustments to the final probability estimates. In application, the analyst would

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[13] This an example only and is not universally true. The FMECA examples identified cases where spurious actuations would occur even given shorting between several conductors within a multiconductor cable. This is a case-specific factor that must be confirmed and cannot be assumed.

select the most representative base case, and then apply the modifiers to estimate likelihood of the failure mode(s) of interest.

In this discussion, we presume that the analyst has by this stage identified the circuits where specific treatment of distinct failure modes is of potential risk importance. Hence, we assume the analyst has available information regarding the cables of interest, where in the plant the cables are located, how they are routed, the types of fire threats that the cables might see, and any salient features of the associated plant circuits. Further, we presume that the analyst has completed the FMECA for the circuits of interest and knows which cable failure modes require further consideration. At this point the analyst is seeking an estimate of the relative likelihood of certain specific failure modes for the identified application.

The analyst could then turn to a set of preselected base cases representing relatively simple cable configurations and applications. The base cases would reflect a range of the most critical influence factors and the most commonly encountered plant installation features. For example, one base case might be a single two-conductor control cable installed in a conduit. This might be used as the base case for other more complex configurations involving control cables in conduits. For each base case, a distribution for the likelihood of each potential failure mode of interest would be made available to use as a base distribution in a specific case analysis. These distributions would presumably derive either from actual test data or from the elicitation of an expert panel. Given the base cases, the analyst selects that case that is most similar to the specific application under analysis.

Once the base case is selected, the base case failure mode likelihood distribution would then be adjusted to reflect the influence factors that are characteristic of the specific application of concern. That is, the base distribution might be treated as a “prior” distribution and updated statistically, using a Bayesian approach. The influence factors impacting each base case would be some subset of the influence factors discussed in Section 2.5. Not all factors would apply, or be significant, to all base cases; hence, the list of influence factors for each base case might be narrowed substantially. In the example cited above, two-conductor control cable in conduit, the influence factors might include existence of a three-conductor rather than a two-conductor cable, or coexistence of more than one cable in the conduit of interest. For each factor, or potentially for a given combination of factors, a modifier on the base distribution would be applied. The result would be a case-specific probability distribution for the specific failure mode of interest.

This approach has several potential advantages. First, the approach would have clear advantages with regard to guiding future testing efforts. That is, one could design test programs specifically to provide data supporting clear characterization of one or more base cases and the associated influence factors. Further, the base case - influence factor concept would allow for multiple parties to independently address individual base cases and/or influence factors and yet provide data that would easily be fit into the overall analysis framework. This would allow for many smaller testing efforts to independently contribute to a broader refinement of the method.

Another advantage is that the overall problem, which is highly complex, is immediately divided into more manageable pieces. For example, an expert panel could be convened to (1) define the appropriate base cases, (2) identify the critical influence factors for each base case, (3) seek a consensus on the base case likelihood distributions, and (4) seek a consensus on the methods and values for addressing the influence factors in a given application. This recommendation was made in early drafts of this report, and as of the writing of this final version, EPRI had convened such a panel. A licensed material report has been published by EPRI documenting the results [36].

While it is recognized that data, in particular regarding the impact of the influence factors, is currently lacking, the approach has the advantage of establishing a basic framework which is readily adaptable given future developments and data. Base cases might ultimately be added, deleted, or adjusted as the knowledge base expands. Similarly, influence factors associated with a given base case might also be added, deleted, or adjusted. This would all, however, fit within the overall framework of base cases and influence factor approach.

5.3.2 Criteria for Selection of Base Cases

There are a number of criteria that might be used in selecting the base cases. These potentially include the following:

- Critically important influence factors: It may be appropriate to select the base cases so as to capture those influence factors either known or suspected to be critically important to failure mode likelihood. One example taken from the data review would be cables with shield/drain arrangements as distinct from general multiconductor cables. The data show that the conductor-to-conductor hot short probability for shield/drain arrangements is substantially lower than the same probability for a general multiconductor. Hence, base cases may be chosen to represent both groups. This has the distinct advantage of eliminating influence factors that would substantially change the likelihood distribution so that ultimately the base case adjustments required to address specific applications have only modest impact. This would likely reduce the final uncertainty.

- Common plant application features: The base cases should be chosen to represent a range of common plant applications without the need to apply numerous or extensive modifiers. For example, base cases may be appropriate for each of the unique types of raceway configurations that might be encountered including horizontal cable trays, vertical cable trays, air drops, and conduits.

- Circuit types: The base cases may also be selected in part based on the nature of the circuits of potential interest. In particular, separate base cases may be appropriate for power, control, and instrument circuits. Each circuit type may have unique failure mode concerns. For example, conductor-to-conductor shorts in a power cable may well have the same impact as a conductor-to-ground failure (e.g., tripping of the power source) so that distinguishing between these failure modes would not be important. In this case cable-to-cable failures may be the primary concerns. In contrast, for a control circuit, conductor-to-conductor failures may be of critical concern whereas cable-to-cable failures may be of little or no concern. A second example would be whether or not CPTs are used to power a control circuit. Recent industry tests [13] have shown this to be a critical factor impacting spurious actuation likelihood.

- Risk importance: Insights based on potential risk importance may also influence the selection of the base cases. For example, conductor-to-ground failures involving power circuits may be of relatively modest risk impact if, for example, the failure only results in tripping of a motor control center and does not propagate to a load center. This failure mode is, in effect, already treated using typical fire risk analysis methods, and may be recoverable if the source of the ground fault can be isolated. Hence, selection of a more limited set of power circuit base cases may be appropriate. In contrast, spurious operations due to control circuit faults may be of greater potential risk significance, so selection of a broader range of control circuit base cases may be appropriate.

5.3.3 Examples

This section provides a limited set of example base cases. This is intended only to illustrate the types of features that might be captured in the base cases. The examples are not intended to be exhaustive. In these examples we have focused on the cable type as the primary factor distinguishing between base cases, with routing and circuit information as secondary factors. This choice is somewhat arbitrary, but is consistent with the observation that there are substantial differences in behavior among various cable classes as discussed in Section 5.2 above.

Example 1: Unshielded, unarmored multiconductor cables:

In conduit: One base case might be a simple two-conductor control cable, without shield or drain or armor, installed by itself in a conduit. The primary modes of interest for this case would be conductor-to-conductor hot shorts versus conductor-to-ground where the ground is the conduit. This case could then be extrapolated through influence factors to potentially cover other actual applications including single cables with more than 2 conductors in a conduit, more than one single conductor cable in a conduit, and more than one multiconductor in a conduit. Influence factors would likely include circuit voltage, cable size, total conduit fill, total conductor count, various circuit design features, and potentially factors associated with the fire exposure (intensity, duration, etc.)

In horizontal trays: This case would be quite similar to the above case except that the cables are presumed to be in a cable tray. The differences between conduits and trays may be of sufficient significance so as to warrant treatment of the two as separate base cases. In particular, cable trays typically support the cables at discrete points (the tray rungs) rather than uniformly as in a conduit. In a horizontal tray, these points of support may represent points of substantial localized loading, and this may substantially impact the likelihood of, for example, cable-to-tray failures as compared to cable-to-conduit interactions. Other features and the influence factors would likely be similar to those cited for the previous base case.

Example 2: Cables with a shield and drain:

Grounded-shield/drain: A likely base in this group would be a simple two-conductor instrument/control cable with a grounded shield/drain arrangement installed in open air (such as an air drop). This base case might be extrapolated to cover most any cable with a grounded shield/drain arrangement in most any installation configuration. This is because the presence of the grounded shield/drain will severely limit the potential failure modes. In this arrangement only conductor-to-conductor within the shield wrap versus conductor-to-shield failures would be of interest. Cable-to-cable interactions independent of the grounded shield are highly unlikely. For this case a relatively small number of influence factors might still apply including cable size (wire gage), circuit voltage level, and the intensity/duration of the fire exposure. Many other influence factors might be dismissed potentially including those that only impact the behavior external to the shield wrap. This might, for example, include factors associated with raceway type and raceway loading.

Ungrounded shield/drain: A second base case within this group might be needed for applications involving cables where the shield/drain is not grounded. In this case, multiple shorts to the shield/drain may mimic a conductor-to-conductor hot short. Concerns related to shorting to other adjacent conductor pairs or even adjacent cables may also resurface. Hence, the desired probability distributions may be substantially different for this case as compared to the previous base case (grounded shield/drain). Ultimately, the same data sets would likely be used to generate base case likelihood distributions for both this base case and the previous base case. However, the fact that the potential modes of failure are substantially expanded may make this worthy of a separate base case designation. The influence factor list may also expand as compared to the previous base case because some behaviors external to the shield wrap may need to be addressed.

Example 3: Armored Cables:

Grounded armor: Similar to the cases involving shield wraps, armored cables are unique in that cable-to-cable interaction independent of the armor wrap are presumed to be highly unlikely. In the case where the armor is either explicitly grounded, or exposed and grounded by virtue of contact with the supporting raceway, the failure modes of interest are reduced to the question of conductor-to-conductor within the armor and conductor-to-armor. As in the case of grounded shield/drain arrangements, this will limit the number of influence factors that would need to be considered.

6 CONCLUSIONS AND RECOMMENDATIONS

Conclusions and recommendations have been developed in two areas. Section 6.1 discusses conclusions and recommendations associated with the estimation of cable failure mode likelihoods. That is, Section 6.1 deals with those aspects of the study related to the physical behavior of cables when exposed to a fire environment, and cable failure behavior. Section 6.2 covers conclusions and recommendations related to the overall process of circuit analysis and the incorporation of advanced circuit analysis methods into fire PRA.

6.1 Conclusions and Recommendation on Cable Failure Mode Likelihood

A number of conclusions regarding cable failure modes and mode likelihoods have been reached. These include insights arising from the data review, insights from the review of the 1975 Browns Ferry fire, and insights from a recent review of 25 major fire events throughout the world [29]. A considerable body of test data on fire-induced cable failures does exist and was reviewed as a part of this study. These data do provide both specific and general insights into cable failure behavior. Conclusions arising from this review include the following:

- The available data indicate clear distinctions in the relative likelihood of an initial failure mode involving conductor-to-conductor shorts dependent, at the very least, on cable type. Substantial (order of magnitude) case-to-case variations were confirmed by the data. Therefore, the use of any single hot short (or spurious actuation) probability (or distribution) for all cables under all conditions is not appropriate.

- Specific insights obtained from the experimental data regarding the likelihood of conductor-to-conductor shorts in general, and hot shorts in particular, include the following:

    - For general multiconductor cables without armor, shields, or drain wires, the test data demonstrate that the likelihood of an initial fault being a conductor-to-conductor short is relatively high. The available data taken together indicate a likelihood of on the order of 0.7 to 0.8 with various factors having a substantial influence on the value applicable to a given situation.

    - In multiconductor armored cables, there is a substantial likelihood that initial faults will involve conductor-to-armor shorts. Since the armor is likely to be grounded this would have the same effect as a conductor-to-ground fault. Hence, the relative likelihood of a conductor-to-ground fault appears higher for an armored cable than for a general non armored multiconductor cable. (The conductor-to-conductor short probability is correspondingly lower for armored cables.) The data are, however, too sparse to provide a significant estimate of the hot short probability for armored cables.

    - The data indicate that the hot short probability for multiconductor cables with shield and drain arrangements (i.e., conductor-to-conductor shorts that do not involve the shield/drain) is substantially lower than the corresponding value for cables that lack a shield/drain arrangement. For the one case tested (a two-conductor instrument or control cable with shield/drain) the conditional conductor-to-conductor short probability was estimated at 0.05 (as compared to 0.7 to 0.8 for general multiconductors as noted above).

  - The recently completed industry tests involving a surrogate MOV control circuit demonstrated a relatively high spurious actuation likelihood given cable damage. Depending on how the data are parsed, some test configurations experienced as high as 70% spurious actuations given cable failure. Other configurations showed considerably lower likelihoods, again emphasizing the complexity of the behavior. The spurious actuations were dominated by intra-cable hot shorts, but a few cases involving inter-cable hot shorts were also noted.

- The data on conductor-to-conductor shorts for multiconductor cables indicates that any number of conductors may be involved in the shorting behavior. That is, conductor-to-conductor shorts between conductor pairs are not the only potential concern. Rather, it was clear that conductors may short in individual pairs or in larger groups. For cables with larger conductor counts, conductors may also form multiple independent shorting groups. Hence, the circuit analysis must consider the possibility of conductor faults involving any number of conductors and different conductor combinations.

- The experimental data on the duration of conductor-to-conductor shorts in multiconductor cables indicates a wide range of potential hot short and spurious actuation durations. The data do show that given a severe and sustained fire exposure, all conductors will eventually short to ground. However, shorter or less intense exposure may lead to sustained hot shorts. Hot short and spurious actuation signals that were sustained for times ranging from momentary (i.e., less than one second) to about 15 minutes are reported, even under continuous fire exposure conditions. Because the behavior is dependent on fire intensity and/or duration, no single statistical estimate of the hot short duration can be made.

- The available data also indicate that loss of continuity conductor failures are highly unlikely as an initial failure mode. Indeed, such failures, even as a secondary failure mode, were only noted under two conditions as follows:

  - If the energy potential (voltage potential times maximum circuit fault current) of one or more cables involved in the shorting behavior is high enough, then loss of continuity failures may be observed due to high-energy discharges at the point of failure leading to melting or vaporizing of the conductor itself. The energy threshold associated with this behavior remains indeterminate.

  - In a limited number of tests involving prolonged and severe fire exposures, cables of low energy potential were found broken (had lost continuity) in post-test examinations. However, the loss of continuity condition was not detected because the associated conductors shorted to the raceway well before the loss of conductor integrity, and the raceway itself acted to “complete the circuit” even given the broken conductors. Hence, even in these cases, the initial fault mode was likely not loss of continuity.

- Post-test examination is not a reliable method for determining whether or not cable failure occurred during a fire test, let alone failure mode. Several test programs saw conductor failures during a fire exposure that "healed" (recovered some substantial insulation resistance) upon cool-down.

- Reviews of fire incidents revealed very few cases where the reports have focused on operational aspects of the fire incident in addition to the more traditional fire protection and fire fighting aspects of an incident. The 1975 Browns Ferry fire remains the one most notable example of a fire incident for which substantial operational impact data is provided. A review of the 1975 Browns Ferry fire did identify cases where it appears likely that sustained hot shorts and spurious operations were, in fact, experienced. However, definitive conclusions regarding specific cable failure modes and effects could not be made due to unresolved uncertainties.

- Factors that could influence the relative likelihood of different cable failure modes and the duration of hot shorts were identified and qualitatively assessed. In addition, the existing experimental data on cable behavior during fires was evaluated to identify evidence of the importance of each of these parameters. The data clearly illustrates the importance of some factors. These factors include the following:

    - presence of a drain/shield arrangement
    - number of conductors
    - armoring
    - air drops versus other routing configurations (i.e., conduits or trays)
    - circuit type or function, especially including voltage/current levels
    - routing in conduits versus cable trays
    - use of CPTs to power a control circuit
    - circuit to cable wiring configuration

- Several additional factors of potential importance have been identified for which little or no direct experimental evidence is currently available. These include the following:

    - cable size (wire gage)
    - cable tray type
    - raceway loading
    - raceway orientation (horizontal vs. vertical)
    - bundling of cables during routing
    - various fire exposure factors (e.g., intensity, heating mode, and duration)

- Many different test monitoring schemes have been used in an attempt to detect the onset of cable failure. Meaningful cable failure monitoring circuits, including high energy cable circuits, can be implemented safely during both large- and small-scale fire tests. However, many of the approaches reviewed were found to yield less than ideal data and insights. The recently completed industry/USNRC cooperative tests implemented two monitoring schemes, one based on a surrogate MOV circuit and one based on monitoring of insulation resistance (IR) for individual conductors.

The use of the two measurement schemes in tandem provided insights that would not have been gained otherwise.

Recommendations arising from these conclusions include the following:

- A framework for performing cable failure mode likelihood estimation using a predefined set of "base cases" and "influence factors" has been proposed. This analysis framework also provides a framework for identifying both general and specific data needs. That is, future test programs could be designed specifically to characterize one or more base cases, and/or to investigate one or more influence factors for a given base case or set of base cases. This would allow for many independent efforts to be undertaken and yet ensure that the data gathered would fit within an overall cable failure modeling framework. It is recommended that peer comments on this proposal be sought.

- It is recommended that fire researchers be encouraged to include in future testing programs specific provisions to monitor cable performance and to seek information on the modes of cable failure observed. It is further recommended that the USNRC support these efforts by providing opportunities to consult with USNRC and contractor experts in the design and planning of future test programs. Since this recommendation was made in early drafts of this report, EPRI has convened such a panel. As of the writing of this final report, the results of the EPRI panel were not yet public.

- Note that early drafts of this report recommended that an expert panel be convened to address both immediate and long term needs with regard to cable failure likelihood analysis. Much in the spirit of this recommendation, an expert panel was convened by EPRI to address short-term needs related to interpretation of the NEI and NRC cable failure modes test data [13,14]. A report documenting the results has been published by EPRI [36]. However, long term needs may be served in the future through additional expert elicitation. In particular, as additional test data and/or experience become available, use of an expert panel in the interpretation of the data may be appropriate.

- Future cable experiments should, at every opportunity, be carefully designed to provide information on cable integrity, and the onset and duration of different cable failure modes. Many different cable monitoring methods have been tried in the past, and it is recommended that in designing future test programs, the lessons learned from the past experiments be used as a guide to building better and more reliable failure mode detection protocol.

- The recently completed industry/USNRC cooperative cable fire tests have provided valuable data and insights directly relevant to the circuit analysis problem. Additional data analysis would likely yield additional insights, potentially including quantitative insights into failure mode likelihood, hot short duration, and potential combinatorial models for estimating the likelihood of specific conductor shorting combinations. It is recommended that additional analysis of this data set be undertaken.

6.2 Conclusions and Recommendations on Circuit Analysis and Fire PRA

The following identifies conclusions reached from the review of important circuit features and circuit analysis methods:

- A number of circuit design features have been identified that affect the potential for different circuit faults associated with fire-induced cable damage. Several of these circuit features are listed below.
    - One of the most important features is whether or not the circuit is grounded. This affects the potential for hot shorts between cables and the potential for low-impedance shorts to ground.
    - The existence of latching relays, or similar logic that locks in a command signal, can lead to sustained spurious component operation initiated by a momentary hot short. These spurious operations may not be mitigated even after the short is removed.
    - “Double breaks” in circuits introduced by open contacts at both ends of a circuit leg are an effective means of mitigating the spurious operation potential for some types of circuits. This approach, in effect, de-energizes cables that might normally be energized and/or isolates conductors that might otherwise cause spurious operation if shorted to an energized conductor.
    - Use of CPTs to power a control circuit was found to be an important factor in the likelihood of spurious actuation. Use of a CPT limits the total power available to support fault currents, and appears to substantially reduce the spurious actuation likelihood.
    - The presence of a ‘mitigating’ conductor within a multiconductor control cable (i.e., a conductor that would mitigate or prevent a spurious actuation if it became involved in the conductor-to-conductor shorting behavior) was found in the FMECA analyses to be an important circuit feature. It is recommended that additional investigation into the role of such conductors in spurious actuation likelihood be undertaken.
- A process for incorporating circuit analysis into a fire PRA has been suggested. This process includes the use of typical PRA screening techniques to identify risk-significant fire compartments and limit the number of circuits requiring analysis. It also includes the use of existing Appendix R circuit analysis supplemented by additional analyses, including the analysis of non-Appendix R equipment credited in the PRA.
- A quality Appendix R circuit analysis can be effectively used in a fire PRA. However, it is essential that the limitations of the Appendix R circuit analysis be understood and compensated for in the PRA. These limitations include:
    - Not all components credited in a fire PRA are Appendix R safe shutdown equipment. Thus, a large portion of the equipment modeled in the fire PRA may not have been subjected to

circuit analysis. Additional analysis of these circuits may be required to ensure their availability.

  - Appendix R analyses typically assume that a cable failure results in the worst possible component or system fault mode (dependant on the nature of the circuit and impacted system). In a determinist analysis this is conservative because the cable failure mode leading to this impact may not be the most likely. However, if the PRA model were to similarly consider only the worst case failure mode, coupling that failure mode to an estimate of failure mode likelihood may lead to underestimating the fire-induced risk. That is, the risk assessment should also consider the risk contributions associated with more likely, but perhaps less severe, cable failure modes.

  - Some Appendix R analyses have assumed that only one hot short occurs at a time (except for those components in high/low pressure interfaces). In reality, data and experience show that multiple concurrent hot shorts and spurious actuations may be induced by a fire in a relative short time. To realistically evaluate the risk from fires, the potential for multiple hot shorts should be addressed.

  - Appendix R analyses commonly assume that hot shorts exist until action has been taken to isolate the affected circuit from the fire area or other actions are taken to negate the effects of a spurious actuation. The experimental data indicates that conductors will eventually short to ground given a sustained fire exposure. Hence, the assumption of a sustained hot short with no time limit is conservative for many components that require continuous power (e.g., non-latching relays, contactors or solenoids) to maintain operation of the component.

  - Failure of a circuit breaker to open on demand (for example, due to an over-current condition generated by fire-induced cable failures) could lead to tripping of an upstream breaker and a loss of power to multiple components. This would not be captured by either a typical Appendix R analysis, or a breaker/fuse coordination analysis as these analyses assume that the breaker would function as designed to isolate the initial fault.

- One method for performing circuit analysis, Failure Modes and Effects Criticality Analysis (FMECA), was reviewed in this study as a means to supplement the circuit analysis performed in an Appendix R assessment. The FMECA analysis was found to provide information that can be used to advance both the circuit analysis and human factors portion of a fire PRA. The information obtained from this approach includes:

  - the possible component faults that can occur,
  - the number and nature of the cable failures either internal to the circuit or involving other circuits that might lead to or mitigate each component fault,
  - whether or not a given component fault is recoverable through operator actions (either remote or local),
  - indications of when a cable failure might lead to isolation of a power source including control or instrument power sources,

  - important timing information, and
  - whether or not indications of the fault would be available to the operator.

- The FMECAs performed for several nuclear industry component control circuits provided unique insights that may not have been identified using other circuit analysis techniques. An example of this is an identified MOV scenario where both directional control contact coils would be energized simultaneously leading to a phase-to-phase shorting fault on the 480 Vac power supply to the valve motor. This situation would cause the circuit breaker to open, making the valve inoperable.

- Potentially significant circuit issues that may need to be addressed in a fire PRA include those related to associated circuits for systems credited in the PRA. Associated circuits are those safety or non-safety related circuits whose failure could prevent operation or cause mal-operation of required mitigating systems or components. While associated circuit issues are generally addressed for Appendix R systems in the Appendix R analysis, for PRA, the scope of these assessments must be expanded to all systems credited in the PRA (i.e., to include credited non-Appendix R circuits). It may also be necessary to expand the analysis to include multiple concurrent hot shorts if such were not included in the Appendix R analysis.

The following are recommendations related to the incorporation of circuit analysis into a fire PRA:

- A process for incorporating circuit analysis into a fire PRA has been suggested. This process includes the use of existing Appendix R circuit analysis supplemented by additional analyses of non-Appendix R equipment credited in the PRA. It is recommended that a demonstration analysis be undertaken to more fully develop this process. (Note that since this recommendation was first made, the USNRC Office of Research has embarked on a cooperative effort to re-quantify fire risk at two U.S. nuclear power plants. The work is being conducted in cooperation with EPRI, and will fulfill the intent of this recommendation.)

- The use of FMECA to perform circuit analysis has been demonstrated in this study and found to provide useful information regarding control and instrumentation response during fires. It is recommended that the relevance of these types of insights be assessed as part of future developments in the area of human factors analysis methodology. (Note that the requantification studies cited immediately above will likely fulfill the intent of this recommendation.)

- Additional analysis of a spectrum of circuit designs is recommended in order to identify additional circuit design features that can influence the potential for fire-induced failures. The identification of important features may allow for additional screening of circuit faults in a fire PRA. This is recommended as a likely activity for industry to undertake.

- The FMECA process is time-consuming; hence, approaches are needed to appropriately focus and limit the extent of such analyses that must be performed to support a PRA. This can be addressed in part though appropriate screening methods. However, this can also be addressed over time through development of a “catalogue” of circuit analysis results. While there are significant plant-to-plant variations in circuit design, there is also substantial overlap. As more and more such analyses are performed it would be extremely useful to compile these analyses into a common catalogue for use by other risk analysts. (Note that the requantification studies cited immediately above will likely contribute to initiation of such efforts.)

- Additional investigation is needed to assess the merits of combinatorial models that purport to estimate the likelihood of hot shorts involving specific combinations of conductors within a multiconductor cable. The recently completed industry/USNRC cooperative cable tests have provided new data that may support additional development of these models. It is recommended that additional analysis of this data set be undertaken.

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APPENDIX A

SUMMARY OF CABLE FIRE TEST DATA RELEVANT TO FAILURE MODE LIKELIHOOD ESTIMATION

A.1 Overview

One of the key features of the improved fire PRA circuit analysis framework is explicit treatment of the unique system impact that results from various modes of cable failure. For example, depending on the nature of the circuit itself, a cable that shorts to ground may render the system unavailable while a conductor-to-conductor short within that same cable may cause a spurious component or system operation. These two system behaviors may have unique implications for a fire PRA. Each circuit is somewhat unique and the actual impact of any given fault mode must be determined on a case-specific basis using tools such as the failure modes and effects approach described in the body of this report. Ultimately, in order to treat these differences quantitatively, it is necessary that one be able to estimate the relative likelihood that, given a fire-induced cable failure, a particular mode of cable failure will be observed. The objective of this appendix is to document a review of currently available data on cable failures and an assessment of the relevance of the available information to the development of cable failure mode likelihood distributions.

The failure modes of interest are:

- Conductor-to-conductor short circuit: this failure mode involves formation of a short circuit between two (or more) conductors independent of any external ground. Such behavior may involve the conductors within a single multi-conductor cable (intra-cable shorting) or the conductors of two (or more) separate cables (inter-cable shorting). One special case of the conductor-to-conductor short circuit is the so-called hot short. A hot short involves conductor-to-conductor failures where one (or more) conductor is energized, one (or more) conductor becomes energized as a result of the failure, and none of the shorting conductors is grounded.

- Conductor to external ground short circuit: this is a short circuit between one (or more) energized conductors and an external ground plane. In this case several sources of the ground plane may be of interest. Hence, a further subdivision of these failures is necessary as follows:

  - Cable-to-raceway: this is a short circuit failure between one (or more) energized conductors and the supporting cable raceway. Typical raceways include cable trays and conduits.
  - Conductor-to-shield/drain: this is a unique failure mode associated with certain types of primarily instrument wires which include a shield wrap (typically a wire mesh or foil wrap) and/or drain wire (an un-insulated conductor) as a part of the cable construction. A typical configuration would involve conductor pairs that are shield wrapped with or without a drain wire.
  - Conductor-to-armor: this is a unique mode of short circuits to ground associated with armored cables. The armor is typically made of a metal mesh or a continuous spiral-wrapped metal sheath (similar to flexible conduit). This sheath is typically grounded. A conductor short circuiting to the armor is, in effect, short circuiting to an external ground.

  Note that a conductor-to-conductor short that involves a grounded conductor is a unique subset of the conductor-to-conductor failure mode. The circuit fault effects are identical, but in the mechanistic vier of cable failure behavior, these failures would be treated as on possible outcome of a conductor-to-conductor short circuit failure mode.

- Loss of conductor continuity or open circuit cable failure: this is a failure that results in the loss of conductor integrity, that is, breaking of the conductor. In general, this mode of failure is considered likely for prolonged fires, but unlikely as the initial mode of cable failure. As noted below, no test has ever observed a loss of conductor continuity failure as the first mode of cable failure.

The specific interest of this review is the identification and assessment of data that would shed light on the relative likelihood that a fire-induced cable failure would be manifested as any one of these various failure modes. Note that it is not the objective of this appendix to discuss the impact of a given failure mode on any given circuit. That is the role of the failure modes and effects analysis. The objective here is focused only on the behavior of cables under fire-induced heating. For example, this appendix will discuss data that illustrates the conditional probability that a cable might experience a hot short as the initial mode of failure under fire conditions. However, not all hot shorts will lead to a spurious actuation. Rather, certain combinations of conductors shorting together (possibly excluding other conductors) may be required while other combinations will have other impacts and may mitigate or prevent an actuation. Hence, except under very special conditions, it is inappropriate (albeit potentially conservative for many cases) to equate the nominal cable hot short probability to the spurious actuation probability for any circuit. The potential circuit functional impacts must be established through circuit analysis.

It is important to recognize that this review is searching for relative likelihood data regarding failure mode given a cable failure rather than data regarding the likelihood of cable failure given a fire. That is, the study presumes that a fire-induced cable failure has occurred (or is predicted), and the objective is to quantify the relative likelihood that the observed cable failure was manifested as a particular failure mode.

This appendix summarizes the cable failure data available from fire testing programs as reported over the past three decades specific to the topic of failure mode likelihood. A great deal of research on cable fires has been performed. The available reports and papers on the subject of cable fires easily number in the hundreds. When the focus is narrowed to discussions of fire-induced cable electrical failures, a literature review still identified approximately 40 reports and papers (totaling over 2000 pages of documentation). Even given the narrowed focus, much of the available data has little or no relevance to the current review. Of these 40 identified reports, 21 contained specific and unique information on cable failures observed either during small- or large-scale fire tests. The other 19 documents were found to contain high level discussions lacking in specific detail, or were subsidiary documents that presented information already available in the other 21 primary documents.[1]

Since the time of the aforementioned literature search, an additional series of cable fire tests have been conducted. These tests were sponsored by EPRI and NEI and conducted at Omega Point Laboratories in Elmendorf, Texas. Sandia personnel were invited to participate in these tests by the industry and the U.S. Nuclear Regulatory Commission. Sandia's participation involved making real-time insulation resistance measurements of the individual conductors within the multi-conductor cable bundles. The cables were exposed to fires under a large variety of conditions. In all, eighteen tests were performed in this test series. A report (yet to be published) documents the results and conclusions of cable failure mode detected by the insulation resistance measurement system.

The discussions that follow are intended to provide comprehensive coverage of unique cable failure data sets. This includes data that is, and is not, relevant to the current objectives. These discussions are presented in the form of an annotated bibliography of the 21 documents identified as containing unique cable failure data. Each report is identified, described generally, and then assessed for potential relevant information regarding cable failure modes.

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[1] The 19 subsidiary documents that are not explicitly reviewed here are identified at the end of this appendix.

From a statistical standpoint, information available on the relative likelihood of one failure mode versus another is sparse at best. There have been a very limited number of tests performed to specifically assess cable failure mode and likelihood questions. The paucity of specifically applicable data can be attributed to the general nature of the cable fire research undertaken to date. The research generally focused on one of two objectives:

- Cable flammability and fire propagation: This has been the primary objective of most of the large-scale fire tests performed to date, as well as many of the small-scale tests. This group includes tests that have examined the effects of extinguishing systems, protective coatings, cable insulation and jacketing material properties, exposure fire intensity, and/or fire barriers. In most such tests, there was no explicit monitoring of cable electrical performance (these cases will not be identified further in this review). In most of those cases where consideration of electrical performance was included, it was included only as a limited supplemental objective. In only a very few cases was cable electrical performance monitoring considered a primary test objective.

- Failure threshold testing: Several test programs have investigated the failure thresholds of electrical cables. These are typically small-scale simulation tests. That is, a simulated fire exposure is created using either radiant heating lamps or an air-oven. Cable samples are exposed to the simulated environment until failure is observed. The purpose of this type of testing is generally to determine failure thresholds, and the consideration of failure mode has been, at best, a secondary concern. The threshold is usually stated in terms of a critical heat flux or minimum threshold exposure temperature. In many cases, exposure temperature or heat flux versus time data is also available.

The discussions that follow cover all of the identified sources of either large- or small-scale cable fire test data that explicitly report unique information on cable failures.

A.2 Review of Data Sources

The two primary sources of fire-induced cable failure data are test programs sponsored by the Electric Power Research Institute (EPRI), and those sponsored by the USNRC. Data arising from these sources are discussed in Sections A.2.1 and A.2.2 respectively. Section A.2.3 discusses the other sources of experimental data including DOE sponsored tests, test performed by Electricité de France (EdF), and tests by cable manufacturers. For each section the available documents are presented and discussed in chronological order.

A.2.1 Industry-Sponsored Tests

This section describes the publically available information from test programs sponsored by the U.S. Nuclear Power industry including in particular EPRI and the Nuclear Energy Institute (NEI). This section discusses various tests sponsored by EPRI and performed by Factory Mutual Research Corporation (FMRC) during the late 1970's and early 1980's. A range of small- to large-scale tests were performed under these programs. In three of the test programs cable functionality was measured directly. The three primary test reports generated through these efforts are described below in chronological order. The final effort described is a very recent effort conducted by EPRI and NEI during 2001. This final effort is of particular note in that the tests were based on direct observation of the circuit faulting behavior of a surrogate Motor Operated Valve (MOV) circuit.

EPRI NP-1675: J. S. Newman and J. P. Hill, *Assessment of Exposure Fire Hazards to Cable Trays*, FMRC, January 1981.

This 1981 report describes a series of 42 large-scale fire tests. The objective of the tests was to assess the fire hazard to cable trays due to exposure fires (a fire source external to the cables themselves).

The first 37 tests (1-23 and EP001-EP014) involved no cable trays. These were scoping tests performed to assess the behavior of various liquid fuel pool exposure fire sources. In just one of these tests (EP014) individual lengths of cable were installed in the test enclosure and monitored for electrical integrity. No cable failures in this one test were detected. These tests provide no data of direct interest to the current study.

The last 5 tests (24-28) involved from one to four cable trays exposed to a pool fire source. Tests 24-26 were interrupted by sprinkler activation within less than two minutes of fire ignition. Tests 27 and 28 were free-burn tests with no suppression. In test 27, a “baffle” (apparently a solid barrier placed across the bottom of the tray) was used to protect the one exposed cable tray. Test 28 also involved a single tray but no baffles were used.

In each of the last five tests, one or more cables were monitored for electrical degradation. The configuration of the test circuit was described verbally but no schematic was provided. The electrical configuration can be inferred with confidence based on the verbal description, and is illustrated in Figure A-1. Note that the report’s description of a 10 VDC voltage divider circuit as the energizing circuit is rather clear. However, we have inferred that both the negative side of the circuit and the cable tray were grounded. This is based on the observation that in test 28 some of the conductors showed a definite trend towards leakage currents to ground. This is seen in that the voltage levels for some conductors were drawn down for some period of time below the lowest voltage of the divider circuit. This would imply that these conductors did have access to a local ground plane and in turn that both the circuit and tray were, in fact, grounded.

Ultimately, failures were only detected in one of the five cable tray tests (test 28). Some interesting insights can be gained by examining the response of the failed cable. In this test the instrumented cable was an IEEE-383 qualified, EPR/hypalon, 7-conductor, 9 AWG cable. For the test, a single continuous length of cable was looped repeatedly through the cable tray to form the total tray fill. Thus, the instrumented cable actually makes numerous passes through the fire zone. The response of this cable during the test is illustrated in the EPRI report in Figure 3-11 which is reproduced here as Figure A-2.

In interpreting this figure, it is important to note that conductor 7 was apparently connected directly to the positive side of the 10 VDC power source. Hence, drawing its voltage significantly below this value would be indicative of fault currents that exceed the capacity of the power supply. In this case, only a minor draw down of the source voltage is observed. Without detail regarding the voltage supply capacity, the significance of this draw-down cannot be assessed.

Note that there appear to be three distinct behaviors being displayed in degradation of this cable. The first notable behavior involves conductors 1, 2 and 7. Note that conductors 1 and 2 illustrate a clearly coupled behavior. This is seen in that both conductors are being drawn up in voltage, and by the fact that the voltage traces show a very similar pattern of behavior, particularly between 12 and 14 minutes (mirroring of peaks and dips). Further, it can be inferred that these two conductors are interacting with conductor 7 because both conductors 1 and 2 are drawn well above their base voltage, and conductor 2 is actually drawn above the voltage of conductor 6, which was energized with the second highest voltage potential in the circuit. From this behavior one can infer that conductors 1, 2 and 7 are shorting to each other, although the short circuit being formed retains some impedance. The impedance cannot, however, be inferred because the other resistance values in the circuit are unknown.

The second notable behavior involves conductors 3, 4 and 5. In this case, the three conductors appear to be shorting to each other, and are drawn down in voltage, presumably through interactions with ground. By about 12 minutes, all three of these conductors have been drawn down below the original potential of conductor 3. Because conductors 1 and 2 were drawn up in voltage well above this level, this clearly indicates some interaction with the ground plane.

The final unique behavior is seen in conductor 6. In this case, the conductor is initially drawn down in voltage indicating a likely interaction with the conductor 3-4-5 grouping and ground. However, it ultimately settles at an intermediate voltage. This may be indicative of interactions with both of the other two shorting groups described above.

Summary of Results: Cable electrical failure was detected in only one of the tests described in this report. In this test a 7-conductor, 9 AWG wire experienced interesting failure behaviors. The data appear to show that two groups of three conductors each formed interacting failures, and that one of these two groups was also interacting with the local ground plane. It would also appear that at least some of these failures were not dead-shorts because the various conductor voltages remained distinct. This test illustrates that failure behavior for multiconductor cables can be complex, and than not all conductors are likely to experience the exact same failure mode even within a single cable.

EPRI NP-1767: J. L. Lee, *A Study of Damageability of Electrical Cables in Simulated Fire Environments,* FMRC, March 1981.

This 1981 report describes an extensive series of small-scale cable damageability experiments performed by FMRC under EPRI sponsorship. A broad range of cables was evaluated. All tests were performed in the FMRC small-scale heat flux exposure facility. In each test, a single length of wire was extended through the exposure apparatus while resting on a grounded aluminum plate. Radiant heating lamps then exposed a short section of the cable (0.1 meters) to a pre-determined heat flux. The time to electrical shorting was then measured.

A DC power source was used to energize the cable conductors. The conductors were placed in a series circuit with a known resistor between one conductor and the next. The voltage applied was such that the drop from one conductor to the next in the circuit was 70 V. Hence, for a 7-conductor cable, the applied voltage for the first conductor in the circuit would be 490 VDC. A single voltage potential was measured to detect failures. The cable monitoring circuit is shown in Figure D-3, a reproduction of Figure 2-3 of the EPRI report. The arrangement nominally allowed for the independent detection of conductor-to-conductor and conductor-to-ground failures. Conductor-to-conductor shorts would be indicated by an increase in the measured voltage and a short-to-ground by a drop in the measured voltage.

Summary of Results: While this report contains substantial data on cable failures, it is ultimately of little or no interest to the current review. This is because only the time of failure, and not the mode of failure, is reported. There is some potential that if the data remains available at FMRC, some re-analysis may reveal additional insights. However, this is beyond the scope of the current review.

EPRI NP-1881: P. S. Sumitra, *Categorization of Cable Flammability: Intermediate-Scale Fire Tests of Cable Tray Installation,* FMRC, August 1982.

This 1982 report describes a series of "intermediate-scale" cable tests performed at FMRC facilities under EPRI sponsorship. In fact, the tests are what most facilities would refer to as "large-scale" tests because fires were set in stacks of actual cable trays loaded with cables. FMRC apparently distinguishes between "intermediate-scale" and "full-scale" tests, the former involving limited mock-ups of a partial installation and the latter involving full-scale mock-ups of complete installations.

The primary objective of the tests was to assess the fire growth behavior of the cables. The report does make reference to some assessments of cable functionality. While in most tests the information is limited to post-test examination of the cables, in two tests direct measurements of cable function were made.

In particular, in tests 10 and 11, five cable samples in each test were monitored for electrical performance. The circuit used appears to be similar to that used in prior FMRC tests and apparently involved a simple voltage divider circuit. The maximum voltage potential in the test appear to be about 0.6 volts. Based on the observed faulting behavior, it would appear that in this case the energizing circuit was un-grounded. This is because (1) in cases involving the conduits, the conduit was energized, (2) in cases involving armored cables, the armor was energized, and (3) in all of the observed failures the voltages tend towards the average voltage of the energized elements with no draw-down to zero voltage. Plots of the cable/conductor voltage are presented in Figures 3-8 and 3-9 of the report. Four functional failures were observed in these two tests.

In test 10, the failure of an armored, 3-conductor power cable was noted. This test is of particular interest because each conductor and the armor sheath were all energized at different voltage potentials. In this case there appears to be relatively uniform degradation of all three of the insulated conductors. The initial failure appears to be driven by interactions between conductor 1 and the armor. In this case, it would appear that a short-circuit formed more or less simultaneously between all three conductors and the armored sheath. It is also interesting that, after the fire went out, the cable insulation resistance recovered to near the original levels. That is, as the cables cooled off, the short-circuit damage healed. This has been observed in various test programs.

In Test 11 three of the five instrumented cables showed short-circuits. An armored 3-conductor power cable (apparently identical to that which failed in test 10) was observed to fail in test 11 as well. In this case, the failure is a fairly sharp and solid short-circuit between all three conductors and the armor sheath roughly simultaneously. No healing of the cable was observed in this case.

A second cable, a seven conductor cable in conduit, also failed. In this case, it would appear that all of the conductors short-circuited to each other in a sustained hot short. There was some indication of interactions with the conduit, but ultimately the hot-short was maintained independent of the conduit.

A third cable, a 3-conductor cable in conduit, also failed. In this case, the behavior is quite unusual. The initial failure occurred between two of the three cable conductors. Within approximately 1 additional minute, the third conductor appears to have shorted to the conduit while the hot-short between the other two conductors was maintained independently. It would then appear that the short circuit to the conduit was broken, and the three cable conductors formed an independent hard short. The conductor-to-conductor hot short was maintained for the remainder of the test, although the insulation resistance between the conductors and the conduit continued to recover. By the end of the test, the conduit had recovered to near its original voltage potential indicating substantial recovery of the cable-to-conduit insulation resistance.

Summary of Results: Four cable failures were observed in these tests. Two involved three conductor armored power cables, and two involved multiconductor cables inside conduits. The power cables appear to have formed nominally simultaneous short circuits between all three conductors and the armor sheath. In one case the observed damage healed upon cooling of the cables after the fire was out. For the other two cases, some unexpected behaviors were noted. In one case, the seven conductors of one cable formed a sustained hot short without shorting to the surrounding conduit. In the second case the initial failure was a short between two of three conductors. This was followed by a short between the third conductor and the conduit. This was in turn followed by a hard hot-short between all three of the cable conductors with the insulation resistance to the conduit recovering as the cables cooled.

EPRI/NEI Circuit Tests 2001:

A series of 18 room-scale cable fire tests was performed under the joint sponsorship of EPRI and NEI during 2001. The NEI/EPRI tests were explicitly designed to support resolution of USNRC concerns relating to fire-induced circuit fault analysis. The tests implemented a surrogate MOV circuit, passed the circuit control cable through the burn room, and monitored the circuit for faulting behavior. Cable failure would be manifested primarily by either opening protective fuses in the energizing legs of the circuit, or as a spurious actuation of the circuit.

Due to the importance of this particular test set to the current discussions, and due to the unique nature of the tests, an extended discussion of the NEI/EPRI tests is provided as Appendix D to this report.

A.2.2 USNRC-Sponsored Tests

A large number of cable fire tests were performed under the USNRC-sponsored fire protection research programs between 1975 and 1986. The tests were primarily performed at Sandia National Laboratories (SNL) facilities, although some tests were also performed at Underwriter's Laboratory (UL) facilities. Also included in this group is one risk analysis report generated out of the UCLA programs that describes information gathering efforts undertaken as a part of an early fire risk assessment methods development and application effort.

Most of the USNRC-sponsored test programs focused on issues of cable flammability and the benefits to be gained through various fire protection features such as barriers, coatings, use of low-flame-spread cables, spatial separation, and suppression. However, many of the test series did include substantial efforts to measure cable electrical performance during the exposures. The tests were predominately large-scale fire tests, but a number of small-scale investigations were also undertaken.

Note that in examining certain of the very early (1975-1981) tests, the authors have included information taken from unpublished documents in the SNL record archives. This includes unpublished "Quick-Look Reports" submitted by SNL to the USNRC following each of the early tests. Many, but not all, of these reports have survived in the SNL archives. Also considered were intermediate contractor reports provided by UL to SNL during tests performed under sub-contract to SNL.

SAND77-1424: Leo J. Klamerus, *A Preliminary Report on Fire Protection*, SNL, October 1977.

This report describes a single large-scale cable tray fire test performed by SNL under USNRC sponsorship. The objective of the tests was to assess the adequacy of the Regulatory Guide (RG) 1.75 cable tray separation criteria. The test involved 15 horizontal cable trays arranged in two stacks. Each tray was loaded with IEEE-383 qualified XPE/XPE cables. Two types of cables were used: a 3-conductor 12 AWG cable and a single-conductor 12 AWG cable. The test setup also had cables in several schedule 40 pipes (as a surrogate for conduit). Fire eventually involved the entire cable array.

Summary of Results: No circuit integrity tests were preformed during the actual fire test. Continuity and insulation resistance measurements were taken after the fire on cables in the various pipe sections, but only after the test was completed. Short circuits were detected in all conduits above the third level. These tests provide no data of direct interest to the current review.

SAND78-0518: Leo J. Klamerus, *A Preliminary Report on Fire Protection Research Program Fire Retardant Coatings Tests (December 7, 1977 - January 31, 1978)*, SNL, March 1978.

NUREG/CR-0366: Leo J. Klamerus, *Fire Protection Research Quarterly Progress Report (October - December 1977)*, SAND78-0477, SNL, August 1978.

NUREG/CR-0381: Leo J. Klamerus, *A Preliminary Report on Fire Protection Research Program Fire Barriers and Fire Retardant Coatings Tests*, SAND78-1456, SNL/USNRC, September 1978.

These three test reports are quite similar in nature and will be discussed as a single group. These reports represent a series of reports generated periodically as a part of the original USNRC Fire Protection Research Program. Each report document a specific set of cable fire experiments. The objective of the various tests was to assess the fire behavior of cables and the potential benefits of certain fire protection measures; namely, cable tray fire barriers (covers over the top and/or bottom of a tray) and fire retardant coatings.

The reports describe both large- and small-scale tests. In the small-scale tests, there was no monitoring of cable electrical integrity. In the large-scale tests, however, cable electrical function was monitored. Unfortunately, the configuration of the energizing and monitoring circuits is not discussed. The only information provided is a statement that "(e)lectrical resistance measurements of the cable and cable-to-ground were made before and after each test. Current measurements were made before and after each test and as recorded throughout each test." A search of the SNL archive records revealed no additional insights.

Summary of Results: The reports do list the times of electrical shorting observed in each test. However, it is not known what mode, or modes, of failure were monitored. There is no discussion of failure mode provided in any of these three reports. Hence, the data is not of interest to the current review.

NUREG/CR-0596: Leo J. Klamerus, *Preliminary Report on Fire Protection Research Program Fire Barriers and Suppression (September 15, 1978 Test)*, SAND78-2238, SNL, Dec. 1978.

This report describes a single test performed at UL facilities under sub-contract to SNL as a part of the USNRC-sponsored Fire Protection Research Program. The objective of the test was to assess the thermal performance of a refractory fiber based cable tray thermal wrap system.

The test involved five vertical cable trays, each carrying numerous lengths of cable. The cables were 3-conductor, copper, 12 AWG, polyethylene (PE) insulated and polyvinyl-chloride (PVC) jacketed (PE/PVC). The cables were not qualified per the IEEE-383 cable performance standard. Cables were bundled in groups of eight. Each bundle then made two passes through a given tray. That is, a bundle would be routed down from the top of the tray and secured to the tray rungs. At the bottom of the tray, the bundle would be double-backed upon itself and routed back up the tray (but not adjacent to the tray rungs). All terminations were made well above the tops of the trays. Seven such bundles were installed in each tray.

For circuit integrity monitoring all of the conductors in each tray were energized using a low-voltage power source (actual voltage is not specified). However, the various cables were all “ganged” together to form just three circuits in each tray. That is, the like-colored conductors for all of the cables in a given tray were ganged together to form a single circuit.

It is stated that the circuit was designed to allow for the determination of what the initial failure mode was; namely, either conductor-to-conductor or conductor-to-tray. While not discussed explicitly in this particular report, a review of the SNL archive records revealed that the circuit used for detecting cable failures was identical to that used in the later 20-Foot Separation Tests as reported in NUREG/CR-3192 (and discussed further below). Based on the review performed here, this circuit was indeed capable of determining whether the initial failure was conductor-to-conductor or conductor-to-tray.

Note that, by virtue of the test design, this test was inherently incapable of detecting cable-to-cable failures. Further, the first failure in any of the 56 cable segments in a given tray would be the only failure detected. Subsequent failures involving other cable segments within that same tray would not be detected independently. The circuit was nominally capable of detecting conductor-to-conductor to conductor-to-tray transitions, but not vise-versa. No failure transitions are, however, noted.

Conductor-to-conductor failure was detected and confirmed for one of the five trays (tray 3). The failure was noted at 3:13 (min:sec) into the burn and was confirmed during post-test examination. There was no subsequent transition to a tray (ground) failure noted, although the fire did burn for a total of 40 minutes. (The experimenters did expect to be able to detect this transition and would have likely noted the fact if the instrumentation had indicated such a transition.)

Post test examination revealed that the cables in tray 3 had been partially burned at the lowest extreme of the tray where the cable bundles folded back on themselves. The lower extremity of the trays was noted in other cases as the point of most severe cable damage, although no other cable trays experienced actual failures. It is reasonable to postulate that the tension created by the cable bend, coupled with the fact that the most severe effect occurred at this same location enhanced the likelihood that conductor-to-conductor failure would be observed.

Three of the four other cable trays did display some significant signs of “melted and charred” cable insulation during post-test inspection. However, no other cable failures were detected. A second tray (tray 1) experienced intermittent failure indications during the burn test. However, in post-test analysis no failures were detected. The report attributes the intermittent signals to contact between cable terminations well above the cable trays and concludes that they were not associated with any actual fire damage.

Summary of Results: This test indicates that one-of-one observed initial failures was a conductor-to-conductor failure within a multi-conductor cable. The failure was sustained, and was also confirmed after completion of the test. No transition of the failure to a ground or tray short circuit was noted despite some apparent substantial burning within the subject tray and a total fire duration of 40 minutes. In this case, the existence of a sharp bend in the cable bundle may have been an influencing factor. That is, the tension at the bend location may have enhanced the likelihood of a conductor-to-conductor failure. Indeed, cable loading conditions (radial bends, conduit bends, air-drop transition points) may be a factor in many situations that would likely influence the hot short or short to ground probabilities. Unfortunately very little data of this type is available.

NUREG/CR-0833: Leo J. Klamerus, *Fire Protection Program Corner Effects Tests*, SAND79‑0966, SNL, Dec. 1979.

This report describes a series of six fire tests involving two horizontal cable trays per test. The objective of the tests was to assess the impact of wall-ceiling corner proximity on the fire growth and damage behavior of cable trays. The primary measures of the proximity effect included measurements of heat flux, total mass loss, and time to electrical failure of the cables. These tests were performed at SNL facilities in Albuquerque, New Mexico.

All of the cables in the six tests were 3-conductor 12 AWG cables. Three tests involved unqualified PE/PVC cables and three tests involved qualified cross-linked polyethylene (XLPE) insulated and jacketed cables (XLPE/XLPE). For each tray in each test, a continuous length of cable was passed repeatedly through the tray for a total of 90 passes per tray.

The test report states that “measurements for short circuits and open circuits were made before, during, and after each test.” Indeed, while no open circuit failures were detected, the report does provide independent times for “cable to cable” and “cable to tray” failures noted during testing. It would appear, however, that “cable to cable” shorts as used in the original report would correspond to “conductor-to-conductor” failures as used in the current report. This is because each tray was loaded with, in effect, one single cable looped repeatedly through the tray. Hence, there was no potential for the detection of “cable to cable” failures as that term is used in the current report. In the discussions that follow, reports of a “cable to cable” failure in the original document are interpreted here as conductor-to-conductor failures.

The exact configuration of the cable integrity test circuit was not described in the test report. Sample plots of the “tray current” and “tray to ground” voltage recording plots are provided in the original report for just one cable/tray. A review of SNL archived information provided no additional insights. Discussions with two of the technicians involved in the original tests (D. Lambert and P. Walkington) did not reveal any additional information on the test circuit configuration.

Summary of Results: The results, as stated in the report, indicate failures in all of the tested cable trays. For the 6 qualified cables tested (2 cables in each of three tests), the initial failure mode reported was shorts to the tray in all cases. In 5 of the 6 cases, subsequent conductor-to-conductor shorts are also reported as occurring 1 to 8 minutes after the initial ground failures. Of the 6 unqualified cables tested, 4 report an initial cable-to-tray failure followed one minute later by a conductor-to-conductor failure. The remaining two samples report simultaneous occurrence of both conductor-to-conductor and cable-to-tray failures. The installation of the cables as a single length of cable looped repeatedly through the fire zone likely influenced the mode of failure. In particular, each monitored cable makes numerous passes through the fire zone in direct contact with the rungs of the cable tray. This arrangement may have enhanced the likelihood of shorts to the tray.

NUREG/CR-2258: M. Kazarians, G. Apostolakis, *Fire Risk Analysis for Nuclear Power Plants*, UCLA‑ENG‑8102, UCLA, Sept. 1981.

This report was published by UCLA as a part of USNRC-sponsored fire risk methods development efforts. While no actual experiments were performed, the report does cite that test results from several sources were used to estimate the conditional probability of a hot-short given a cable failure. The study cites an upper bound estimate of 0.1 and a mean probability of 0.068. This distribution was explicitly intended to include conductor-to-conductor hot shorts in a multi-conductor cable. The distribution was subjective in nature based on discussion with the reports primary author (M. Kazarians). The cited distribution is based primarily on a subjective assessment of the behaviors reported from the 1975 Browns Ferry fire and on very limited test data.

Of potential interest to the current review, the report cites three sources of data used in the development of the hot-short probability distribution. Two of these three citations are readily available journal articles, and are reviewed in Section A.4 below (Bhatia and McIlveen). The third source is a 1969 report from Boston Insulated Wire, and we have been unable to obtain access to this reference (as of this writing, efforts to obtain this document continue). A review of the two other cited references reveals little useful information. In particular, neither reference provides any indication of the mode of cable failure that was observed during testing, but they do cite that in many tests short circuits did occur. In some of these tests, some additional insights might be gained if the original data were made available, but this appears unlikely given the vintage of the papers.

<u>Summary of Results:</u> This report cites three cable failure data sources. Two of the three sources are journal articles and are reviewed in Section A.2.3 below. The third source is a BIW test report that is not currently available for review. Neither of the two journal articles provides specific information regarding the relative likelihood of any given failure mode. The two articles that have been reviewed do not appear to provide direct support for the hot-short probability distribution cited in NUREG/CR‑2258.

<u>NUREG/CR-2927</u> L. L. Lukens, *Nuclear Power Plant Electrical Cable Damageability Experiments*, SAND82-0236, SNL, Oct. 1982.

This report describes two distinct series of cable damage tests. One series involved the testing of cables in an air-oven chamber, and the second involved the exposure of cables in a cable tray to radiant heating. In both cases, the explicit objective of the tests was to assess cable electrical performance behavior. Two types of cable were tested; one a PE/PVC unqualified cable and the second a Exane/Exane IEEE-383 qualified cable. The results of these tests are ultimately of little or no applicability with regard to failure mode likelihood estimation.

First, consider the air-oven tests. In these tests cables were “cooked” in an air oven at a set temperature for a pre-determined time period. While in the oven, the cables were subjected to a number of different load configurations including simulated air drops, and cables wrapped on a mandrel. Pre-test measurements of insulation resistance were made, and the cables were then inserted in the oven. After the prescribed exposure time, the cables were removed from the oven and allowed to cool. Post-test insulation resistance measurements were then made. There was no performance monitoring during the actual thermal exposures.

By design, these tests were only capable of detecting the existence of a sustained post-test conductor-to-conductor short (after cooling of the cables). There was no opportunity for the detection of either cable-to-cable or cable-to-tray failures. Hence, these tests provide some information regarding cable failure thresholds, but no information on the relative likelihood of one failure mode versus another.

In the case of the radiant heating tests, cable electrical performance was nominally monitored during the actual exposures. In each test, the cables were energized to 320 volts DC and 5 amps AC. The AC and DC currents were then measured independently during the tests. The AC current was, apparently, intended to detect an open circuit failure (which would drive the AC current to zero) while the DC current was intended to detect cable-to-tray failures (which would result in a non-zero DC fault current).

By design it would appear that these tests were inherently incapable of detecting either conductor-to-conductor or cable-to-cable failures. Many failures were detected, all involving cable-to-tray failures. No open circuit failures were detected.

Results Summary: The air-oven tests provide no data whatsoever regarding the relative likelihood of a given failure mode. In the radiant heat tests, cable-to-tray failures were detected in most of the experiments. However, the predominance of cable-to-tray failures is not meaningful with regard to the relative likelihood of a given failure mode because that is essentially the only failure mode that was sought. At most the tests illustrate that open circuit failures for this configuration are highly unlikely.

NUREG/CR-3192: D. D. Cline, W. A. von Riesemann, J. M. Chavez, *Investigation of Twenty-Foot Separation Distance as a Fire Protection Method as Specified in 10CFR50, Appendix R*, SAND83-0306, SNL, Oct. 1983.

This report describes a series of ten large-scale room/enclosure fire tests executed at UL facilities in Northbrook Illinois. Four "experiments" and six "tests" where performed (we will refer to all ten fires as tests, and will call out E1-4 and T1-6 to distinguish between the "experiments" and the "tests"). Each of the ten tests did include cables as thermal damage targets. In T1-6, cables were also included as a part of the fire source. In all cases, the target cables were separated from the fire source by 6.1 m (20-feet) per the then new 10CFR50 Appendix R regulations.

The primary objective of this study was to assess the adequacy of the "20-foot separation criterion" set forth in Appendix R as one means of protecting redundant cables from damage due to fire. Hence, assessing the electrical performance of the target cables was a critical aspect of the program.

Each test involved two horizontal target trays located in a vertical stack above the door of the enclosure. The test configuration for the each of two target cable trays involved one single continuous cable looped continuously (back and forth) through each tray. For each tray, 43 passes of the target cable were installed. Both IEEE-383 qualified and unqualified specimens were tested. All of the target cables were 3-conductor 12 AWG cables.

The differences from test-to-test involve the use of either qualified or unqualified cables, the size of the room, the size of the doorway into the room, and for some tests the use of passive fire protection features including fire-retardant coatings and tray covers.

The two circuits used to assess cable functionality are illustrated in Figure A-4. The circuit used to monitor the upper tray in each test (shown as the upper circuit in the figure) was basically designed so that a series of light-emitting diodes (LEDs) would illuminate if any failures occurred. By noting which diodes lit, the mode of initial failure could be determined. It should be noted that the diode system was likely capable of accurately identifying the initial failure mode as either conductor-to-conductor within the multiconductor cable, or conductor-to-tray. However, the circuit would not be capable of detecting any of the following failure modes:

- A conductor-to-conductor failure following a conductor-to-tray failure: In this case, the conductor to tray failure would dominate the circuit and a subsequent conductor-to-conductor failure may not be indicated. Hence, reports of conductor-to-conductor failures after the onset of a conductor-to-tray failure are considered unreliable.
- Cable-to-cable failures: These failures were not detectable given the configuration of the installed target cables. In effect, the target cable in each tray was one continuous cable. Hence,

a cable-to-cable failure would either lead to no indication of failure (if one of the three conductors shorted to itself at a crossing-point) or the same indication that would result from a conductor-to-conductor failure.

- Conductor-to-tray following a conductor-to-conductor failure: In this case, the circuit may have provided indication of a conductor-to-conductor to conductor-to-tray failure transition, but only if the conductor-to-tray failure was a true, zero-resistance, dead short. In this event, the "B" LED should go out, while the "A" LEDs would remain lit. However, if there were even a very small residual resistance in the conductor-to-tray short, then the "B" LEDs would have likely remained lit. Hence, the likelihood that this mode transition would have been detected is considered very low.

The circuit used to monitor the lower tray in each test is shown as the lower circuit in the figure. This circuit is quite different from that used to monitor the upper tray, and the results must be viewed carefully. Note that in this case, each conductor is subjected to an imposed current flow. Two conductors are subjected to an outflow current, and the third conductor (shown in the upper right of the figure) is used to carry the combined return current. It is stated in the report that this third (return) conductor was grounded. Hence, when the report cites a conductor-to-ground failure in the lower tray, what this means is ambiguous. Lower tray failures as reported in NUREG/CR-3192 should be interpreted as follows:

- A reported conductor-to-ground or conductor-to-tray failure represents two failure modes; namely, one of the energized (outflow) conductors shorting to the tray, or one of the energized (outflow) conductors shorting to the grounded (return) conductor. In either case, the failure is indicated by the light for the energized conductor going out. No distinction between which of these two failure modes was actually observed can be made.

- A reported conductor-to-conductor short indicates that a short occurred between the two energized (outflow) conductors. This would have been indicated by both of the installed ampmeters reading identical current values rather than the original different values and the indicating lights remaining illuminated.

Ultimately, cable failures were observed in 2 of the 4 "experiments" and in 4 of the 6 "tests." These failures are summarized as follows:

For the Upper Trays:
- In Test 1 (unqualified cable) a conductor-to-tray failure was detected at 244s
- In Test 2 (qualified cable) a conductor-to-tray failure was detected at 775s
- In Test 5 (unqualified cable) a conductor-to-conductor failure was detected at 642s

For the Lower Trays:
- In Experiment 2 (unqualified cable) a conductor-to-ground failure was detected at 614s
- In Experiment 4 (unqualified cable) a conductor-to-ground failure was detected at 735s
- In Test 1 (unqualified cable) a conductor-to-ground failure was detected at 262s
- In Test 3 (unqualified cable) a conductor-to-conductor failure was detected at 1043s
- In Test 5 (unqualified cable) a conductor-to-conductor failure was detected at 775s

Summary of Results: In all, eight independent failures were detected in this test series. For the upper tray circuit, two of the three failures were conductor-to-tray, and one of three was conductor-to-conductor. For the lower tray, three of five failures were conductor-to-ground and two of five failures were conductor-to-conductor. Recall that conductor-to-ground failures in the lower tray may be either shorts to the grounded conductor or shorts to the tray.

NUREG/CR-5384: S. P. Nowlen, *A Summary of Nuclear Power Plant Fire Safety Research at Sandia National Laboratories, 1975-1987*, USNRC, Dec. 1989.

In addition to a broader summary of the USNRC-sponsored fire protection research program, this report documents the results of a series of cable damage tests conducted in 1983/84 (see Section 6.2.4 of the cited report).[2] These tests were intended as an abbreviated series of cable thermal damage scoping tests in preparation for the anticipated transient cable damage tests (see discussion of NUREG/CR-4638). The same two types of cable that had been used in the 20-foot separation tests (NUREG/CR-3192) were used in these tests as well; namely, an unqualified PE/PVC and a qualified XLPE/XPLE, were tested. All samples were 3-conductor 12 AWG.

There were a total of 29 tests performed. Each test involved exposure of three cable samples in a small convection oven. The samples were placed on a short section of steel cable tray and instrumented. The cables were in direct contact with the cable tray rungs. The convection oven was pre-heated to the desired temperature, and the cable tray and cables were then inserted. The time to electrical failure was then noted.

There is very little discussion of the cable energizing circuits and only a very coarse conceptual schematic wiring diagram is presented. The original letter report cites that two of the three cables in each test were energized using a 320 VDC power source with an impressed base current flow. For these cables the current flow to the cable was monitored. The third cable was connected to a HP 4329A Insulation Resistance Meter run at 500 VDC. It is unclear from these discussions whether or not cable-to-tray failures were monitored. Conductor-to-conductor shorting was monitored.

Summary of Results: The tests described in this report do provide some unique time/temperature failure threshold data. However, no discussion of the cable failure mode is provided. It would appear that the tests did consider conductor-to-conductor shorting. It is not clear what failure modes were monitored for or detected.

NUREG/CR-4638/V.1 of 2: W. T. Wheelis, *Transient Fire Environment Damageability Test Results: Phase I*, SAND86-0839, SNL, September 1986.[3]

This report documents a series of 1986 tests designed to reproduce the cable failures observed in the earlier 20-Foot Separation Tests. In particular, the tests focus on the question of whether or not fire suppression activities might have prevented the observed failures.

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[2] The original documentation of these tests was the following unpublished letter report: J. M. Chavez, *Quick Look Test Report: Steady State Environment Cable Damage Testing*, SNL, July 14, 1984; a letter report submitted to the USNRC under cover from J. M. Chavez of SNL to Dr. Amar Datta, USNRC/RES/EEB/DET, July 16, 1984. The discussion presented here includes consideration of the unpublished letter report in addition to the NUREG/CR document cited.

[3] Note that while this report is cited as Volume 1 of 2, there is in reality no corresponding Volume 2. The work intended for the second phase testing was never performed.

One feature of the 20-foot separation tests was the placement of several fusible link sprinkler heads along the ceiling of the test enclosure. These heads were instrumented to determine the time of activation, but were not charged with water. Hence, even though the sprinklers did fuse during the tests, no water was discharged to suppress the fires.

The objective of this particular study was to determine whether or not sprinkler activation would have prevented cable failures. Hence, the test program was designed to follow the measured temperature profiles from the original tests, but to then interrupt the profile at the observed time of sprinkler head activation. A special air oven test chamber was constructed for this purpose.

A total of 13 tests were performed. Two types of cable were tested consistent with the original 20-ft Separation Test Program. One cable was an IEEE-383 qualified XLPE/XLPE cable and one was an unqualified PE/PVC cable. Both cables were 3-conductor 12 AWG.

The cables were monitored for conductor-to-conductor and conductor-to-tray shorts by connecting each conductor to one phase of a 3-phase 208 VAC power supply. This resulted in each conductor being energized at 208 VAC conductor-to-conductor and 120 VAC conductor-to-ground. The tray was grounded. Ballast (or load) resistors were placed on each phase of the power source to limit fault currents. The cable monitoring circuit is illustrated in Figure A-5.[4]

This connection scheme theoretically allowed for the determination of specific conductor-to-conductor short combinations by virtue of the phase differences. If two conductors shorted to each other, the measured conductor-to-ground voltage for both conductors would simultaneously drop to the average of the two phases (e.g., ~60 VAC). If one conductor shorted to the grounded tray, the conductor-to-ground voltage on that one conductor would drop to zero while the others would remain at elevated voltage. If all three conductors shorted together, the conductor-to-ground voltage on all three conductors simultaneously drops to the same level, and if the short circuit formed is of low impedance, then the recorded voltage would be zero.

While in theory this allowed for determination of conductor-to-conductor versus conductor-to-tray failures, several test features interfered with the measurements. These include the following:

- There are two failure modes that would be impossible to distinguish one from the other given this arrangement. That is, a simultaneous low-impedance short between all three conductors would yield the same indication as a simultaneous short of all three conductors to the grounded tray. However, provided that the conductors fail in some discrete order, the nature of both initial and subsequent failure modes should be discernible.

- In the first two tests (Tests A and B) the cable failures were attributed to “end effects.” That is, the cables terminated inside the air oven, and failures were attributed to shrinkage of the insulation away from the cable end which exposed the conductors. This renders the results of these two tests of little or no interest to the current study.

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[4] This figure was not presented in the original report, but is based on discussions with one of the supporting investigators responsible for instrument design, B. Spletzer of SNL.

- In some experiments failures were attributed to shorting to thermocouples inserted under the jackets of the energized cables. These thermocouples were used in Tests A, B, and 1-6. Tests 7-11 used no such thermocouples. This topic is discussed further below.

- In tests 7-11 the energized cables were thermally and electrically isolated from the tray. Hence, there was little or no possibility for conductor-to-tray failures to occur.

The issues related to insertion of thermocouples under the cable jacket raise a number of troubling questions with regard to the reliability of this particular data set. The thermocouples used were very small and metal sheathed. As noted above, they were used in 8 of the 19 tests performed, including four of the six tests where failures were observed. Two specific issues associated with these thermocouples are summarized as follows:

- First, the presence of the thermocouples introduced into the heart of the cable a ground plane that would not normally be present (since the thermocouple sheaths were grounded). This would substantially increase the likelihood of a short to external ground. A short between any conductor and a thermocouple sheath would mimic a short to ground. At least some cases of this were observed. Two such cases were detected by correlating extreme excursions of the thermocouple readings to the observed failures. However, it is not clear that all cases of this behavior would be detected by this approach. Other data seems to mirror the thermocouple faulting behavior and yet are not listed as thermocouple-induced failures.

- Second, the report notes that the thermocouples themselves might have impacted the heating of the cables. In some tests a secondary non-metallic insulating sheath was placed over the metal thermocouple sheath from the point that the lead emerged from the cable jacket and extending out of the exposure chamber. This reduced the potential rate of heat transfer via the thermocouple sheath. Measured temperatures using the insulated thermocouples were as much as 50°F lower than those taken with un-insulated thermocouples. This is a clear indication that the thermocouples themselves acted as a conduit for heat transfer into the cables. This may have distorted the temperature response of the cables, in particular near the thermocouples. This would increase the likelihood of cable failures at the location of the thermocouple, and indeed, increase the likelihood of failures to the thermocouples.

The observed failures are summarized as follows:

- Tests A and B: For these two tests, the cable failures were attributed to “end effects.” This renders the results of no interest to this program.

- Tests 1 and 3: Each of these two tests had two energized cable samples. The initial failures in one cable in each test were specifically attributed to shorting to thermocouples. However, the second cable in each of these two tests illustrated virtually identical failure behavior to that presented for the two conductors known to have shorted to the thermocouples. Further, all of the initial failures occur at very similar times during each test (between 245 and 294 seconds). Secondary failures on these cables were not observed until 2-5 minutes later in the test. This is considered strong evidence that all four of the cables in tests 1 and 3 may have experience premature ground failures as a result of interactions with the thermocouples. Hence, the data are considered unreliable.

- Test 7 and 9: As noted above, the cables in these tests were thermally and electrically isolated from the cable tray. Hence, there was essentially no potential for failures to ground to occur in these tests and only conductor-to-conductor failures were anticipated. Indeed, the failures that did occur (in tests 7 and 9) were conductor-to-conductor failures.

Summary of Results: Cable failures were observed in 6 of the 13 tests described in this report. However, none is considered to provide a reliable indication of the relative likelihood of conductor-to-conductor versus conductor-to-tray failures. In two tests (A and B) cable failures were attributed to cable "end effects" rather than breakdown of the cable insulation. In two additional tests (1 and 3) it would appear that the placement of thermocouples under the jackets of the instrumented cables compromised the integrity of the tests. In the final two tests (7 and 9) the energized cables were thermally and electrically isolated from the cable tray so there was virtually no potential for a short to the tray or other external ground to occur. Hence, these tests provide little or no useful information on the relative likelihood of one failure mode as compared to another.

NUREG/CR-5546: S. P. Nowlen, *An Investigation of the Effects of Thermal Aging on the Fire Damageability of Electric Cables,* SAND90-0696, SNL, May, 1991.

The tests described in this report were specifically designed to investigate the impact of cable aging on cable failure thresholds. An important conclusion of the report is that thermal aging didn't result in significantly increased vulnerability to failure. Some differences in the degradation behavior for, in particular, one of the two cables tested were noted, but is it not clear if this observation has any implications for failure mode likelihood.

Two types of qualified cable were tested: a 3-conductor 12 AWG Rockbestos light power cable and a 2-conductor 16 AWG, with shield and drain, Boston Insulated Wire (BIW) instrumentation cable. Exposures were conducted in an air-oven facility at SNL. Virtually all of the tests were conducted for a time period sufficient to result in cable failure.

The cables were energized during testing using a three-phase 208V power source (120V phase-to-ground potential). Each conductor was connected to one phase of the power source, and was open-circuited at the opposite end. For the BIW cable, the drain wire was also energized as if it were a third conductor. Leakage currents on each phase/conductor were then monitored over time. This monitoring circuit is illustrated in Figure A-6.

The results of these tests are of limited interest to the current study for one significant reason. That is, only single cable lengths were tested, and the cables were thermally and electrically isolated from the supporting tray structure during tests. This eliminated the potential for either cable-to-cable or conductor-to-tray failures.

There is, however, some interesting information available by comparison of the two cable types, one to the other. The Rockbestos cable was a simple 3-conductor cable while the BIW cable was a 2-conductor with shield and drain. In this case, the shield was a foil wrap over the two conductors and the drain was a 16 AWG bare conductor that ran the full length of the cable contiguous with both of the two conductors. This configuration is illustrated in Figure A-7.

In the tests, the leakage current for each conductor was monitored versus time. For the BIW cable this included the leakage current for the drain wire. (Note that in the data plots, the drain wire for the BIW cable is consistently plotted as the solid line on each graph.) There are clear differences in the performance of the samples:

- For the Rockbestos cable, the three individual conductors display “lock-step” leakage behavior throughout the period of initial degradation. Ultimately, one or two or all three conductors would fail tripping the circuit, but up until that time, the three conductors display virtually identical leakage current behavior in each of the tests performed. This is true for both the unaged and aged samples. This illustrates relatively uniform degradation and relatively uniform distribution of the fault currents from one conductor to the others.

- For the unaged BIW cable, the behavior is quite similar to that observed for the Rockbestos cable. The one significant difference is that the BIW cable showed less early degradation over time and a more sudden transition to full short-circuit.

- For the aged BIW cable, early degradation behavior is more pronounced than that of the unaged BIW samples. Further, the drain wire shows a pronounced tendency to experience the highest leakage currents of the three energized conductors . In most cases the drain wire current is nearly twice that of the individual insulated conductors. This tends to indicate that for the aged samples there was a pronounced tendency for the insulated conductors to leak current to the shield and drain conductor rather than to each other.

- For both the aged and unaged BIW cables each incidence of initial failure was generally associated with the drain conductor. That is, in only two cases out of 40 observed failures was there an initial short between the two insulated conductors that excluded the drain conductor.

Summary of Results: In general, the data from these tests is of limited interest to the current study. This is because the only mode of cable failure monitored was conductor-to-conductor failures. The rather interesting behavior of the BIW samples illustrates the potential importance of shield and drain arrangements in the failure behavior. As noted above, in only two cases out of 40 observed failures for this particular cable was there an initial short between the two insulated conductors observed that excluded shorting to the shield/drain wire as well. This would tend to indicate that for this configuration at least, conductor-to-conductor failures that would exclude the drain conductor are of low probability (nominally on the order of 0.05 per failure).

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

This conference paper postulates that cable thermal damage information gathered in Equipment Qualification (EQ) testing can be used to estimate cable fire-induced thermal damage thresholds. The paper compares the results of air-oven tests performed for the USNRC fire protection research program (see discussion of NUREG/CR-5546 above) to results for the same cables when tested under loss of coolant accident (LOCA) conditions (results documented in NUREG/CR-5655). The results compare quite favorably.

The paper proposes that the environment created by superheated steam in a LOCA test is similar in nature to the hot dry environments typically encountered in fire tests. Hence, correspondence between the test results is not surprising. This nominally opens up to fire risk analysts a very wide range of data on many types of cable including both specific cable products and general classes of cables. This is because far more cables have been subjected to LOCA testing than have undergone fire environment damage testing. Unfortunately for the current study, the results are limited to information on cable failure thresholds. This is because of the manner in which cable EQ tests are performed.

In a typical cable EQ test, the insulation resistance to ground of each insulated conductor is periodically measured during both the aging process and the LOCA exposure. However, in making this measurement all of the other conductors in the test chamber are grounded so as to create a solid and stable ground plane against which to make the measurements. That is, only the conductor being measured is energized while all other conductors are grounded. This makes it impossible to distinguish between conductor-to-conductor, conductor-to-raceway, and cable-to-cable leakage; hence, failure mode information is not available.

<u>Summary of Results:</u> This paper proposes that the available data on fire-induced cable damage thresholds can be expanded substantially by relying on data from LOCA tests as an indication of the expected performance in a fire environment. Unfortunately, the EQ/LOCA test data does not provide information relevant to failure mode likelihood analysis because of the manner in which those tests are performed. Note that a range of EQ/LOCA test reports were reviewed to confirm this finding.

<u>SAND94-0146:</u> S. P. Nowlen and S. Ross, *An Evaluation of the Fire Barrier System Thermo-Lag 330-1*, SNL, Sept. 1994.

This report describes a set of three ASTM E-119 fire endurance tests and one ampacity derating test performed by SNL under USNRC sponsorship. The tests were performed to assess the performance of cable tray fire barriers constructed from the fire barrier material Thermo-Lag 330 (a trademark product of Thermal Science Inc.). The ampacity derating test is of no interest to the current study. However, during each of the three fire endurance tests the function of four segments of cable was monitored.

The cable functionality circuits were designed specifically to duplicate manufacturer performed qualification tests.[5] Four separate monitoring circuits were used, one for each instrumented cable segment. The four circuits were each designed to measure one given mode of cable failure; namely, "circuit-to-system" integrity (open circuit failures), "circuit-to-ground" (conductor-to-ground) failures, and two circuits monitoring "circuit-to-circuit" (conductor-to-conductor) failures. The tests involved low-voltage (28 VDC) power sources and simple indicating lights that would either light or extinguish upon a detected failure. In the SNL tests an additional voltage monitoring circuit was installed across the indicating lamps to provide a digitally recorded record of any failures that might occur. However, the detection circuits were largely of a "pass/fail" design. The circuits used are illustrated in Figure A-8.

<u>Summary of Results:</u> In each of the three fire endurance tests, failures in three of the four monitored cables were detected.[6] In each of the two circuits designed to detect conductor-to-conductor failures such failures were detected. In the one circuit designed to detect conductor-to-ground failures, a short to ground was detected. Unfortunately the data provides no indication of the relative likelihood of one

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[5] Note that the original manufacturer tests reported no cable/circuit failures so there is no data in these manufacturer tests of potential interest to this review.

[6] The fourth circuit, the one designed to monitor for open circuits, was not expected to detect failures because it was anticipated that ground failures would precede any open circuit faults. No faults were detected on this circuit, but in post test examination some broken conductors were found.

failure mode versus another because each circuit was designed specifically to detect one and only one mode of cable failure. Comparison of failure times for different circuits is also not useful because each monitored cable was of a different size and each was located in a different position within the tray.

NUREG/CR-6776: F. J. Wyant, S. P. Nowlen, *Cable Insulation Resistance Measurements Made During Cable Fire Tests*, USNRC, June 2002.

This report describes the results and findings of cable insulation resistance (IR) measurements made during 18 room-scale cable fire tests conducted under EPRI-NEI sponsorship. Each of the 18 tests involved at least one cable or cable bundle instrumented for IR monitoring. Most of the tests involved one 7-conductor cable bundled with three single-conductor cables. In one test, two separate 5-conductor cables were monitored. In two tests, bundles comprised of three 3-conductor cables were tested.

The Sandia IR Measurement System was designed to identify and quantify changes in insulation resistance occurring between the any given pair of cable conductors and between each individual conductors and ground. As a result, the exact mode of conductor shorting and failure mode transitions were determined.

Eighteen separate fire tests were conducted between January and May 2001. Of the 18 tests, four tests resulted in no cable failures (where failure is defined as a measured IR of less than 100 ohms), three tests were run without a ground connection for the IR system (i.e., these tests used an un-grounded DC power source) thus the IR system was unable to detect short-to-ground failures. Four additional tests were run with a wiring fault in the IR Measurement System and were consequently able to determine only total changes in leakage current through the measuring circuit but not the mode of failure. The remaining seven tests form the basis of the findings and conclusions in the report relevant to the question of cable failure modes.

A 4-20 mA DC simulated instrument circuit (a current loop circuit) was also monitored in the final six tests run. All these instrument cables failed (significant degradation of output signal) at some point during the test. However, these particular measurements are not considered relevant to the current discussions.

Summary of Results: The IR data provided in the report explicitly identifies the initial failure mode for each of the seven tests where cables did fail and the failure mode was detected. The results can be parsed in a number of ways. In particular, the data illustrate contrasts in the failure mode likelihoods for intra-cable versus inter-cable shorting, cable trays versus conduits, and to a limited extent armored versus non-armored cables.

With regard to intra-cable shorting in multi-conductor cables, the tests appear to indicate a strong influence of the raceway type on the mode of failure. For cables in trays, intra-cable conductor-to-conductor shorts were dominant. For the tray configurations, four out of the five multi-conductor cable failures observed involved intra-cable conductor-to-conductor shorts rather than conductor-to-ground shorts. However, for cables in conduits, conductor-to-ground shorts were dominant. Two tests involved multi-conductor cables in conduit that failed. In one test one 5-conductor cable was tested, and in the second a bundle of three 3-conductor cables was tested. In each case (e.g., all four cables in the two tests), the initial conductor failures involved shorts to ground rather than conductor-to-conductor shorts.

With regard to inter-cable shorting, the typical test configuration involved three single conductor cables bundled with one 7-conductor cable. There were 13 single-conductor cables in this configuration that failed during the tests. The potential modes of failure would be inter-cable conductor-to-conductor or conductor to ground for each case. Of these 13 cables, nine failed first by shorting to ground. The other four experienced cable-to-cable failures initially. It should be noted that this bundling arrangement was somewhat contrived and would not be typical of actual installations. Hence, the data likely over-estimate the actual likelihood of inter-cable conductor-to-conductor shorts as compared to an actual installation.

Some further indications relating to inter-cable shorting were also obtained in Tests 18. In this test the IR system monitored a bundle of three 3-conductor cables placed in a conduit. (Test 14 used an identical configuration but saw no failures.) In this test, the first failure mode observed for each of the three cables was shorting to ground. No inter-cable conductor-to-conductor shorts were observed (at the least, not prior to conductors having shorted to ground).

In the case of armored cables, only two tests were performed, but failures were observed in only one of these two tests. In this one case, the initial failure mode for the conductors was shorting to the metal armor which would normally be grounded. There were some concerns regarding this particular test in that the minimum bend radius specified for the cable was violated. This may have influenced both the likelihood of cable failure and the mode of cable failure. Hence, these results are considered inconclusive.

A.2.3 Other Data Sources

The bulk of the available test data was gathered under EPRI and USNRC sponsored programs as discussed in Sections A.2.1 and A.2.2 above. However, there are other sources of data that were identified. These include tests performed in France, tests sponsored by the U.S. Department of Energy (DOE), and some early cable manufacturer tests. This subsection describes the additional data sources.

BIW: "BIW Bostrad Cables - Flame and Radiation Resistant Cables for Nuclear Power Plants," Boston Insulated Wire & Cable Co., Boston, MA, Report No. B901, Sept. 1969.

This report is a manufacturer report citing results of certain harsh-environment qualification test results for a particular cable product. Included in the report is the discussion of both "flame tests" and "bonfire tests." Some circuit integrity testing was performed as a part of these tests. Also note that this is one of three data sources cited in NUREG/CR-2258.

In the flame tests, a single length of cable was exposed to a Bunsen burner flame. The cable was nominally monitored for open circuits and conductor-to-conductor failures. However, there was no raceway. All failures detected were conductor-to-conductor, but this result provided no data specific to estimating the conductor-to-conductor hot short probability. For this configuration, open circuit failures (breaking of the conductor) would not be expected because the exposure is simply not severe enough to cause failure of the copper conductor.

In the first set of bonfire tests, a single length of cable routed repeatedly through a vertical cable tray was exposed to a fire from oil-soaked burlap. Again, circuit integrity was monitored. Nominally failures including cable-to-tray and conductor-to-conductor would be detected. However, the energizing/monitoring circuit was quite similar to that shown in Figure A-10. In particular, one of the conductors was connected to the neutral/ground, and to the cable tray. Hence, conductor-to-conductor shorts involving the core conductor and conductor-to-tray failures cannot be uniquely distinguished. The report only cites the time to electrical shorting if shorting was observed, but does not state the mode of shorting.

In the second set of bonfire tests, a bundle of six cables was suspended over a small pool of burning transformer oil. The circuit integrity included an indicator lamp circuit similar to the first set of bonfire tests. In addition, insulation resistance measurements were also made during the fire. However, it is not specified how the insulation resistance was measured nor what it represents (e.g., conductor to conductor, cable to cable, or conductor to ground). In a third set of bonfire tests, a group of 12 apparently single conductor cables was tested in a manner very similar to that of the second set of bonfire tests. For each test, the time to shorting and insulation resistance over time is shown. Again, there is no distinction between the mode of failure observed.

Summary of Results: The results from this test report do cite times to electrical failure for a number of cable products under four different exposure configurations. However, the report provides no indication of the mode of failure observed in any of the tests. Indeed, the test procedure was not capable of distinguishing between conductor-to-conductor failures and conductor-to-tray failures for those tests involving cable trays. It is also not clear if any monitoring of inter-cable conductor-to-conductor shorting was implemented for the two test sets that appear to have involved bundles of individual cables. Hence, this data set provides no data useful in estimating the relative likelihood of one failure mode versus another.

McIlveen: Edward E. McIlveen, “Fire-Retardant Cable Systems,” *IEEE Transactions on Industry Applications*, Vol. IA-11, No. 3, May/June 1975, pp. 301-307.

This 1975 IEEE Transactions paper presents some limited discussion of results from cable fire tests performed by the Okonite Corporation, a major supplier of cables to the U.S. nuclear industry. The tests explored a number of factors associated with flammability testing of electric cables. The work was done largely in support of then ongoing efforts to establish the flammability test that was eventually included in the IEEE-383-1974 cable qualification test standard. It should also be noted that this is one of three sources of test data cited in NUREG/CR−2258 as the basis for the cited hot short probability distribution.

The primary focus of the tests was placed on ignition and flame spread behavior. However, during the early development of the flammability test methods, many tests were apparently performed that included assessments of cable functionality. The paper does illustrate the typical cable integrity monitoring circuit used by Okonite in its tests. The circuit used a +/-120 VAC (240 VAC) power source such as that commonly encountered in residential and light commercial domestic power systems. One side of the source would be tied to one or more of the cable conductors, the opposite side would be connected to the opposite side of the source, and one conductor or the cable drain wire would be hooked to the power source neutral and to the cable tray effectively grounding both the tray and one cable conductor. A series of four indicating lights would light or go out indicating various modes of cable failure.

Given this configuration, the circuit was nominally capable of detecting failures that occurred within a given cable. However, the circuit could not independently detect a conductor-to-conductor failure from a conductor-to-tray failure because one conductor and the tray were directly connected. Even within a single cable, only limited information is available. This is because if a cable had more than three conductors, the conductors would be ganged into groups for the electrical connection. The test would then detect failures between any pair of the ganged conductors only.

Summary of Results This particular data set might provide relevant insights for two particular applications: cables that include drain wires and/or shield wraps, and multiconductor cables that explicitly include one or more grounded conductors. This is because the circuit would detect whether or not the two conductors (or two groups of conductors) shorted together or shorted to the grounded drain wire or conductor. However, there is only minimal data on times to failure presented in this paper. No information on failure mode is provided. Further, no supporting references that might provide more detailed discussions of the underlying data are cited. A literature search on the author also revealed no subsequent publications of a similar nature. Overall, this paper provides no explicit data of interest to the current study. If access to the underlying test observations (of changes in the status of the four indicating lights) then some additional insights might be gained, but this is beyond the scope of the current review.

Bhatia: Premnath Bhatia, “Silicone-Rubber-Insulated Cables for Calvert Cliffs Nuclear Power Plant,” *Nuclear Safety*, V. 16, No. 6, Nov-Dec 1975, pp. 714-719.

This 1975 paper from *Nuclear Safety* describes the process by which Calvert Cliffs chose silicone-rubber as its preferred cable insulation. The paper describes, in abbreviated detail, flammability and functionality tests conducted on 57 different types of cable insulation. Note that this is one of three failure data sources cited in NUREG/CR-2258. The failure time results from these tests are also cited (indeed are stated more clearly) in Table 6-1 of EPRI NP-1200.

The tests performed did include measurement of the time to cable failure. However, the circuit used was very simplistic and was not capable of detecting conductor-to-conductor failures independent of cable-to-tray failures. This is because (1) conductors in a given multiconductor cable would be electrically ganged into two groups, and (2) one of the two conductor groups in each cable would be grounded. The second conductor group in each cable was energized to 120 VAC, and the circuit was only capable of measuring the time to shorting of any one conductor in this energized group to ground where the ground could be either the other conductor group or the tray.

Summary of Results: The tests described in this paper were inherently incapable of distinguishing the mode of cable failure. Hence, the results are of no interest to the current review.

UL,: “Flame Propagation Tests of Power and Control Cables,” UL File NC555, Project 74NK8900, Underwriters Laboratory, 23 Aug. 1976.

This is an unpublished (but copyrighted) report from Underwriters Laboratories Inc. documenting a series of cable fire tests performed in 1976. The tests were sponsored by the Nuclear Energy Liability - Property Insurance Association of Hartford Connecticut. The tests involved flame propagation tests for cables in both vertical and horizontal cable trays.

The vertical tray configuration was a modified IEEE-383-1974 style of arrangement that was specifically intended to produce a more severe fire exposure than that of the standard. A 16-foot open-ladder type vertical cable tray was placed adjacent to the two wall surfaces of an open corner. The horizontal test configuration utilized four 10-foot long stacked cable trays spaced 1-foot apart and installed in a simulated corridor. For the horizontal tray tests, the burner was placed above the bottom tray (hence, in some cases the bottom tray saw no circuit failures). Three fire source intensities were used (70,000 BTU/hr, 210,000 BTU/hr, and 400,000 BTU/hr), all using a standard IEEE-383 gas ribbon burner. In all, there were 49 vertical trays tests, and 49 horizontal tray tests.

In each test, six lengths of the subject cable were installed in each tray in the each test (hence, there were six cable specimens in each vertical test and 24 in each horizontal test). Each cable length was separated from the neighboring cable length by a distance equal to one-half the cable diameter. For the vertical trays, the cables were strapped to every other tray rung using nylon wire ties. The horizontal tests apparently had no such restraints, although the cables were carefully laid to achieve the desired spacing.

The cables used in the tests were all 12 AWG, 7-conductor copper cables. Eight different combinations of cable insulation and jacketing material were tested. However, the test report specifically obscures the actual cable type used in any given test. Instead, eight sets of three randomly selected letters (e.g., CSA) are used as a surrogate to identify the individual tests. Hence, without some further information, the tests may provide some indication as to whether or not the cable insulation type had a substantial impact on failure mode, but the specific types of insulation and their impacts cannot be assessed. This is discussed further below.

The tests did include circuit integrity monitoring performed during each test. The energizing circuit utilized a relatively simple two-phase plus ground power source, as illustrated in Figure A.10, although the energizing voltage and circuit monitoring strategy is not specified. (Given the configuration, one might speculate that common utility service line with a +/- 120 VAC circuit may have been used, and that circuit integrity was monitored based on phase-to-phase or phase-to-ground current flow.)

Given this configuration, a phase-to-phase failure would be a clear indication of a conductor-to-conductor short circuit. However, a phase-to-ground failure might be indicative of either a conductor-to-conductor short circuit or a conductor-to-tray short circuit. The phase-to-ground short circuit has an ambiguous implication because both the tray and one of the cable conductors was connected to ground. Hence, the primary interest with these tests is the relatively large number of phase-to-phase failures that were observed as discussed below. Note that because the cables were installed with a “maintained spacing” arrangement, there was no real potential for cable-to-cable electrical interactions.

For the horizontal tests, the report explicitly states that the six cables in any given tray were “wired in parallel.” Hence, for the horizontal tray tests, only the first cable failure in each tray would be detected (potentially giving four data points per test, one for each tray). The discussion of the vertical tray tests is more ambiguous, but given that only on circuit failure data set is given for each vertical test, it is presumed that the cables in the vertical tray were also wired in parallel yielding a single circuit integrity measurement per test. In all, there are 49 potential failure measurements from the vertical tests and 196 potential failure measurements for the horizontal tests. The results are characterized in Table A-1.

The test results include the identified time observed in each test before the first phase-to-phase and phase-to-ground failure. Note that the test report states that phase-to-ground short circuits that occurred subsequent to a phase-to-phase short circuit would not be detected. Phase-to-phase short circuits that occur subsequent to a phase-to-ground short circuit are, however, reported.

Given the experimental setup and limitations, it is possible to identify those initial failures identified as phase-to-phase as conductor-to-conductor hot shorts. Phase-to-ground failures, as noted above, are ambiguous. Treating all phase-to-ground short circuits as cable-to-external ground failures would produce the most optimistic possible assessment of the cable hot short potential (i.e., the lowest possible frequency of hot shorts based on this data set). No information on the duration of a hot short is available, however, because transition from a hot short to a ground short was not detectable.

In all, 43 of the 49 vertical cable tests saw failures (one cable type experienced no failures in six tests). Of the 43 observed failures, 32 were characterized by an initial phase-to-phase (conductor-to-conductor) short (74.4%). The remaining 11 failures were characterized by initial phase-to-ground (indeterminate mode) shorts (25.6%).

Table A-1. Summary of test results from UL NC555. [27]

Ref. Table	Configuration / Cable / Tray	Non-Failures	Phase-to-Phase Failures	Phase-to-Ground Failures
Ill. 8	Vertical / CSA / (n/a)	0 / 7	7 / 7	0 / 7
9	Vertical / EMD / (n/a)	0 / 6	5 / 6	1 / 6
10	Vertical / FVT / (n/a)	0 / 6	4 / 6	2 / 6
11	Vertical / KPB / (n/a)	0 / 6	5 / 6	1 / 6
12	Vertical / LUH / (n/a)	0 / 6	4 / 6	2 / 6
13	Vertical / OWR / (n/a)	0 / 6	4 / 6	2 / 6
14	Vertical / XGY / (n/a)	6 / 6	0 / 6	0 / 6
15	Vertical / ZQJ / (n/a)	0 / 6	3 / 6	3 / 6
	Vertical Test Totals:	6/49	32/49	11/49
16	Horizontal / CSA / Top Tray	2 / 6	2 / 6	2 / 6
	Second Tray	0 / 6	6 / 6	0 / 6
	Third Tray	0 / 6	6 / 6	0 / 6
	Bottom Tray	6 / 6	0 / 6	0 / 6
17	Horizontal / EMD / Top Tray	2 / 7	3 / 7	2 / 7
	Second Tray	2 / 7	5 / 7	0 / 7
	Third Tray	0 / 7	7 / 7	0 / 7
	Bottom Tray	5 / 7	0 / 7	2 / 7
18	Horizontal / FVT / Top Tray	2 / 6	1 / 6	3 / 6
	Second Tray	2 / 6	5 / 6	0 / 6
	Third Tray	0 / 6	6 / 6	0 / 6
	Bottom Tray	5 / 6	1 / 6	0 / 6
19	Horizontal / KPB / Top Tray	2 / 6	4 / 6	0 / 6
	Second Tray	0 / 6	4 / 6	2 / 6
	Third Tray	0 / 6	6 / 6	0 / 6
	Bottom Tray	4 / 6	2 / 6	0 / 6
20	Horizontal / LUH / Top Tray	0 / 6	2 / 6	4 / 6
	Second Tray	0 / 6	5 / 6	1 / 6
	Third Tray	0 / 6	3 / 6	3 / 6
	Bottom Tray	4 / 6	1 / 6	1 / 6
21	Horizontal / OWR / Top Tray	2 / 6	3 / 6	1 / 6
	Second Tray	2 / 6	4 / 6	0 / 6
	Third Tray	0 / 6	4 / 6	2 / 6
	Bottom Tray	6 / 6	0 / 6	0 / 6
22	Horizontal / XGY / Top Tray	6 / 6	0 / 6	0 / 6
	Second Tray	6 / 6	0 / 6	0 / 6
	Third Tray	6 / 6	0 / 6	0 / 6
	Bottom Tray	6 / 6	0 / 6	0 / 6
23	Horizontal / ZQJ / Top Tray	2 / 6	4 / 6	0 / 6
	Second Tray	2 / 6	4 / 6	0 / 6
	Third Tray	0 / 6	5 / 6	1 / 6
	Bottom Tray	5 / 6	1 / 6	0 / 6
	Horizontal Test Totals:	78 / 196	94 / 196	24 / 196

There were 118 failures observed in the horizontal tests out of a total of 196 opportunities for failures. The 78 “non-failures” were scattered among the various tests and trays. Most “non-failures” involved cables in the bottom trays. Indeed, for the bottom tray, only 8 failures were noted out of 49 opportunities for failure. There was also once cable type that experienced no failures in any of the four trays during six separate tests (a total of 24 failure opportunities including six bottom tray opportunities also counted immediately above). The remaining non-failures were all associated with cables in the upper two trays of the four tray stack.

Of the horizontal tray test failures, 94 out of 118 were characterized by initial phase-to-phase (conductor-to-conductor) failures (or 79.7%). The remaining 24 out of 118 failures were characterized by initial phase-to-ground (indeterminate mode) failures (or 20.3%).

Based on these results, the relative proportion of phase-to-phase versus phase-to-ground shorts was only modestly impacted by the tray configuration. Indeed, the impact is reversed from what one might nominally anticipate. The horizontal trays experienced a modestly higher rate of phase-to-phase shorts than did the vertical trays. However, the trays in all cases were very lightly loaded. Hence, the results may not be indicative of the results for more general and in particular, heavier cable tray loadings. For the horizontal trays, a heavier cable load may lead to a higher proportion of conductor-to-tray failures due to the added weight of cables pushing down onto the cable rungs. In this test set, there was very little weight (only that of the individual cables) on the rungs. In the vertical tests, the cables were strapped to the tray, and this may have acted to increase the probability of conductor to tray interactions.

The tests also show no pronounced trend with cable type. The most significant effect in this regard is clearly seen in the number of observed failures. One cable type (that designated XGY) saw no failure in either the horizontal or vertical tray tests. (Given the cable specifications cited in the report, and other available information on cable fire performance, this was almost certainly the Silicon-glass/asbestos cable, although the test report does not state this). The performance of other cable types does show distinct effects of cable robustness as well in terms of both the damage times and damage potential. However, there is no clear indication that cable type seriously impacted failure mode.

<u>Summary of Results:</u> In all, 43 of the 49 vertical cable tests saw failures (one cable type experienced no failures in six tests). Of the observed failures, 74.4% were characterized by an initial phase-to-phase (conductor-to-conductor) short. The remaining 25.6% of failures were characterized by initial phase-to-ground (indeterminate mode) shorts. Of the 118 horizontal tray test failures, 79.7% were characterized by initial phase-to-phase (conductor-to-conductor) shorts. The remaining 20.3% were characterized by initial phase-to-ground (indeterminate mode) shorts. Assuming that all of the phase-to-ground shorts are, in fact, conductor-to-tray shorts, these tests indicate a nominal conductor-to-conductor hot short probability of between 74% and 80%. No data on hot short duration is available. The tests also indication the for lightly loaded trays, the tray orientation (vertical versus horizontal) is of relatively minor importance to failure mode probabilities. The tests also appear to indicate that cable type has little impact on failure mode assuming that failure does occur.

<u>Boeing:</u> L. E. Meyer, A.M. Taylor, and J. A. York, “Electrical Insulation Fire Characteristics. Volume I: Flammability Tests,” Report No. UMTA-MA-06-0025-79-1,I Boeing Commercial Airplane Co., Seattle, WA, Dec. 1978.

This report documents a series of tests performed by the Boeing Company under the sponsorship of the U.S. Dept. of Transportation. (Note that the companion Volume II apparently deals with toxicity issues only.) The tests explored flammability behavior for a number of cables used in various transportation applications. The particular transportation system of primary interest appears to have been an underground “rapid transit vehicle.”

While not the primary focus of the report, a discussion of certain circuit integrity tests is provided. The report states that those circuits “whose function is necessary to safely evacuate the passengers and crew from a rail transit car or tunnel in the event of fire” are required to operate “while experiencing a fire condition for the minimum time to perform the evacuation.” Hence, a series of circuit integrity tests was performed to assess the cable failure behavior. The tests were intended only to provide a relative assessment of electrical durability under fire exposure for a range of cable samples that were contributed to the program by both manufacturers and end users.

The circuit integrity tests involved two very simplistic test configurations; one for single conductor cables and a second for multi-conductor cables. In each case, a single length of instrumented cable was placed into a small-scale holding apparatus and exposed to the flame from a Bunsen burner. Time to failure was then monitored. The test apparatus was a variation of a similar setup originally used by Boston Insulated Wire (BIW). The setup is primarily designed for single conductor cables, and some modifications were made to accommodate multi-conductor cables. The two test set-ups are described as follows:

> For single conductor cables: One end of the cable sample was anchored to the base of the test cell, the cable was routed upwards through a 1" ID metal ring, makes a slight bend in passing through the ring, is routed over an insulated pulley, and a weight was attached at the opposite end of the cable. This arrangement was such that a lateral force was applied to the sample cable by and against the fixed metal ring. The time to failure is the time to shorting between the insulated cable and the metal ring. This was detected using a simple 120 VAC source and a lamp to indicate that the circuit had closed (the conductor had shorted to the ring).
>
> For multi-conductor cables: The cable entered a small test cell horizontally, made a 90-degree bend upwards (not less than 4" radius), and was routed out the top of the test cell. The cable was exposed to the flame from a Bunsen burner in the area of the radial bend. The cables were nominally monitored for conductor-to-conductor shorts, and conductor to ground shorts where the ground was present in the form of at least one grounded conductor in the sample cable, and for four of the 19 tested cables, grounding of a metal shield.

The single conductor tests are of no interest to the current study since only one mode of failure was possible; namely, shorting of the conductor to the ring. The multi-conductor tests are of potential interest, however, the monitoring circuits limits the usefulness of the data.

Nineteen different multi-conductor cables having from 2 to 148 conductors were tested. Two energizing circuits were used to monitor cable integrity. Each circuit is illustrated in the report as applied to a seven conductor cable with a metallic shield. Each circuit diagram shows that the metal shield was grounded for those cables having a shield (four of 19 sample cables tested did have metal shields). However, the circuits also show that (at least) one conductor was also grounded. In the illustrations the conductor at the center of the seven-conductor cable is shown as grounded. For other cables, it is not clear how many conductors were actually grounded. (The circuits are quite similar to those illustrated in Figure A-10).

Ultimately, each of the two circuits was only designed to detect failures that occur within the cable (there was no raceway involved in the tests and each test involved only a single length of cable). For those cables that did not have shields the only mode of failure monitored was conductor-to-conductor shorts even though one conductor is grounded. That is, ground faults as defined in the Boeing study for those cables without a metal shield, 15 of the 19 cables, are actually conductor-to-conductor failures. Hence, the results are no real interest because 100% of failures for these cables are, by design, conductor-to-conductor failures.

For those four cables that did have metal shields, the illustrations imply that both the shield and at least one conductor in each cable were grounded. This makes the results for ground faults ambiguous for cases involving shielded cables. With a shield present, a ground fault may be either a short to the shield or to the grounded conductor(s) and there is no way to tell which was actually observed.

The data was also of potential interest because times for both the first and second failure indications are cited in the summary tables. However, the report is not specific as to which failure was observed first. Hence, even these results are of limited usefulness. At most, the tests provide some indication of the potential timing of initial and secondary failures. However, in all cases the tests simply illustrate the transitions between failures involving groups of conductors rather than actual transitions in failure mode. For the shielded cables transitions from conductor-to-conductor to conductor-to-shield might have been nominally detected, but are not reported as such.

The limited insights that can be gained from these tests are as follows:

- Three of the samples (two silicon rubber and one “Tefzel” insulated cable; Tefzel is a trade name product) showed no failures after a 30 minute exposure to the burner flame.

- The times between detection of the first and second failures ranged from one second to over 1000 seconds. This is a very broad range and appears to be a function of both the insulation material propertied and cable size (smaller cables transition more quickly). As noted, the nature of these transitions is not specified.

- For three of the 19 cable types tested, the report notes that the initial indication of failure was a very dim illumination of the indication lamp that gradually built to full illumination. The behavior apparently was not observed for all samples, even of a given cable type. For one sample (an ethylene-propylene rubber (EPR) insulated cable) seven of eight samples showed this behavior and for those samples, the breakdown took an average of 315 seconds to complete. In the second case (a mica-Teflon (FEP) insulated cable) the transition for “some failure indications” was noted as “gradual” but no time is specified. In the third case (a polyolefin insulated cable) the relative number of samples showing this behavior is not noted, but the average breakdown time is given as 68 seconds. All of the other 16 samples apparently showed more abrupt transitions from intact to fully shorted. This shows that some cable types are likely to experience a gradual transition from full integrity to full shorting while others will experience a rapid transition. However, even for those cables that may show a gradual transition, some samples may still show sudden transitions.

Summary of results: The results of this test program are of very little relevance to the current review. This is because for each cable there was only one real mode of cable failure that was monitored. Hence, there is no data that would help quantify the relative likelihood of one failure mode as compared to another.

Illinois: *Hinsdale Central Office Fire Final Report*, a joint publication of the Office of the State Fire Marshal and the Illinois Commerce Commission Staff, Springfield, Il., prepared by Forensic Technologies International Corporation, Annapolis Maryland, March 1989.

This forensic investigation report documents the efforts undertaken to assess and understand a fire incident that occurred in a telephone switching center in the town of Hinsdale Illinois. The fire occurred on May 8, 1988. As a result of the fire, telephone service for over one-half million residential and business customers in the Chicago area was disrupted.

As a part of the investigation, several fire tests were performed in an attempt to identify the likely cause of the fire, and to confirm the fire behavior that was being postulated by fire investigators. It was ultimately determined, based on several pieces of evidence and test results, that the fire had been ignited when a low-voltage, high amperage power cable came into electrical contact with the armored sheathing of an adjacent cable. The resulting fault currents heated the spiral-wound armor jacketing (somewhat like a toaster heating element) igniting the fire.

A series of full-scale fire tests was performed to both verify that the postulated ignition source was capable of igniting the fire, and to explain certain features observed during the fire investigation. The results provide some very unique insights into the behavior of electrically initiated fires when the cables involved have a very high energy potential. The test fires involved relatively low voltages (48VDC) but substantial current potential (on the order of 200A). As a result several interesting behaviors were noted.

Included in the full scale tests were several power cables energized using a pair of DC power supplies. The report does note that some few of these cables did fail during certain of the fire tests, but no specific failure data is presented. It would also appear that the tests were not instrumented in such a way that one could distinguish the actual failure mode. This is because several of the non-energized cables in the tray and the tray itself were set up as the current return path in the event of cable failures involving either the energized cables or the ignition source cable. Hence, even given failures it would not be possible to distinguish between cable-to-cable and cable-to-tray failures.

Summary of Results: The tests described in this report do provide a number of very interesting insights regarding self-ignited cable fires, in particular, fires involving cables with a high electrical energy potential. However, no specific information on the cable failures that were observed is provided. Based on the test design, it appears unlikely that further access to the underlying test data would provide any added insights. Hence, this report is found to contain no information of direct applicability to the question of cable failure mode likelihood analysis.

UCRL-ID-110598: H. K. Hasegawa, K. J. Staggs, and S. M. Doughty, *Fire Tests of Wire and Cable for DOE Nuclear Facilities,* Lawrence Livermore National Laboratory, Sept. 1992.

This document describes a series of four tests performed by Lawrence Livermore National Laboratory (LLNL) under DOE sponsorship. The report itself describes several different experimental set-ups intended to assess cable failure times and failure modes given a fire. However, in the end only four experiments using just one of the monitoring schemes were performed.

In each of the four tests, a single cable tray was exposed to fire. Within this tray were four bundles of cables instrumented to measure cable function and failure modes. Each bundle was comprised of four cables, a welding wire, two 37-conductor cables, and one coaxial instrument cable.

Figure A-9 provides a schematic of the cable function monitoring circuit used for each bundle in each of the four tests.[7] The power source in each test was provided by a bank of ten 12 V-DC batteries wired in series/parallel or simple series to provide either 24 or 120 V-DC. This DC circuit was ungrounded.

One end of the welding wire in each test bundle was connected via a load resistor to the negative pole of the battery array. The opposite end of each welding wire was connected directly to the positive side of the battery array completing the circuit. The load resistors were sized to establish a base current of 5 A in each welding wire (this would imply use of 4.8 and 24 ohm resistors depending on circuit voltage).

The remainder of the conductors in each test bundle were connected through shunt resistors to the negative side of the battery and allowed to "float" in voltage level. The tray was connected in the same way.[8] The shunt resistors are described as a bank of 40, 0.1 ohms elements and a single shunt resistor was used for each group of conductors and for the tray.[9]

This arrangement allowed for the measurement of leakage currents for each of the cables in the four bundles as well as the cable tray. This was accomplished by measuring the voltage drop across each load and shunt resistor. However, this arrangement is capable of providing only limited conductor failure insights. The following limitations are noted:

- Each of the conductors in the outer row of a given multi-conductor cable were "ganged" together electrically. The interior conductors were neither energized nor monitored. Hence, the arrangement is inherently incapable of detecting conductor-to-conductor failures in the multi-conductor cables.
- The circuit is unable to detect any failures that do not involve one or more of the welding wires. The only connection between the positive side of the battery array is provided through the welding wire. Hence, if the welding wire is not involved in a failure, no fault currents will be measure in either the tray or the other cables. Specifically, unless the welding wire is actively involved in the failure the arrangement cannot detect: Cable-to-cable failures between the multi-conductor and/or coaxial cables and any other cables that filled the tray, cable-to-tray failures involving the multi-conductor and/or coaxial cables or any of the other cables that filled the tray, or any failures involving the general mass of cable fill that was not energized or monitored.

The circuit can detect the following failure modes:

- Cable-to-cable failures involving the welding wire and any of the other monitored cables,
- Cable-to-tray failures involving the welding wire, or

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[7] Note that the corresponding figure in the original LLNL report contains a minor error. Per the text, the polarity of the battery as shown in the figure was reversed. The figure presented here corrects this error. This is a very minor point that has no impact on the interpretation of test results.

[8] The wiring of the cable tray is not specified in the test report. However, discussions with one of the LLNL authors, K. J. Stagg, revealed that the tray was in fact connected to the negative pole of the battery via a shunt resistor in the same manner as were the other conductors in the bundle. The circuit diagram presented here has been modified to reflect this connection.

[9] Based on discussion with K. J. Staggs of LLNL.

- Open circuits in the welding wires only.

The tests did result in numerous cable failures in virtually all of the tested cable bundles. Failures included cable-to-cable, cable-to-tray, and ultimately open circuit failures. It is not possible from the test data to clearly discern which modes of failure were observed first. In general, the open circuit failures were observed only after repeated failures of other types finally vaporized or melted enough of the copper conductor to result in loss of integrity in the welding wires. It is also noted that due to the manner in which the cable bundles were installed in the trays, the only way that the welding wire could short to the tray was through involvement with other cables in the tray. That is, none of the welding wires was ever installed in direct contact with the cable tray; rather, there was always one or more cables between the tray and the welding wires. Since multiple shorts between the welding wires and the tray were observed, it can be concluded that multiple cable-to-cable failures were also observed. Again, the relative timing of these failures cannot be discerned from the data.

One behavior that is relatively unique for this particular data set in comparison to others is the rather "spiky" nature of the failures. That is, in most tests of cable functionality, one sees a gradual breakdown in insulation resistance of some period of time followed by a sharp failure/shorting. In these tests the failures are characterized by very intense but short-duration spikes in the measured currents.

Discussions with one of the report authors revealed that the failures were extremely energetic in nature. He stated that the sound of many "small explosions" could be heard even outside the test cell. This behavior was attributed to the very high currents flowing through high-impedance short circuits. Note that nominally a 0.1 ohm shunt resistor would allow fault currents of 240A for the 24V circuit and 1200A for the 120V circuit in the event of a dead short to one of the welding cables. Hence, any failure involving the welding wires had the potential for extremely high fault currents. The resulting energy release was sufficient to vaporize or melt the copper at the point of contact, and thus the short circuits would open shortly after being initiated.

Most of the failures appear to involve the cable tray as an active element of the shorting behavior. This would tend to imply that cables may have experienced shorting to the cable tray shortly before or nearly simultaneous with the first shorts to the welding wire. However, it is not possible to definitively state that the actual sequence of failures that were observed in a given test. Ultimately, the author we spoke with described the trays after testing as a "large mass of carbonized insulation" that gave rise to "numerous high-impedance faults."

Summary of Results: These tests do illustrate a unique behavior associated with high-energy electrical circuits. That is, when cables possess a high energy potential, the shorting behavior may result in high-intensity but short duration arcing faults (as compared to the slow degradation followed by sustained low-impedance faults seen in other tests). Further, because of the very short duration of the actual current faults, the authors note that there is a strong possibility that circuit protection devices would not trip. These tests do illustrate that for ungrounded DC circuits multiple high-impedance cable-to-cable and cable-to-tray failures are possible. However, the results provide no specific insights regarding the onset of conductor-to-conductor failures, nor can the results be assumed to accurately characterize the initial onset of cable-to-tray failures.

IPSN: J. M. Such, *Programme Etude probabiliste de Surete Incendie*, (translated as: *Probability Study Program on Fire Safety*), EF.30.15.R/96.442, IPSN, April 1997.[10]

This 1997 report documents one cable fire test (PEPSI 1) performed in France by the French nuclear regulatory authority, IRSN[11]. The primary purpose of the test was to assess the flammability behavior of certain specific cable products under fire exposure conditions. As a part of the testing, twenty cable segments were instrumented for functionality monitoring. It is these cable function tests that are of interest to the current review.

The fire test consisted of five cable trays. Each tray held a single layer of cables arranged across the width of the tray. As discussed below, most of the cables were armored. The source fire was rather substantial; 100 liters of light-weight pump lubricating oil pre-heated to 250°C and poured into a round pan with a 1m^2 surface area. The anticipated burn duration was 91 minutes.

Cables in four of the five trays were energized and monitored for failures. Each of the four monitored trays had a total of 20 cable passes; four passes each of five different cable types. The five cable types used are:[12]

- 3-conductor 16 mm^2 armored power cables (equiv. to 6 AWG),
- 3-conductor 6 mm^2 armored power cables (equiv. to 10 AWG),
- 2-conductor 35 mm^2 armored control cables (equiv. to 2 AWG),
- 7-conductor 1.5 mm^2 armored control cables (equiv. to 16 AWG), and
- 2-conductor 0.5mm^2 (non-armored) instrumentation cables (equiv. to 20 AWG).

The translation states (pg.20) that "the cables enter in the chamber through a leakproof passage (marine type caulk), cross the support four times and exit the site through another leakproof passage." From this we infer that the four passes of each cable type are made using one continuous length of cable. That is, there is just one length of each of the five cable types in each tray, and each length of cable makes four passes through a given tray. This is confirmed by the arrangement shown in Figure 5 of the report.

There were four separate cable energizing/monitoring schemes used in the tests. All of the cables in the four monitored trays carried an applied voltage and base current, and all were monitored for short circuits as well as leakage to ground (the cable armor was connected to ground). Ultimately failures were noted in each of the cables in three of the four trays: one tray about 2 meters directly above the fire source, one tray near the ceiling directly above the fire, and one tray near the ceiling offset from the edge of the fire pan by about 1 meter. This means that 15 cables failed during the tests (three of each of the five cable types). The monitoring circuits and observed failures are summarized as follows.

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[10] This review is based on an English translation of the original report which is written in French. The translation was provided to the USNRC by Scitran Co. of Santa Barbara Ca.

[11] Note that the French nuclear regulatory authority formerly known as IPSN is now known as IRSN. The referenced document was published under the former name IPSN and has been cited as such. However, in general, this report refers to this organization using the latter and more current identifier.

[12] Wire gage conversions (from mm^2 to equivalent AWG) are based on information provided by Industrial Electric Wire and Cable Inc.

Power Cables:

The two power cables in each of the four monitored trays were energized using a common 380 VAC, 3-phase, neutral grounded, power supply (380 is the phase-to-phase voltage and the report cites a measured 224 VAC phase-to-ground potential). Each of the three conductors in each of the eight power cables was connected to one phase of the power supply. The armored sheathing of each cable was grounded. At the opposite end of the cable, a 470 ohm resistor was installed between each conductor and ground. This allowed for each conductor to carry a continuous current load of approximately 0.48 A (224V/470Ω). A differential trip device was also installed with a 300 mA trip setting (i.e., any leakage currents that resulted in a phase-to-phase current imbalance on a given circuit/cable in excess of 300 mA would trip out the supply to the associated cable).

Functional monitoring of these cables consisted of the measured total current on each conductor. This was the sum of the base load current and the leakage current for each conductor. The circuit is nominally capable of distinguishing between conductor-to-conductor and conductor-to-ground/sheath leakage, but only if the three conductors show different rates/levels of degradation. If the conductors degrade at similar rates, then there would be simultaneous leakage of the three phases to each other or leakage of the three phases to ground. These modes would result in similar measured responses and could not be distinguished one from the other. (This is similar to the situation described for NUREG/CR-4638 which used a very similar setup.)

Failures were observed for six of the eight power cables in the test, three each of the 6 mm^2 and 16 mm^2 cables. Of these six failures, five were first manifested as conductor-to-conductor phase-to-phase short circuits, and the sixth is indeterminate. A further explanation of these cases is as follows:

- In one case the voltage traces clearly indicate the phase to phase short circuits.

- In four cases, the voltage traces appear to indicate a conductor short to ground as the initial failure mode given a voltage drop on just one of the three conductors. However, clarifications provided by IRSN (re: Remy Bertrand, IRSN, personal communication) affirmed the conductor-to-conductor failure mode, and asserted that a conductor to ground short circuit was not possible in these cases. The clarification provided states that “contact between a conductor and the grounded armor would provoke the opening of the contactor MI2 (Interface module). This did not occur so we can affirm that the first failure mode was a contact between internal conductors.”

- The sixth case is uncertain due in part to failure of some of the interface modules used in the cable monitoring/energizing system. Two of the three phases appear to be involved in the failure which would tend to indicate a conductor-to-conductor failure. However, while one jumps quite sharply upward, the second shows more modest, sustained and erratic leakage behavior despite an apparent circuit trip. It is not clear where the subsequent leakage is coming from and no explanation is provided in the report. It cannot, for example, be a cross-feed from the other power cable in the same cable tray because that circuit had already tripped out. Given the uncertainties and test failures, this case is classified as indeterminate. IRSN confirmed that interpretation of this case was problematic.

2/C Control Cable:

The 2-conductor (2/C) control cable in each tray was energized using a 125 V DC power source. The power source was nominally capable of a 10A load, but was protected by a 2A circuit breaker. The positive side of the source was connected through a current monitoring device to the first cable conductor. At the opposite end of the cable, the first conductor was connected through a 180 ohm load resistor to the second cable conductor. This second conductor acted as a return current path and was connected to the opposite side of the power supply and also grounded. The cable's armor sheath was also grounded.

Hence, in effect, this cable had one energized conductor, one grounded conductor, and a grounded sheath. The two conductors were each loaded with a base current of about 0.69A. Functional monitoring consisted of the measured total current into the energized conductor. The circuit design allows for the detection of insulation resistance breakdown between the energized conductor and ground, where ground is represented by both the second cable conductor and the cable armor sheath. No distinction between conductor-to-conductor and conductor-to-sheath leakage can be made.

Three of the four monitored cables failed during the test. In each case, the current plot shows a modest but progressive deterioration in the current signal. This may be an indication of simple temperature/resistance effects and likely has no significance. The ultimate failures are quite sharp. Again, the actual mode of failure cannot be determined.

7/C Control Cable:

The 7-conductor (7/C) control cables in each tray were energized using a common 48 V DC power supply. The positive side of the source was connected to the first of the seven conductors. The remaining conductors were then connected into a single continuous series circuit, one conductor after another, until all conductors were commonly connected. The last conductor was then connected through a 100 ohm load resistor to the other side of the supply which was grounded. The cable armor sheath was also grounded.

In effect, all of the conductors were connected together into a single cable circuit. Functional monitoring consisted of the measured current into the conductors. Given the load resistor, the base current load was approximately 0.48A. Nominally one might conclude that this circuit was only capable of monitoring the leakage of the energized conductors to ground and that it was inherently incapable of detecting conductor-to-conductor failures. However, in this specific case, the length of cable involved in the test (estimated at in excess of 150 meters (500 feet)) introduced sufficient internal resistance so that conductor-to-conductor failures could be detected. This is illustrated by examination of the test data.

Three of the four cables of this type failed during the test. In each case, the current signal first shows a jump upwards of on the order of 10 mA (typically from about 465 to 475 mA). After an additional 1 to 14 minutes, a circuit trip occurs. The report concludes that the initial current increase is due to conductor-to-conductor shorting within the cable. This does appear to be a plausible explanation. Indeed, it would require a decrease in circuit resistance of about 2 ohms to account for the increased current. Assuming 4 passes of the seven conductor cable through a tray approximately 6 meters long implies that there was at least 168 meters (551 ft) of conductor in the circuit. The 1.5 mm^2 cable is equivalent to a 16 AWG wire, and the resistance of such a wire is approximately 1.64 ohms per 100 meters of conductor (equivalent to about 5 ohms per 1000 feet of conductor). Hence, the overall resistance of the cable can be estimated as at least 2.75 ohms. If a short occurred between conductors in the cable, then an overall drop in resistance of 2 ohms would easily be postulated and this would account in turn for the temporary increase in current flow. The final circuit trip would result from a short to ground (presumably the cable's armor sheath) which would bypass the load resistor and trip the circuit on over-current. Hence, for all three cases an initial conductor-to-conductor failure is indicated followed in 1 to 14 minutes by a conductor-to-ground failure.

2/C Instrument Cable:

The 2/C instrument cable in each tray was energized using a 12 mA current source. This was chosen as representative of the mid-range current on a 4-20 mA device. One side of the supply was connected to the first cable conductor. The first and second conductors were then connected in series through a 250 ohm load resistor. The second conductor was then connected to the return side of the source which was also grounded. Given 12 mA across a 250 ohm resistor implies a conductor-to-conductor voltage potential of about 3 volts.

Functional monitoring consisted of the measured voltage across the load resistor. This circuit was nominally able to measure leakage currents from the first conductor to ground, where the ground was available either through the second conductor or, presumably, through the cable tray in which the cable was installed. Because one conductor was grounded, it is not possible to distinguish between the modes of ground shorting.

Three of the four circuits showed failure during the test. All illustrated a sharp failure behavior with little degradation noted prior to a circuit trip. No inferences regarding the actual mode of failure are possible.

Summary of Results: 15 cable failure were observed. Of these fifteen, 9 illustrate some important features relating to failure mode and likelihood. First, in the three-phase energized power cables, 4 of 6 failures were clearly conductor-to-ground failures. Both of the other two are classified as conductor-to-conductor failure, although one of these two shows some unexplained behavior following the initial failure. For the 7-conductor control cable, three of three failures involved initial conductor-to-conductor failures. These failures were sustained for 1, 10, and 14 minutes in the three cases (cable runs 1, 2 and 3 respectively). There was then a transition to conductor-to-ground failures in all three cases. Recall that all of the failures for which specific mode information is available involved armored multiconductor cables where the armor sheath was grounded.

EdF: M. Kaercher, *Loss of Insulation Test on an Electric Cable During a Fire,* ENS-IN-99-00412, Electricité de France, April 16, 1999.

This 1999 report documents the results of a single cable failure mode test performed as a part of a large-scale cable fire test in France. The cable performance aspects of the test were performed in cooperation with NEI, and EPRI. SNL provided some consultation on test design through the USNRC Fire Risk Methods research program.

The overall objective of the test was to demonstrate favorable flammability properties of a particular French cable product. As a part of the test a single bundle of US manufacture cables was inserted into the test array and monitored for degradation.

The monitored bundle was made up of eight lengths of 2/C, 16 AWG instrument cable. One length of cable (the source cable) was in the center of the bundle, and the remaining seven lengths (the target cables) completely surrounded the source cable. The objective of this design was to independently monitor for three failure modes:

- conductor-to-conductor shorts within the source cable,
- cable-to-cable shorts between the source and target cables, and
- cable-to-tray shorts involving the target and/or source cables.

For monitoring of cable performance, three voltage potentials were used to energizes various conductors. One conductor in the source cable was energized to 120 VDC. The second conductor in the source cable was energized to 80 VDC. The 14 conductors of the seven target cables were all ganged together and energized to 20 VDC. The cable tray was grounded as was the negative side of the DC power source.

Degradation of the cables was first noted 6:40 (min:sec) into the test. At 8:00 the first short circuit was noted - a conductor-to-conductor short between the two conductors of the source cable. The reports states that “(t)here was no other short circuit.” However, the data do appear to indicate additional interactions between the source and target cables and the energized cables and ground.

In particular, it is quite clear from the voltage plot for the target cables that from 6:40 on through at least 8:40, there is interaction between the target and source cables. This is seen in that the voltage of the target cables is being drawn up, an effect that can only happen if there is some leakage between the higher voltage source conductors and the lower voltage target conductors. At approximately 8:40 into the test it would appear that for all intents a hard short between the source and target cables has formed as all conductors appear to be at, essentially, the same voltages and that voltage is well above the original target cable voltage (in excess of 35 V as compared to the starting voltage of 20 V for the target cable). At 9:00 it appears as if all of the cables hard-shorted to ground.

Note that the data plots include a plot of the current “Imasse” which is referred to in the report as the “leakage current to the ground” (see section 3.2 of the report). Based on the data analysis tables, it would appear that “Imasse” is the simple sum of the three measured fault currents and is by implication the estimated ground fault return path current. It is noted that there is no current on this path “before cycle 50" or 8:20. This indicates that up until this time, all of the leakage is taking place among the energized cables without substantial ground interactions. This is also further evidence that at the very least between 6:40 and 8:20 substantial interaction between the source and target cables is occurring, as noted above. The ground itself becomes the predominant player in the failure only after cycle 54 or 9:00.

<u>Summary of Results:</u> The authors of this review disagree with the data interpretation provided in the original report. The original report cites that a conductor-to-conductor short circuit involving the two conductors of the source cable did occur, but that “(t)here was no other short circuit.” Based on our own examination of the test data, it would appear that the initial failure mode was indeed the conductor-to-conductor failure in the source cable (at 8:00). However, it also appears that the source-to-target cable insulation resistance value degraded continuously, and that a hard short between the source and target cables occurred (at about 8:40). This was then followed (at 9:00) by a short-to-ground involving the tray and both the source and target cables.

A.3 Other References

In addition to the references discussed in detail above, a literature review on cable damage during fire tests identified several other references. As noted above these other references were found to be either subsidiary documents that repeated information obtained in the documents reviewed above, or contained no specific information relevant to the assessment of cable fire damage during a fire. The other documents identified in the literature review are listed in the three subsections that follow.

A.5.1 Other EPRI Documents

J.P. Hill, “Fire Tests in Ventilated Rooms, Extinguishment of Fire in Grouped Cable Trays,” EPRI NP-2660, Factory Mutual Research Corporation, Norwood, Massachusetts, December 1982.

J. S. Newman, “Fire Tests in Ventilated Rooms Detection of Cable Tray and Exposure Fires,” EPRI NP-2751, Factory Mutual Research Corporation, Norwood, Massachusetts, February 1983.

J. S. Newman, “Fire Tests in Ventilated Rooms Detection of Cable Tray and Exposure Fires,” EPRI NP-2751, Factory Mutual Research Corporation, Norwood, Massachusetts, February 1983.

A.5.2 Other USNRC Documents

L. J. Klamerus, “A Preliminary Report on Fire Protection Research Program Fire Retardant Coatings Tests (December 7, 1977 - January 31, 1978),” SAND78-0518, Sandia National Laboratories, March 1978.

L. J. Klamerus, “Fire Protection Research Quarterly Progress Report (October - December 1977),” SAND78-0477, NUREG/CR-0366, Sandia National Laboratories, August 1978.

L. J. Klamerus, “A Preliminary Report on Fire Protection Research Program Fire Barriers and Fire Retardant Coatings Tests,” SAND78-1456, NUREG/CR-0381, Sandia National Laboratories, September 1978.

Donald A. Dube, “Fire Protection Research Program for the US Nuclear Regulatory Commission 1975-1981,” SAND82-043, NUREG/CR-2607, Sandia National Laboratories, April 1983.

"Fire Protection and Hydrogen Burn Equipment Survival Research at Sandia National Laboratories," SAND85-1818C, published in *Conference Proceedings of the Thirteenth Water Reactor Safety Research Information Meeting*, Gaithersburg, MD, USNRC, October 1985.

John Wanless, “Investigation of Potential Fire-Related Damage to Safety-Related Equipment in Nuclear Power Plants,” SAND85-7247, NUREG/CR-4310, Sandia National Laboratories, November 1985.

M. J. Jacobus, "Screening Tests of Representative Nuclear Power Plant Components Exposed to Secondary Fire Environments," SAND86-0394, NUREG/CR-4596, Sandia National Laboratories, June 1986.

J. M. Chavez and L. D. Lambert, "Evaluation of Suppression Methods for Electrical Cable Fires," SAND83-2664, NUREG/CR-3656, Sandia National Laboratories, October 1986.

Donald B. King, et al., "Safety-Related Equipment Survival in Hydrogen Burns in Large Dry PWR Containment Buildings," SAND86-2280, NUREG/CR-4763, Sandia National Laboratories, March 1988.

S. P. Nowlen, "A Summary of the USNRC Fire Protection Research Program at Sandia National Laboratories; 1975-1987," NUREG/CR-5384, Sandia National Laboratories, December 1989.

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

S. P. Nowlen, "The Fire Performance of Aged Electrical Cables," SAND91-0963C, presented at *ANS 15th Biennial Reactor Operations Division Topical Meeting on Reactor Operating Experience*, Bellevue WA, August 11-14, 1991.

M. J. Jacobus, Aging, Loss-of-coolant Accident (LOCA, and High Potential Testing of Damaged Cables, NUREG/CR-6095, SAND93-1803, SNL, Apr. 1994.

A.5.3 Other Miscellaneous Documents

R. L. Scott, "Browns Ferry Nuclear Power-Plant Fire on Mar. 22, 1975," *Nuclear Safety*, Vol. 17, No. 5, September-October 1976. [Congressional hearings also a source.]

"Report on Fire Resistant Cables," File R10925-1, Underwriters Laboratories Incorporated, April 10 1984.

"Sheathed Cables Without Halogen (WH) Test Performed Outdoors," 181298-3, Electricité de France, January 1999.

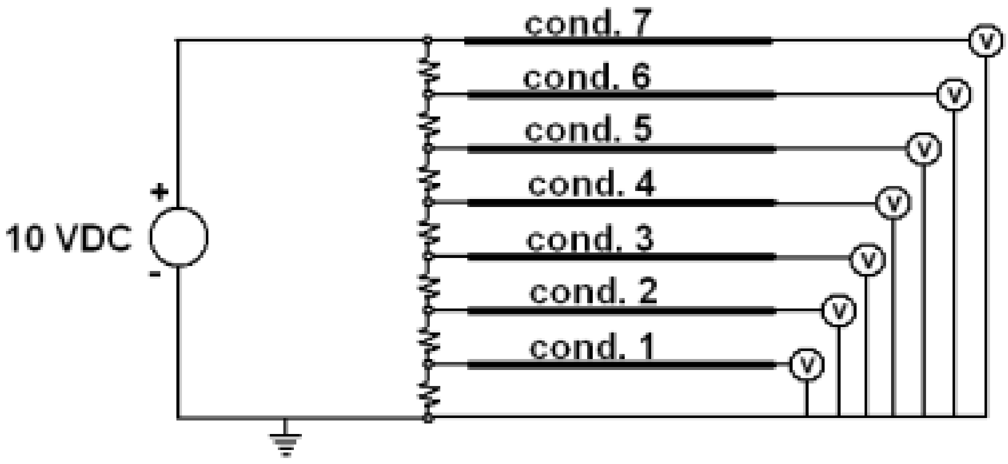


Figure A-1. Schematic representation of the FMRC cable functionality monitoring circuit as inferred from the description provided in the test report EPRI NP-1675.

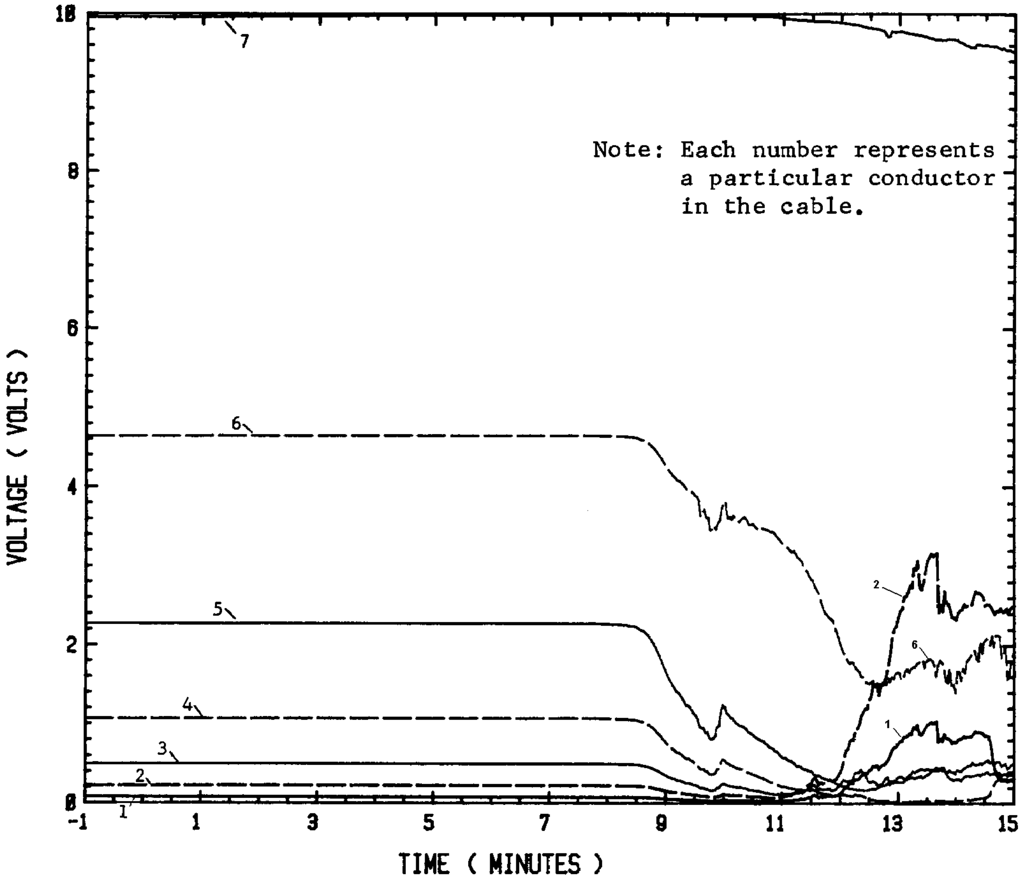


Figure A-2. Figure 3-11 from EPRI NP-1675 illustrating cable functionality measurements during FMRC Test 28.

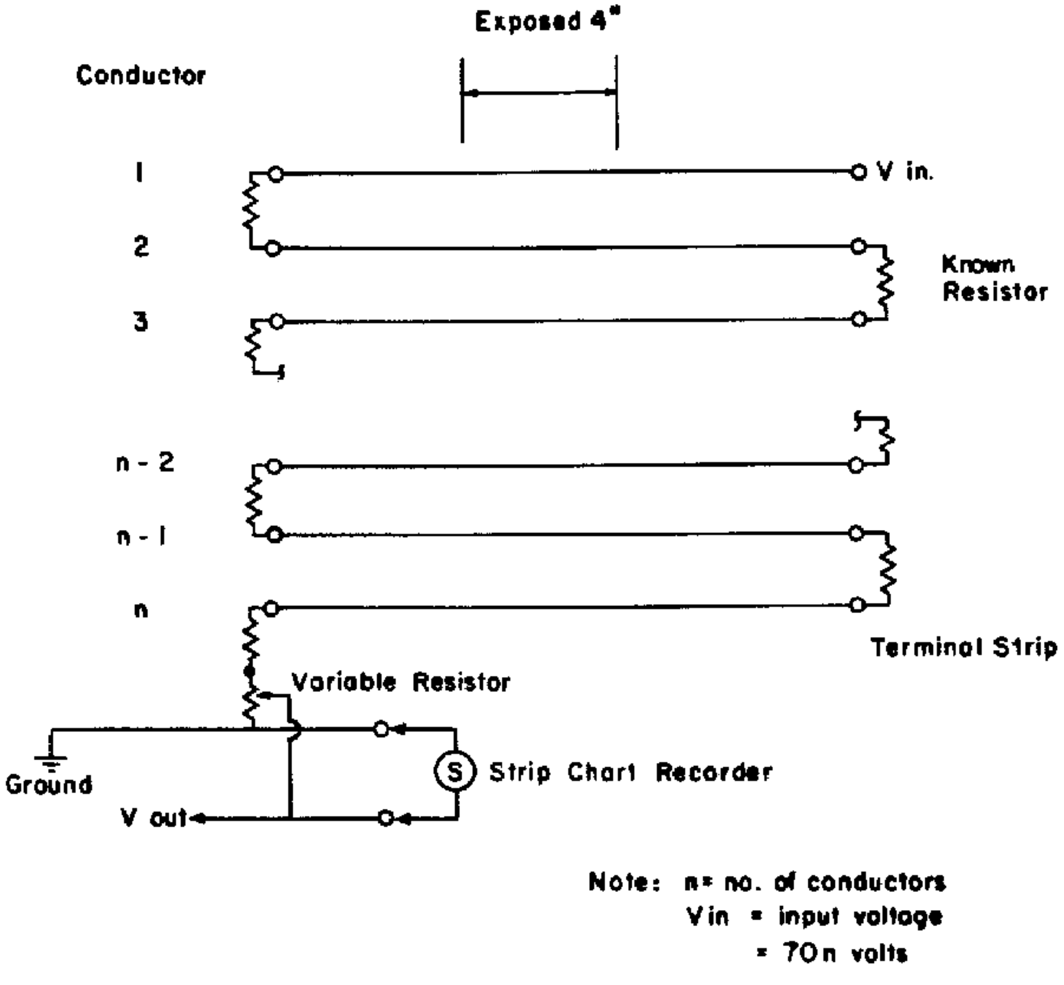
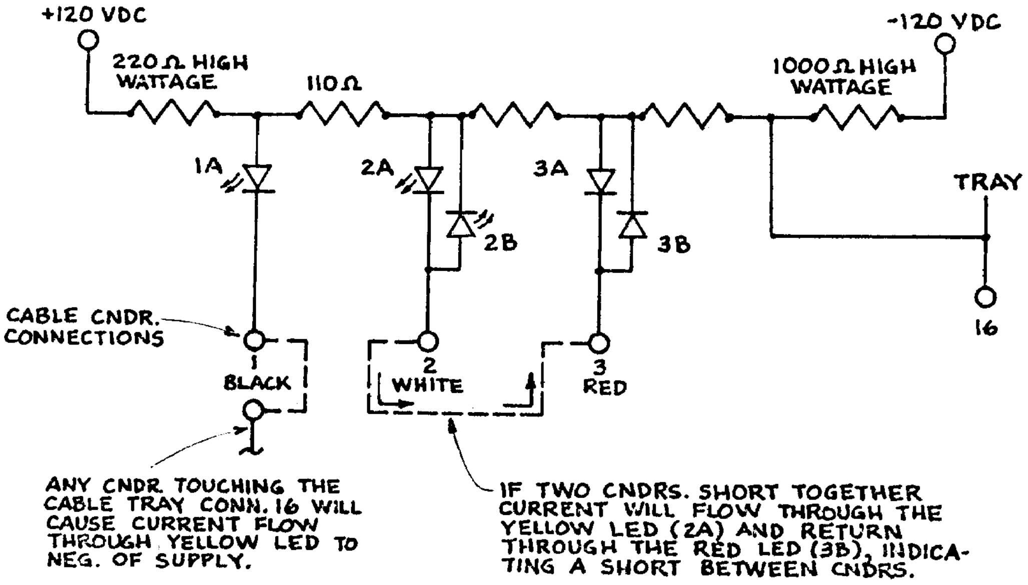
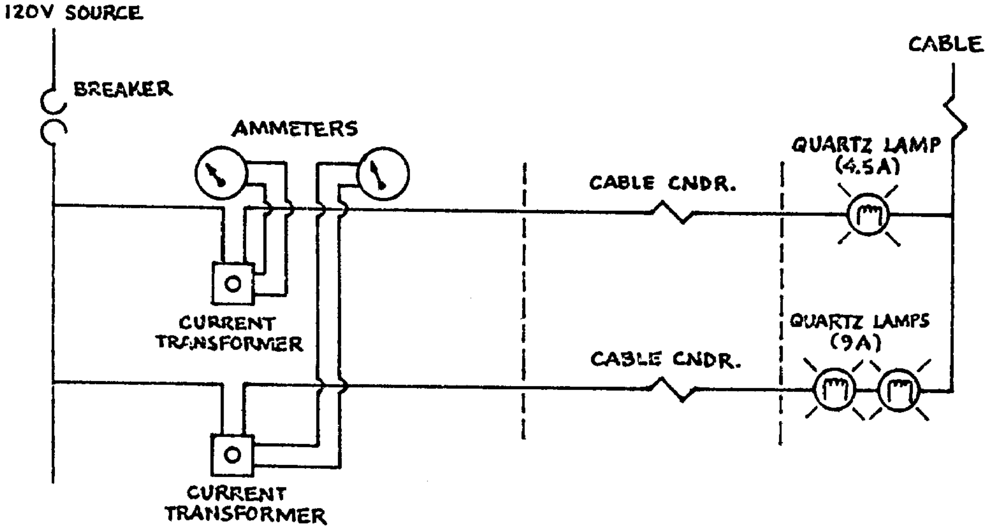


Figure A-3. Circuit used in FMRC tests as documented in EPRI NP-1767 (a reproduction of Figure 2-3 from that same report).



CIRCUIT INTEGRITY DEVICE



ENERGIZED CABLE

Figure A-4. Circuits used in 20-ft Separation Tests. Top circuit used for upper tray and detects conductor-to-conductor and conductor-to-ground failures. Bottom circuit used for lower tray and detects open circuit failures.

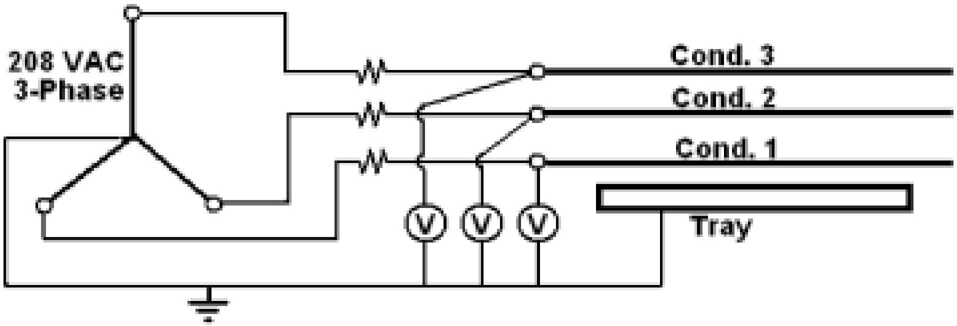


Figure A-5. Cable monitoring circuit used in NUREG/CR-4638. Note the voltage monitors placed on each conductor.

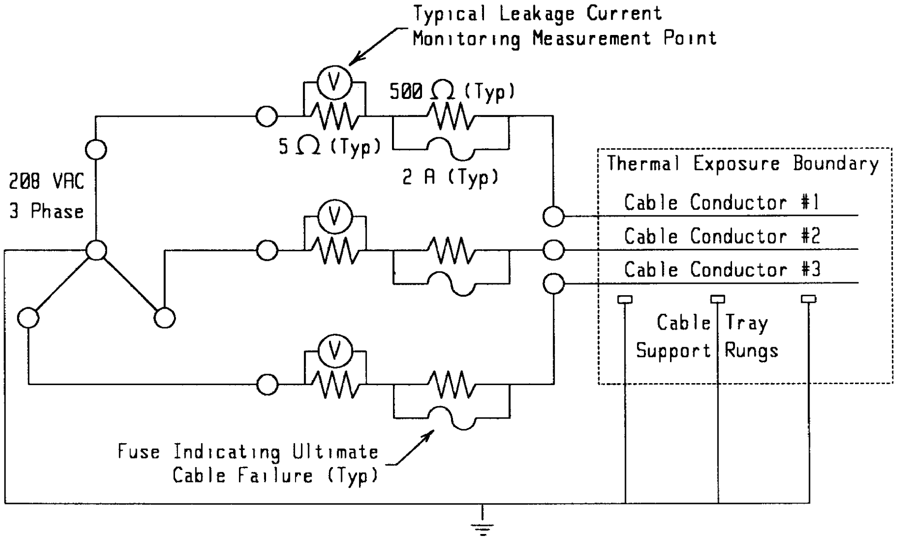


Figure A-6. Circuit used in NUREG/CR-5546 tests.

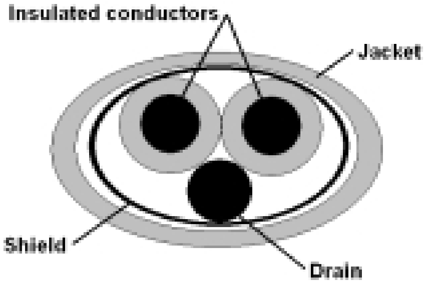
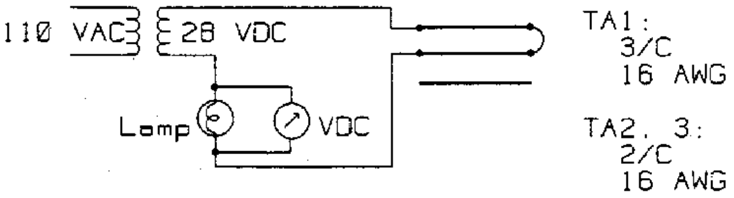
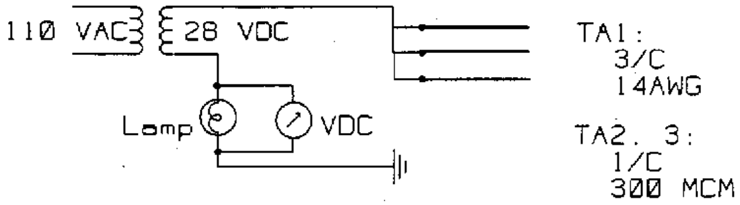


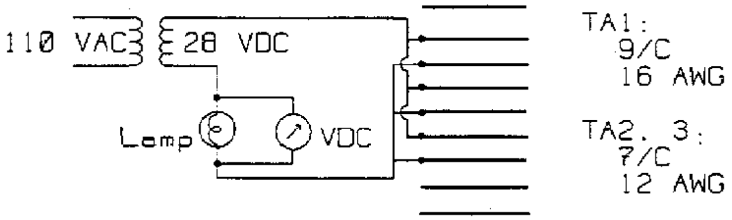
Figure A-7. Schematic representation of the 2/C BIW wire tested by SNL.



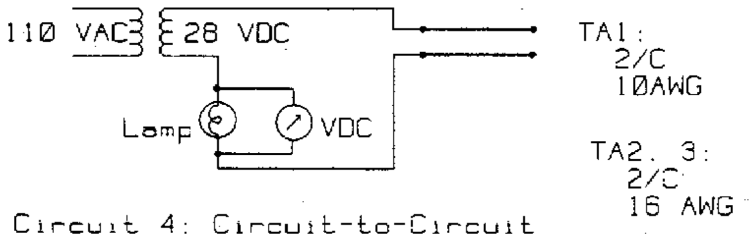
Circuit 1: Circuit-to-System



Circuit 2: Circuit-to-Ground



Circuit 3: Circuit-to-Circuit



Circuit 4: Circuit-to-Circuit

Figure A-8. Four circuits used to monitor cable function in tests documented in SAND94-0146.

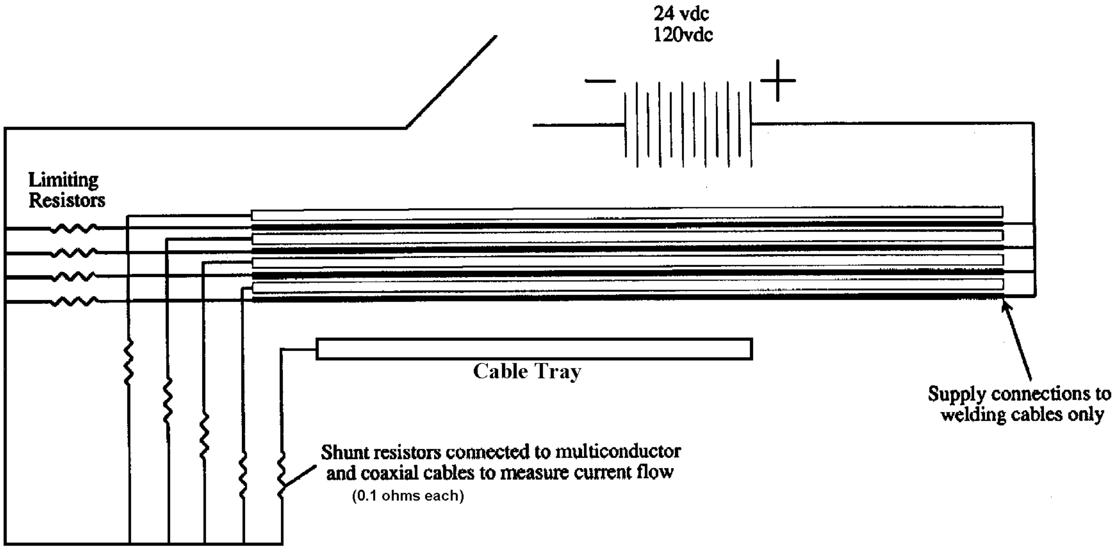


Figure A-9. Circuit used in LLNL/DOE cable fire tests. This is essentially Figure 26 from UCRL-ID-110598, but note that the battery polarity has been corrected and wiring of cable tray is indicated (per discussions with K. J. Staggs).

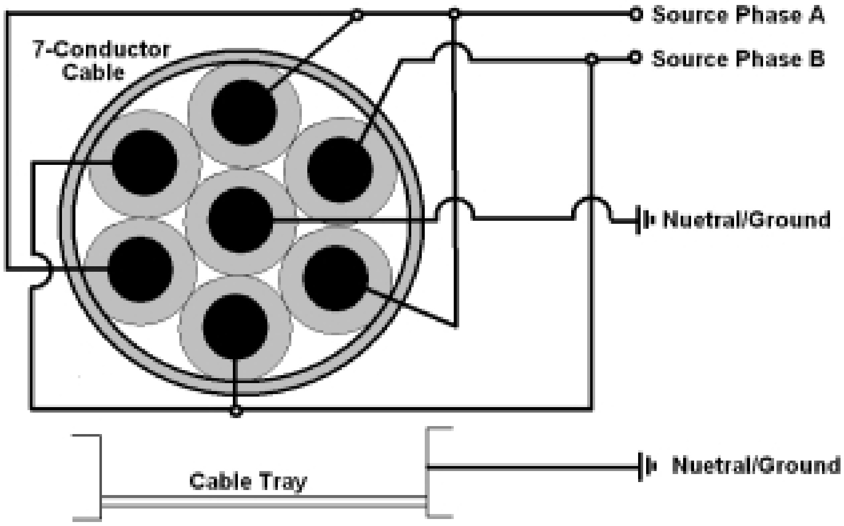


Figure A.10. Schematic of energizing circuit used in UL NC555 cable tray fire tests [27]. Circuit voltage is not specified. Note that center conductor and tray are both grounded.

APPENDIX B

FMECA RESULTS FOR SELECTED CONTROL CIRCUITS

B.1 Introduction

A series of Failure Modes and Effects Criticality Analyses (FMECA) were performed for the control circuits for typical components in nuclear power plants. These include control circuits for a solenoid-operated valve, a motor-operated valve, and a pump; a temperature instrument circuit; and a relay logic circuit. The results of these FMECAs are presented in this Appendix.

B.2 Solenoid-Operated Valve FMECA Results

An FMECA was performed for the solenoid-operated valve (SOV) control circuit shown in Figure B-1. The results of the FMECA are provided in Table B-1.

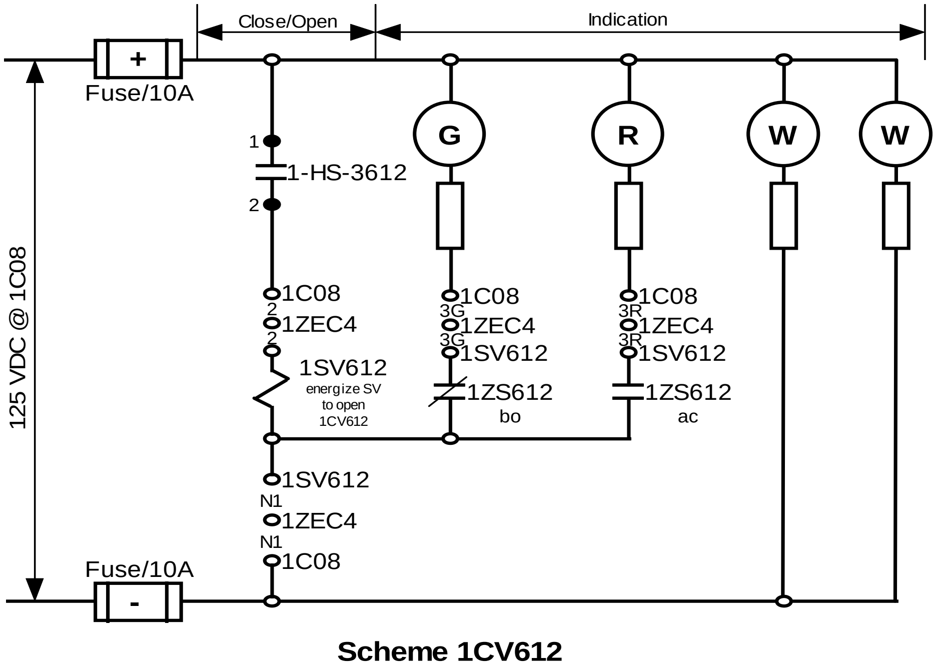


Figure B-1. Solenoid-operated valve control circuit.

Table B-1. NPP Instrumentation and Controls FMECA Summary Results - SOV

Criticality Rank	Definition	Open ckt	Sht-gnd	Ext Shorts	2/c shorts	3/c shorts	4/c shorts	5/c shorts	6/c shorts	TOTAL
0	No effect on valve operability or position and power indication		4	1	1					6
1	Valve operable, loss of valve position indication if valve position changed when fault is present									0
2	Valve operable, loss of valve position or power indication	1								1
3	Valve operable, spurious valve position indication if valve position changed when fault is present	1		1	1					3
4	Valve operable, spurious valve position indication for duration of conductor fault			1	2	1				4
5	Valve inoperable, position and power indication functions	1								1
6	Spurious position indication, valve and position/power indication failures if valve position changed when conductor fault is present					2	1			3
7	Valve and position/power indication failures if valve position changed when conductor fault is present			2	2	1				5
8	Valve inoperable and position and power indication failure	1		2						3
9	Spurious valve operation for duration of conductor fault, position and power indication functions			1						1

B.3 Motor-Operated Valve FMECA Results

An FMECA was performed for the motor-operated valve (MOV) control circuit shown in Figure B-2. The results of the FMECA are provided in Table B-2.

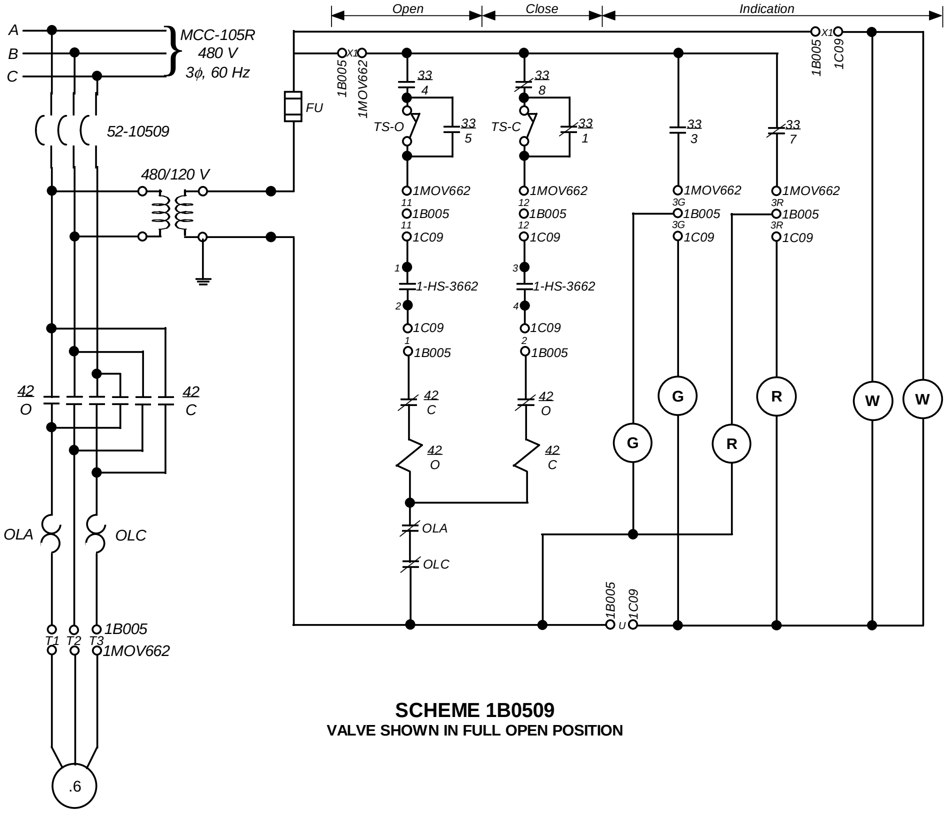


Figure B-2. Motor-operated valve control circuit.

Table B-2. NPP Instrumentation and Controls FMECA Summary Results - MOV

Criticality Rank	Definition	Open ckt	Sht-gnd	Ext Shorts	2/c shorts	3/c shorts	4/c shorts	5/c shorts	6/c shorts	7/c shorts	8/c shorts	TOTAL
0	No effect on valve operability or position and power indication		2	4	6	4						16
1	Valve operable, loss of valve position indication if valve position changed when fault is present	2										2
2	Valve operable, loss of valve position or power indication	2										2
3	Valve operable, spurious valve position indication if valve position changed when fault is present				1		1					2
4	Valve operable, spurious valve position indication for duration of conductor fault	2		4	3	6	4	1				20
5	Valve inoperable, position and power indication functions			1	3	8	5	1				18
6	Spurious position indication, valve and position/power indication failures if valve position changed when conductor fault is present					1	7	10	5	1		24
7	Valve and position/power indication failures if valve position changed when conductor fault is present	4	4		6	7	2	1				24
8	Valve inoperable and position and power indication failure	1	5	1	4	20	41	38	22	7	1	140
9	Spurious valve operation for duration of conductor fault, position and power indication functions			1	5	10	10	5	1			32

B.4 Motor-Operated Pump FMECA Results

An FMECA was performed for the motor-operated pump control circuit shown in Figure B-3. The results of the FMECA are provided in Table B-3.

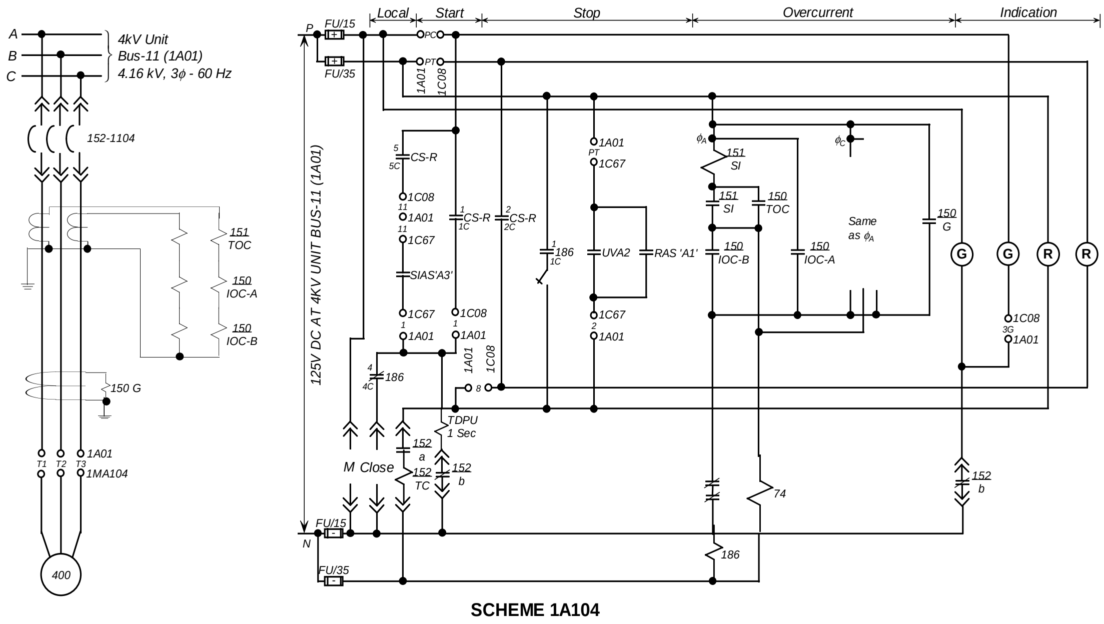


Figure B-3. Pump motor control circuit.

Table B-3. NPP Instrumentation and Controls FMECA Summary Results - Pump

Criticality Rank	Definition	Open ckt	Sht-gnd	Ext Shorts	2/c shorts	3/c shorts	4/c shorts	5/c shorts	6/c shorts	TOTAL
0	No effect on motor operability or status indication		9	3	4	1				17
1	Motor operable, spurious status indication			1	1	1				3
2	Motor operable, loss of status indication	1								1
3	Motor operable, hand switch inoperable	1								1
4	Motor operable, auto-start/run permissives inoperable	4		1						5
5	Motor inoperable, status indication functions									0
6	Spurious status indication, motor and indication failures if actuated while fault is present									0
7	Motor and status indication failures if actuated while fault is present	2		6	1	3	1			13
8	Motor inoperable, status indication failures	1		5	5	9	10	5	1	36
9	Spurious motor operation for duration of fault, status indication functions			2	4	6	4	1		17

B.5 Thermocouple Sensor Circuit FMECA Results

An FMECA was performed for the thermocouple sensor circuit shown in Figure B-4. The results of the FMECA are provided in Table B-4.

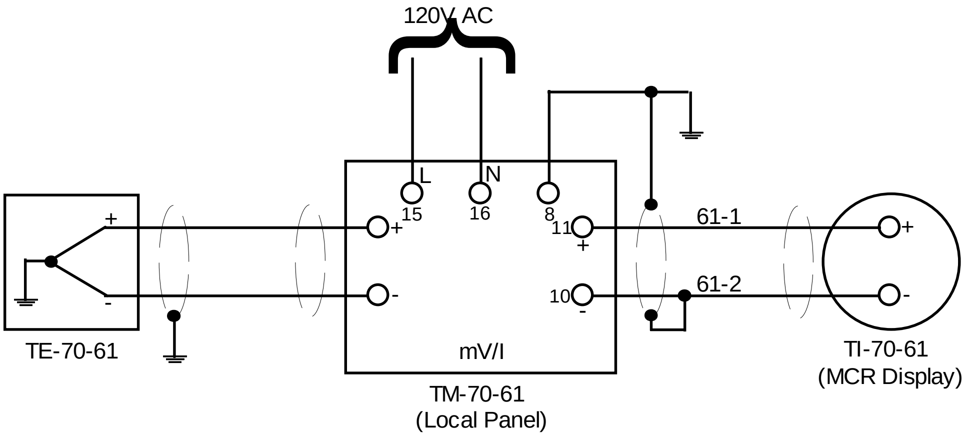


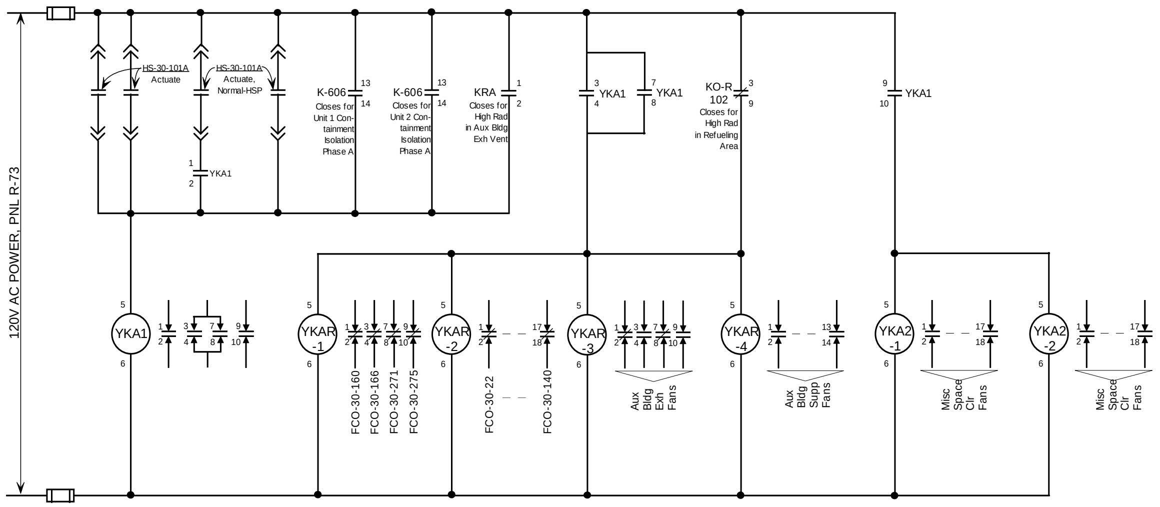
Figure B-4. Thermocouple sensor circuit.

Table B-4. NPP Instrumentation and Controls FMECA Summary Results - Thermocouple Sensor Circuit

Criticality Rank	Definition	Open ckt	Sht-gnd	Ext Shorts	2/c shorts	3/c shorts	4/c shorts	5/c shorts	6/c shorts	TOTAL
0	No effect on instrument operability or readout		3							3
1	(undefined)									
2	(undefined)									
3	(undefined)									
4	Spurious temperature indication	2		8	1					11
5	(undefined)									
6	(undefined)									
7	(undefined)									
8	Instrument inoperable, loss of indication	2	1		1					4
9	(undefined)									

B.6 Auxiliary Relay Circuit FMECA Results

An FMECA was performed for the auxiliary relay circuit shown in Figure B-5. The results of the FMECA are provided in Table B-5.



AUXILIARY BUILDING ISOLATION & HIGH RADIATION IN REFUELING AREA LOGIC BUS

Figure B-5. Auxiliary relay circuit.

Table B-5. NPP Instrumentation and Controls FMECA Summary Results - Auxiliary Relay Logic Circuit

Criticality Rank	Definition	Open ckt	Sht-gnd	Ext Shorts	2/c shorts	3/c shorts	4/c shorts	5/c shorts	6/c shorts	7/c shorts	8/c shorts	TOTAL
0	No effect on system operability			8	18	14	6	1				47
1	(undefined)											
2	(undefined)											
3	(undefined)											
4	(undefined)											
5	Auto-start/control functions lost	14										14
6	(undefined)											
7	Operational system failure if actuated while fault is present		7									7
8	Complete and immediate system failure (inoperable)		7									7
9	Spurious system actuation			6	17	46	65	55	28	8	1	226

APPENDIX C

REVIEW OF THE BROWNS FERRY 1 FIRE-INDUCED CIRCUIT FAILURES

C.1 Introduction

The Browns Ferry Unit 1 fire that occurred in 1975 involved over 1600 cables routed in 117 conduits and 26 cable trays. Various studies of that incident have identified that the fire resulted in spurious initiation of components, spurious control room annunciation, spurious indication light behavior, and loss of many safety-related systems. An example of some of the spurious signal and component behavior is provided in Table C-1. This sequence of events is extracted from Exhibit B1, Page 1 of 9, *Browns Ferry Unit 1 Sequence of Significant Operational Events at Time of Fire*, contained in Regulatory Investigation Report Office of Inspection and Enforcement Region II.

Table C-1. Partial sequence of events from 1975 Browns Ferry Unit 1 fire.

Time	Event and Operator Action
12:35	Fire reported.
12:40	Received following alarms: 1) Residual heat removal (RHR) or core spray (CS) pumps running/auto blowdown permissive 2) Reactor level low/auto blowdown permissive 3) Core cooling system/diesel initiate.
12:42	RHR and CS pump running alarm received. High-Pressure Coolant Injection (HPCI) system pump and Reactor Core Isolation Cooling (RCIC) system pump started Reactor operator stopped pumps and attempted to reset the alarm; pumps stopped, alarm would not reset.
12:44	RHR and CS pumps restarted for no apparent reason. Reactor operator attempted to stop the RHR and CS pumps. Pumps could not be stopped from benchboard.
12:48	The following occurred: 1) Reactor recirculation pumps run back for no apparent reason 2) Began losing electrical boards 3) Indicating lights over valve and pump control switches on panel 9-3 (Emergency Core Cooling System control panel) were glowing brightly, dimming, and going out (reactor operator observed smoke from control wiring under panel 9-3) 4) Lost ½ of reactor protection system 5) Lost remote manual control of a number of relief valves 6) Numerous alarms occurred on all control panels and unit in unstable swing.

To help understand the potential impacts of a fire on circuit behavior, a study of some of the system behavior during the Browns Ferry fire was undertaken. Specifically, an attempt to identify the direct causes of the alarms shown in Table C-1 received at 12:40 and 12:42, and the reason for the apparently spurious operation of the RHR and CS pumps at 12:48. Furthermore, additional drawings were reviewed to gain an understanding of the Emergency Core Cooling System (ECCS) motor-operated valve (MOV) indicating light behavior. The best available documentation for conducting this study were Addendums A, B, and C of *Physical Damage to Electrical Cables and Raceways Involved in the Browns Ferry Nuclear Plant Fire on March 22, 1975*, Report Number BF-DED (BHP-1), Tennessee Valley Authority, April 17, 1975 (the main body of this report is included as Exhibit C1 of the Region II Inspection Report cited above). Addendum A includes 204 cable tabulation sheets and an index listing of each cable, its purpose, termination points, type, the raceway it is located in, and electrical drawing references used for locating cables as to function. Addendum B includes 315 electrical drawings by vendors and TVA showing where each cable is found per its function. Addendum C provides TVA cable routing checkpoint sheets.

It is important to note that the quality of the electric schematic drawings (contained in Addendum B) is in many cases poor and a number of the drawings are very difficult to read. Consequently, some device identification is either missing (illegible on the drawings), or possibly inaccurate (best guess by the study group).

C.2 Evaluation of Annunciator Alarms

The circuit diagrams for the Browns Ferry systems at the time of the 1975 fire were examined in an attempt to understand the cause of several spurious alarms received during the fire. Evaluations were performed for the following alarms:

- RHR or CS Pump Running Auto Blowdown Permissive (12:40)
- Reactor Level Low Auto Blowdown Permissive (12:40)
- Core Cooling System/Diesels Initiate (12:40)
- RHR Pump Start (12:42)
- CS Pump Start(12:42)

C.2.1 RHR or CS Pump Running Auto Blowdown Permissive (12:40)

The “RHR or CS Pump Running Auto Blowdown Permissive” alarm was one of the first received in the control room following the initial report of the fire. TVA drawing 45N620-2 indicates that the input contacts controlling the “RHR or CS Pump Running Auto Blowdown Permissive” alarm on Panel 9-3 are controlled by any one of the relays shown in Table C-2 (they are connected in parallel).

Table C-2. RHR or CS pump running auto blowdown permissive relays.

Relay ID	Contact Numbers
2E-K4	8, 2
2E-K27	8, 2
2E-K19(?)	8, 2
2E-K31	8, 2

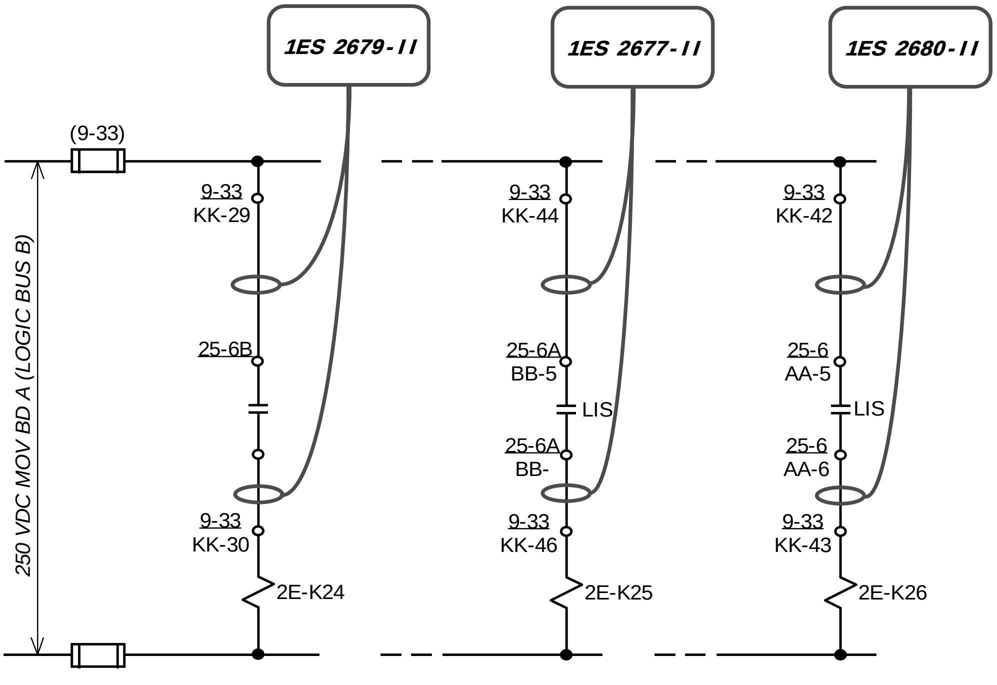
However, markups of the GE elementary drawing (730E929 SH 1) of the Automatic Blowdown System (ABS) indicate the cables listed in Table C-3, affecting circuit annunciator relays, as being damaged in the fire.

Table C-3 ABS cables affecting circuit annunciator relays.

Cable ID	Relay ID	Coil Connection Numbers
1ES 2679-II	2E-K24	13, 14
1ES 2677-II	2E-K25	5, 6
1ES 2680-II	2E-K26	5, 6

These particular relays are intended to initiate alarms for a low water level condition in the reactor. Sheet 2 of 730E929 is referenced in the tables of contact functions on sheet 1 but was not included in the package of electric system drawings. Figure C-1 shows a schematic of the relevant relay branches in the ABS relay logic circuit. Unfortunately, the relay IDs given on the two drawings do not match. It is possible, however, to postulate that internal conductor-to-conductor shorts within an ABS relay logic circuit cable could cause the annunciator alarm.

In addition, information gathered regarding these cables (see Figure C-1) indicates that they all were routed through the zone of fire influence as shown in Table C-4, thus giving credence to the possibility that one (or more) conductor shorts may have occurred to initiate the alarm. It is important to realize that Checkpoint 131 is in the reactor building and is the closest checkpoint to the cable penetration from the cable spreading room where the fire initiated.



(Ref.: GE 730E929 SH 1, Automatic Blowdown System)

Figure C-1. Partial schematic of ABS relay logic circuit.

Table C-4. ABS relay logic circuit cables.

Cable ID	Type	Checkpoint/Cable Tray ID		
		128	129	131
1ES 2679-II	2/c #14	KE-ESII	KE-ESII	MX-ESII
1ES 2677-II	2/c #14	KE-ESII	KE-ESII	MX-ESII
1ES 2680-II	2/c #14	KE-ESII	KE-ESII	MX-ESII

C.2.2 Reactor Level Low Auto Blowdown Permissive (12:40)

The "Reactor Level Low Auto Blowdown Permissive" alarm was another one of the first received in the control room following the initial report of the fire. TVA drawing 45N620-2 indicates that the input contacts controlling this alarm on Panel 9-3 are from the relays shown in Table C-5 (they are connected in parallel).

Table C-5. Relays providing input to the reactor level low ABS permissive alarm logic.

Relay ID	Contact Numbers
2E-K29	12, 11
2E-K24	12, 11

Note that 2E-K24 is one of the relays shown in Figure C-1 and is powered through cable 1ES 2679-II. As discussed above, this cable is known to have been routed through the fire-affected cable trays. Consequently, a conductor-to-conductor shorting event—simulating a low level condition signal from the level switch contacts—is a very definite possibility.

C.2.3 Core Cooling System/Diesels Initiate (12:40)

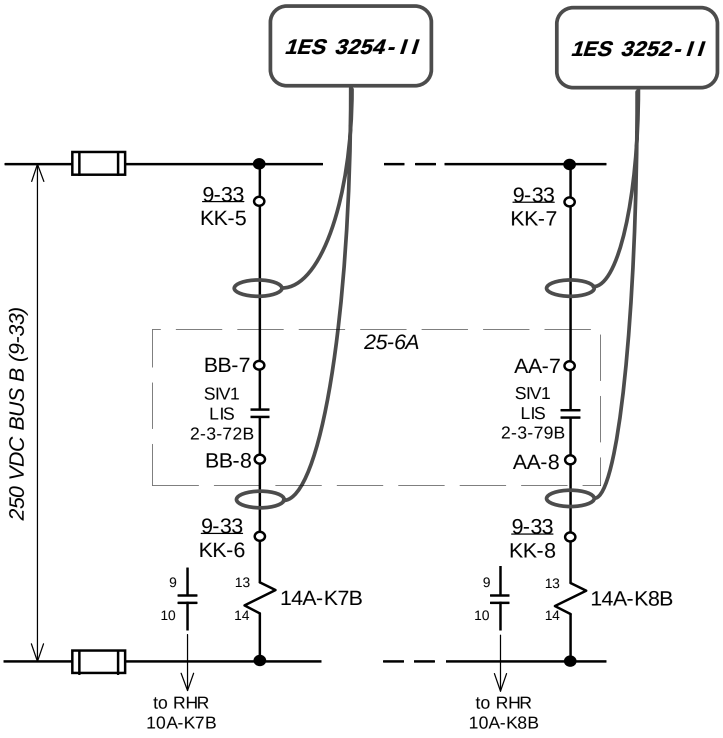
The "Core Cooling System/Diesels Initiate" alarm was the third of the first alarms received in the control room following the initial report of the fire. TVA drawing 45N620-2 indicates that the input contacts controlling this alarm on Panel 9-3 are any of the relays shown in Table C-6 (they too are connected in parallel).

Table C-6. Relays providing input to the CS/diesel initiation alarm logic.

Relay ID	Contact Numbers
14A-K8A	12, 11
14A-K7A	12, 11
14A-K8B	12, 11
14A-K7B	12, 11

The GE elementary drawing (730E930 SH 14) of the Core Spray System indicates that the following cables affecting two of these circuit annunciator relays were identified as being fire damaged.

Figure C-2 shows the relevant portions of the alarm logic relay circuit for the core spray system. Table C-7 indicates the type and cable trays these cables were located in at three of the fire influence zone checkpoints. As a result of this information, it appears that a conductor-to-conductor shorting event—simulating a low level condition signal from the level switch contacts—is a very definite possibility.



(Ref.: GE 730E930 SH 14, Core Spray System)

Figure C-2. Partial schematic of Core Spray relay logic circuit.

Table C-7. Cables for CS alarm logic relay circuit.

Cable ID	Type	Checkpoint/Cable Tray ID		
		128	129	131
1ES 3254-II	2/c #14	KE-ESII	KE-ESII	MX-ESII
1ES 3252-II	2/c #14	KE-ESII	KE-ESII	MX-ESII

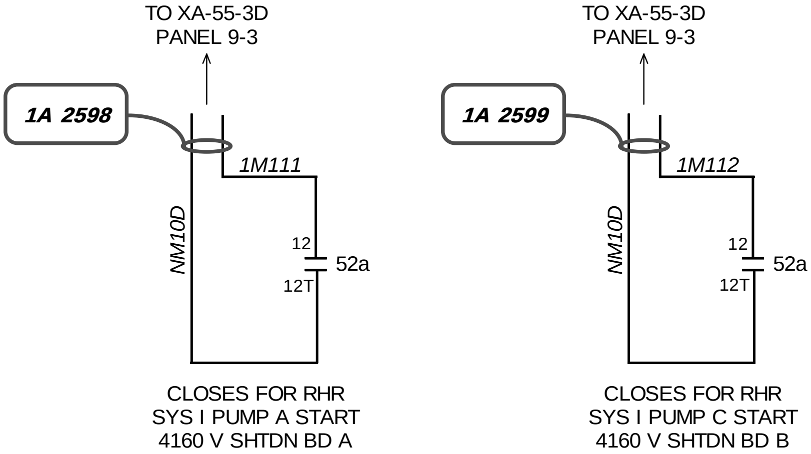
C.2.4 RHR Pump Start (12:42)

TVA drawing 45N620-2 indicates that the input contacts controlling the “RHR Pump Start” annunciator alarms on Panel 9-3 are listed in Table C-8. Figure C-3 shows a partial schematic of the relevant annunciator circuits from the drawing.

Table C-8. Relay contacts controlling the "RHR Pump Start" annunciator alarms on Panel 9-3.

RHR Pump ID	Relay ID	Contact Numbers
Sys. I Pump A	52a	12, 12T
Sys. I Pump C	52a	12, 12T

Information gathered regarding the cable routings indicates different cable identifiers for these circuits (e.g., 2A 2598 vs. 1A 2598). This discrepancy may simply be an error made during the markup of drawing 45N620-2. (Also, assuming the "2A" identifier indicates a system II component, the fact, as will be discussed later, that the drawing package includes markups of the control circuits for RHR pumps 2A and 2C makes this assumption appear to be consistent with the bulk of the available information.) Cables 2A 2598 and 2A 2599 were both routed through the zone of fire influence as shown in Table C-9.



(Ref.: TVA 45N620-2, ANNUNCIATOR SYSTEM)

Figure C-3. Partial schematic of annunciator circuit for the RHR Pump Start alarms.

Table C-9. Cables related to RHR pump start alarm circuit.

Cable ID	Type	Checkpoint/Cable Tray ID	
		128	131
2A 2598	2/c #18	VK	VK
2A 2599	2/c #18	VK	VK

This too indicates that conductor shorting within these two cables was certainly possible, and, if so, would have resulted in the annunciator alarms at panel 9-3 in the control room.

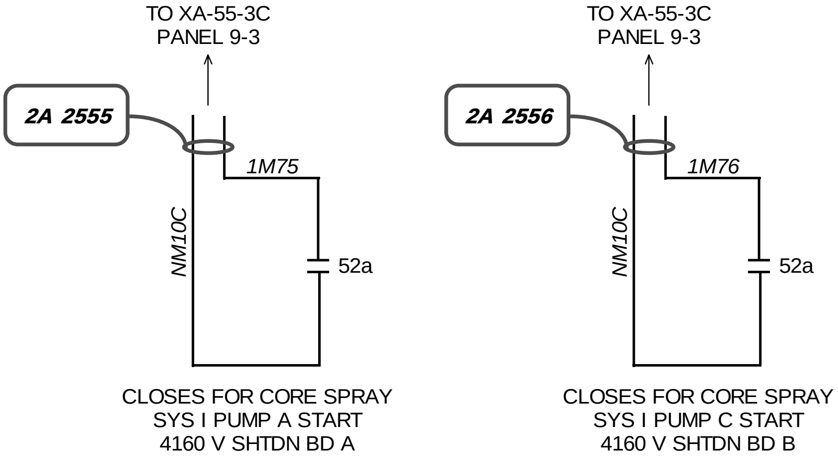
C.2.5 CS Pump Start(12:42)

TVA drawing 45N620-2 also shows the input contacts (see Table C-10) controlling the "CS Pump Start" alarms on Panel 9-3.

Table C-10. CS pump alarm relays.

CS Pump ID	Relay ID
Sys. I Pump A	52a
Sys. I Pump C	52a

Figure C-4 shows a partial schematic of the Core Spray Pump Start alarm circuit. Unlike the case for the RHR pump alarm circuit markups, the CS pump alarm circuit markups indicate cables 2A 2555 and 2A 2556 as the cables of concern (i.e., no discrepancies).



(Ref.: TVA 45N620-2, ANNUNCIATOR SYSTEM)

Figure C-4. Partial schematic of annunciator circuit for the Core Spray Pump Start alarms.

Information gathered regarding the cables indicates that they too were routed through the zone of fire influence as shown Table C-11. Again, this supports the hypothesis that conductor shorting within these two cables would have caused the Core Spray Pump Start alarm on the annunciator panel.

Table C-11. Cables related to CS pump alarm circuit.

Cable ID	Type	Checkpoint/Cable Tray ID	
		128	131
2A 2555	2/c #18	VE	VE
2A 2556	2/c #18	VE	VE

C.3 Spurious Pump Starts

At 12:44 during the Browns Ferry fire, the event log indicates that the RHR and Core Spray pumps started running for no apparent reason. The following discussions are intended to provide some justification for this occurrence based on an analysis of the relevant pump control circuits.

C.3.1 RHR Pumps

TVA drawing 45N765-4 indicates that the cables for the hand switch and auto start/stop relay contacts controlling the RHR pump operation are the ones listed in Table C-12.

Table C-12. Cables related to RHR pump start/stop circuits.

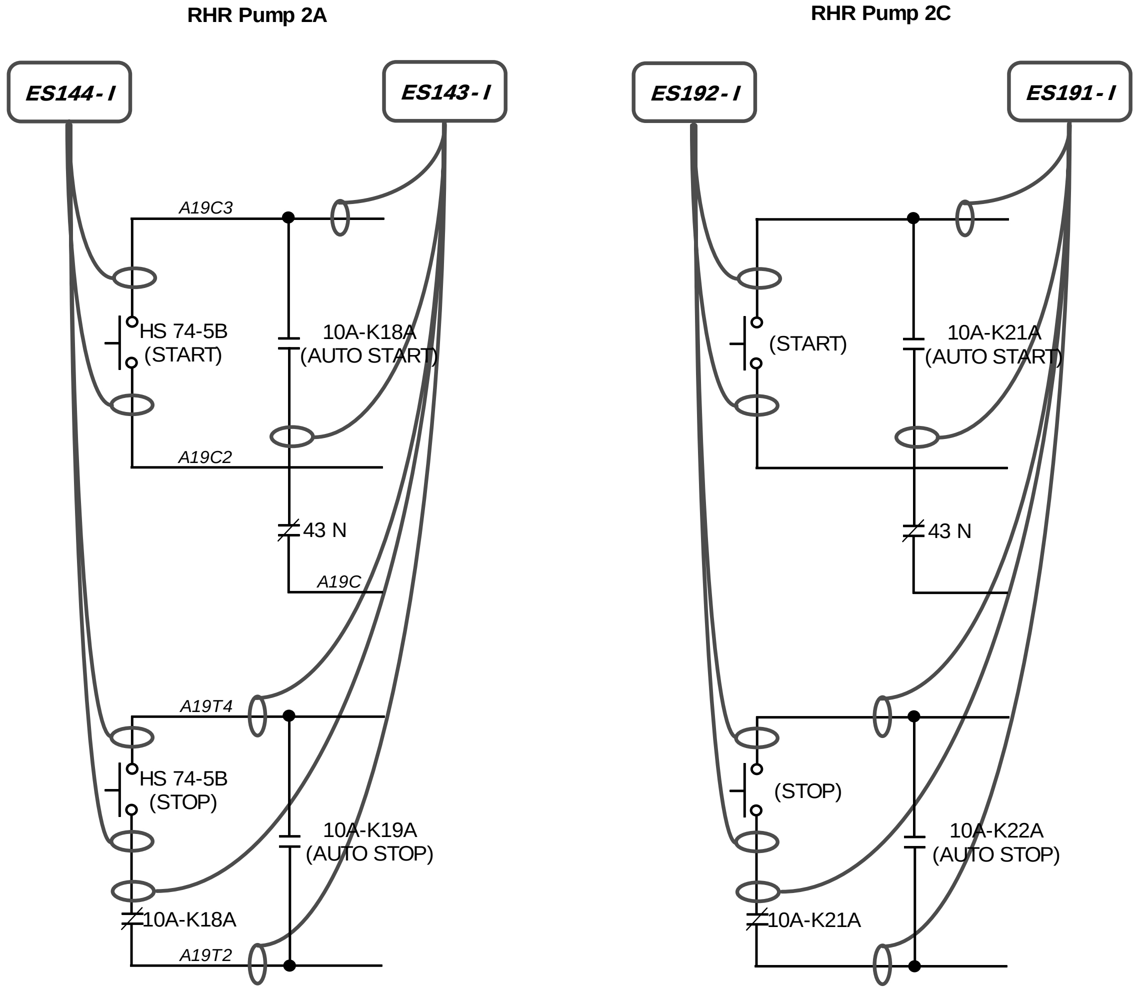
RHR Pump	Cable ID	Hand Switch ID	Auto Start Relay	Auto Stop Relay
2A	ES144-I	HS 74-5B	--	--
2A	ES143-I	--	10A-K18A	10A-K19A
2C	ES192-I	HS 74-5B		
2C	ES191-I	--	10A-K21A	10A-K22A

Figure C-5 shows a schematic of the relay and hand switch branches of the pump control circuit with the fire-impacted cables identified. Information gathered regarding the cables (shown in Table C-13) indicates that they all were installed in conduit that was routed through the zone of fire influence.

Table C-13. RHR pump start/stop cable routing.

Cable ID	Type	Conduit ID
ES144-I	4/c #12	1ES240
ES143-I	?	1ES240
ES192-I	4/c #12	1ES242-I
ES191-I	12/c #12	1ES242-I

It is important to note that shorting of the two conductors going to the hand switch (START) contacts in cable ES144-I (ES190-I) or shorting of the two conductors leading to the auto-start relay in cable ES143-I (ES191-I) would have been able to initiate the pump's operation. Conductor shorting in these cables for the stop (or "trip") circuits is problematical. Shorts that bypass either the hand switch (STOP) contacts or the auto-stop relay contacts should have resulted in tripping the power breaker for the pump motor(s). However, the events log indicates that the operator could not stop the pumps after their spurious restart at 12:44. This might be explained in one of two ways: 1) conductors leading to or from the STOP hand switch contacts may have failed in an open circuit manner (a very convenient explanation) or 2) the trip coil was a time-delay type wherein continuous shorting of the start/auto-start contact conductors could have overridden the influence of the trip coil. There is no information available to determine if one or either of these possibilities is correct.



(Ref.: TVA 45N765-4, RHR Pump Control Circuit)

Figure C-5. Partial schematic of the relay and hand switch branches for the RHR pump

C.3.2 Core Spray Pumps

Much of what was said above regarding the spurious starting of the RHR pumps applies to the Core Spray pumps as well. TVA drawing 45N765-7 indicates that the cables for the hand switch and start relay contacts controlling the CS pump operation are provided in Table C-14.

Figure C-6 shows a schematic of the relay and hand switch branches of the pump control circuit with the fire-impacted cables identified.

Table C-14. CS pump start circuit cables.

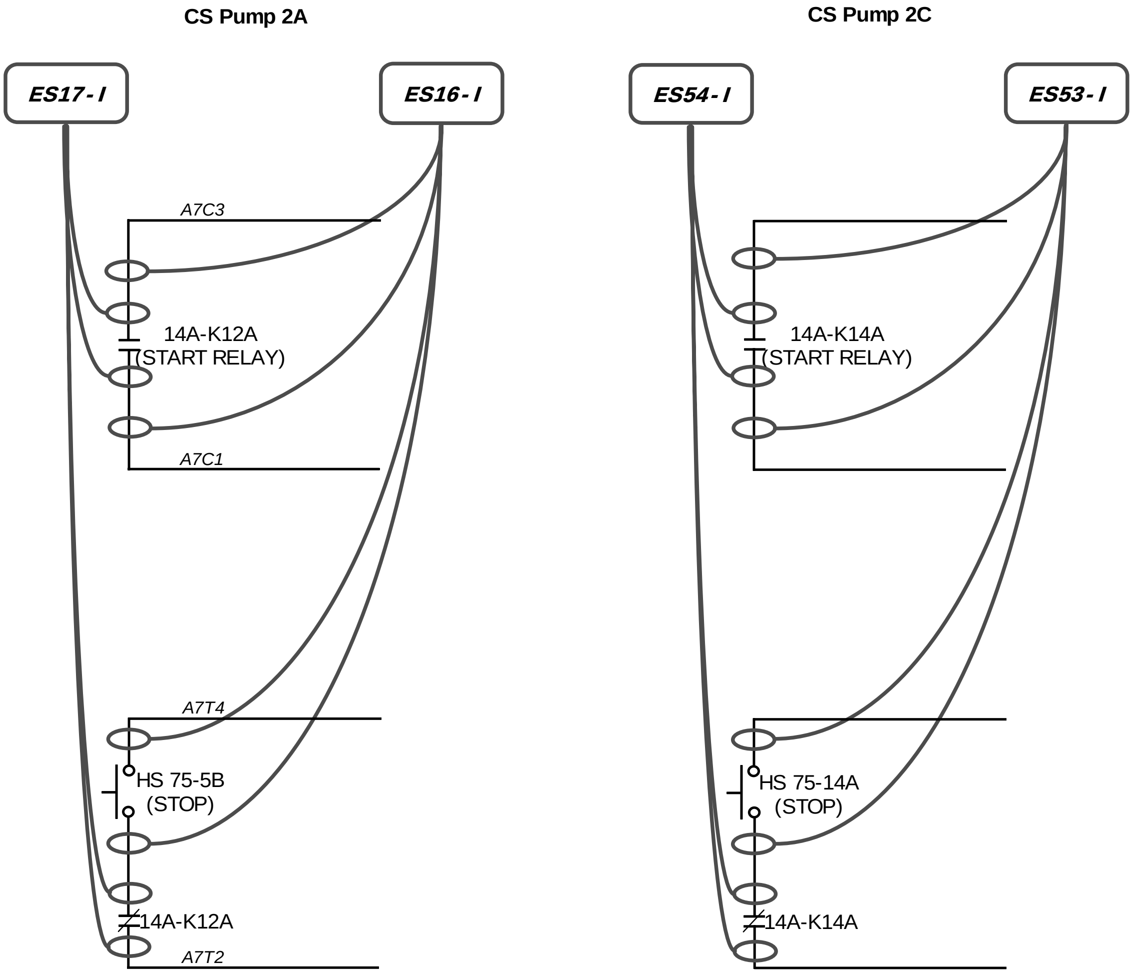
CS Pump	Cable ID	Hand Switch ID	Start Relay
2A	ES17-I	--	14A-K12A
2A	ES16-I	HS 75-5B	14A-K12A
2C	ES54-I	--	14A-K14A
2C	ES53-I	HS 75-14A	14A-K14A

Shorting of the two conductors going to the start relay contacts in cable ES17-I (ES54-I) or in cable ES16-I (ES53-I) would have been able to initiate the pump's operation. Conductor shorting in these cables for the stop circuits also poses a problem. Shorts that bypass the hand switch (STOP)contacts should have resulted in tripping the power breaker for the pump motor(s). Again, the events log indicates that the operator could not stop the pumps after their spurious restart at 12:44. This could also be explained in ways similar to those discussed for the RHR pumps above: 1) conductors leading to or from the STOP hand switch contacts may have failed in an open circuit manner or 2) the trip coil was a time-delay type wherein continuous shorting of the start relay contact conductors could have overridden the influence of the trip coil. Here also, there is no information available to determine if one or either of these possibilities is correct.

Information gathered regarding the cables indicates that they all were installed in conduit that was routed through the zone of fire influence and identified in the damaged cable list of Addendum A.

Table C-15. CS pump cable routing information.

Cable ID	Type	Conduit ID
ES17-I	4/c #12	1ES240
ES16-I	4/c #12	1ES240
ES54-I	4/c #12	1ES240
ES53-I	4/c #12	1ES240



(Ref.: TVA 45N765-7, CS Pump Control Circuit)

Figure C-6. Partial schematic of the relay and hand switch branches for the core spray pump control circuits.

C.4 MOV Board Trip Coil Backfeed

Following the March 22, 1975 fire a number of investigations were conducted. These investigations were intended to identify the root causes of the fire and extensive damage incurred as well as to determine lessons learned from the event. At least two documents published following the fire indicate that a significant contributing factor in the inability to quickly reestablish power to the boards supplying control and power for the various pumps and valves in the ECCS was that the board trip coils were continuously energized through indicating light circuits. For example, in "The Browns Ferry Fire," by J. R. Harkleroad, TVA, the following statement is made.

> *In retrospect, it appears the most significant common failure was the loss of control and position*

> *indication of the valves in the ECCS systems. This resulted from TVA's longstanding design practice of placing an indication light in the control room monitoring continuity of the trip coils of the feeder breakers to the valve control boards. Damage to these indicating light circuits which passed through the fire area resulted in tripping of the feeder breakers. The AC control circuits for the feeder breakers is contained within the board itself except for the indicating light circuit. These cables were considered to be nondivisional because the dropping resistor for the light was located in the respective valve board and the cable circuit was then as being isolated from the breaker control circuit. In the initial recovery phase following the fire, removal of the cable to the indicating lights allowed board restoration.*

In a similar tone, R. L. Scott writes in "Browns Ferry Nuclear Power-Plant Fire on Mar. 22, 1975," Nuclear Safety, Vol. 17, No. 5, September-October 1976:

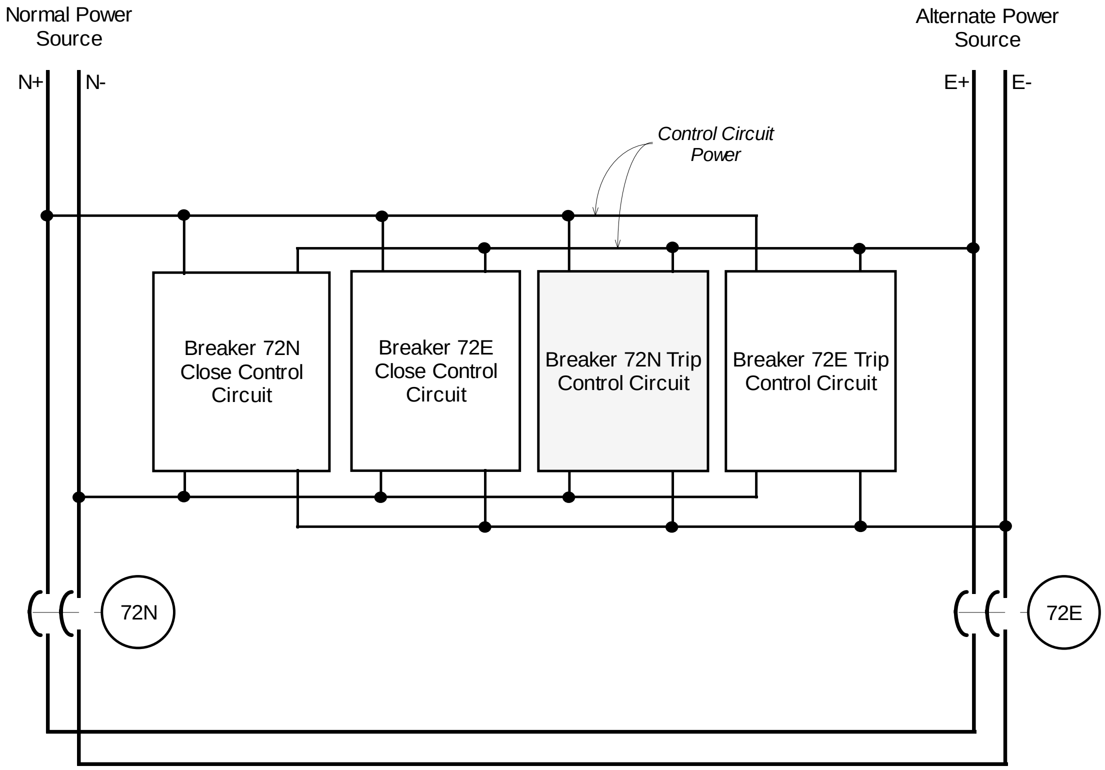
> *The light circuits were thought to be isolated from the power sources and safety circuits by series resistors, but the resistors were ineffective for the types of short circuits that occurred. When the cable insulation had burned away, power was fed backward from the lights to the power and control panels in spite of the resistors, causing breaker trip coils to remain energized and thereby keeping the breakers open. These circuits had not been considered as potential sources of failure of safety equipment, and the separation criteria had not been applied to the cables. They were treated as nonsafety cables whose routing and tray companions were of no consequence.*

Figures C-7 and C-8, below, show schematics of the feeder breaker trip control circuits for a 250 Vdc MOV board. One of the interesting findings was that the same cause prevented either the alternate or normal power sources to be employed. The trip control circuit for the 480 Vac boards is very similar in design.

A review of the TVA drawings revealed that the cables listed in Table C-16 were the conductor pairs associated with the trip coil indicating light circuits.

Table C-16. Cables related to trip coil indicating light circuits.

	Cable ID	**Type**	**Checkpoint/Cable Tray ID**				
			127	145	129	131	
480 VAC Reactor MOV Boards 1A & 1B	1PL 2065	2/c #10	TL-ESII	TL-ESII	TK-ESII	MW-ESII	SAI-ESII
	1PL 2066	2/c #10	TL-ESII	TL-ESII	TK-ESII	MW-ESII	SAI-ESII
	1PL 2067	2/c #10	TL-ESII	TL-ESII	TK-ESII	MW-ESII	SAI-ESII
	1PL 2068	2/c #10	TL-ESII	TL-ESII	TK-ESII	MW-ESII	SAI-ESII
250 VDC Reactor MOV Boards 1A & 1B	1PL 2069	2/c #10	TL-ESII	TL-ESII	TK-ESII	MW-ESII	SAI-ESII
	1PL 2070	2/c #10	TL-ESII	TL-ESII	TK-ESII	MW-ESII	SAI-ESII
	1PL 2071	2/c #10	TL-ESII	TL-ESII	TK-ESII	MW-ESII	SAI-ESII
	1PL 2072	2/c #10	TL-ESII	TL-ESII	TK-ESII	MW-ESII	SAI-ESII



250 VDC Reactor MOV BD Transfer Scheme
(REF. TVA DWG 45N714-7)

Figure C-7. Breaker control circuit block diagram. Note control power is tapped off both sources. (Detail of the 72N Trip Control Circuit is provided in Figure C-8.)

Power to the trip control circuit (Fig. 8) is selectable by setting device 43 to the normal (N) or alternate (E) power supply. This closes the 43N or 43E contacts to the control circuit power supply buses. The breaker is usually tripped manually by a control switch on the switchboard (72 CSN) which allows control power to energize the trip coil (TC) through the closed 72N contacts. These contacts are closed whenever the 72N circuit breaker is closed. In this case, however, both circuit breakers (72N and 72E) were open, thus it is not reasonable to postulate that the trip coil was continuously energized by a current backfed through the indicating light during the fire. Oh the other hand it is reasonable to suppose that a hot short on the indicating light circuit energized the upstream connection to the 72N contacts and only allowed the trip coil to be energized each time the breaker was closed. This, of course, caused the 72N breaker to immediately trip open again. The same scenario applies to the alternate feeder breaker 72E as well as to the normal and alternate feeder breakers on the 480-volt MOV boards.

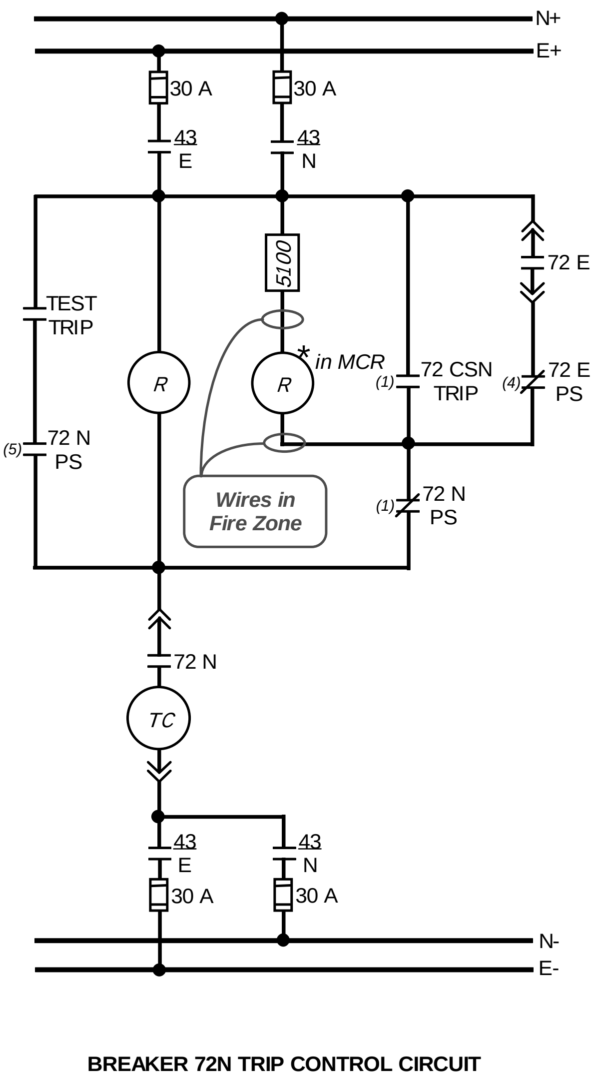


Figure C-8. Direct-current breaker trip control circuit. Alternating-current (480 V) breaker trip control circuit is similar in design. (Ref: TVA Dwgs 45N714-7 & 45N779-6)

It is also interesting to note that of the 73 cables located with in MW-ESII at check point 131, almost half were control or power cables. Thus hot shorts to the trip coil indicating light circuits likely occurred.

C.5 Cable/Tray Locations In Initial Fire Area

Figure C-9 shows the location of many of the cables discussed in this summary with respect to the early stages of the fire. In other words, at or near the penetration between the cable spreading room and reactor building. As a reminder, checkpoint 131 is on the reactor building side of the penetrations and closer to it than any other checkpoint.

This figure also helps explain the timing of the alarms received early in the fire event. The Core

Spray pump start alarm circuits are contained in tray VE, where the fire started, and the RHR pump start alarm circuits are contained in tray VK just next to VE. The auto-blowdown and core spray logic circuitry is located two trays above VE (in MX-ESII), and with the fuel loading of trays MX-ESII, MD, and VE it is conceivable that the fire would spread to MX-ESII very rapidly. Finally, the trip coil indicating light circuits are all contained within tray MW-ESII, further away from the ignition point than the other three trays, hence, the effects should have been noted later in the event (as indeed they were).

Looking South from Cable Spreading Room toward Reactor Building

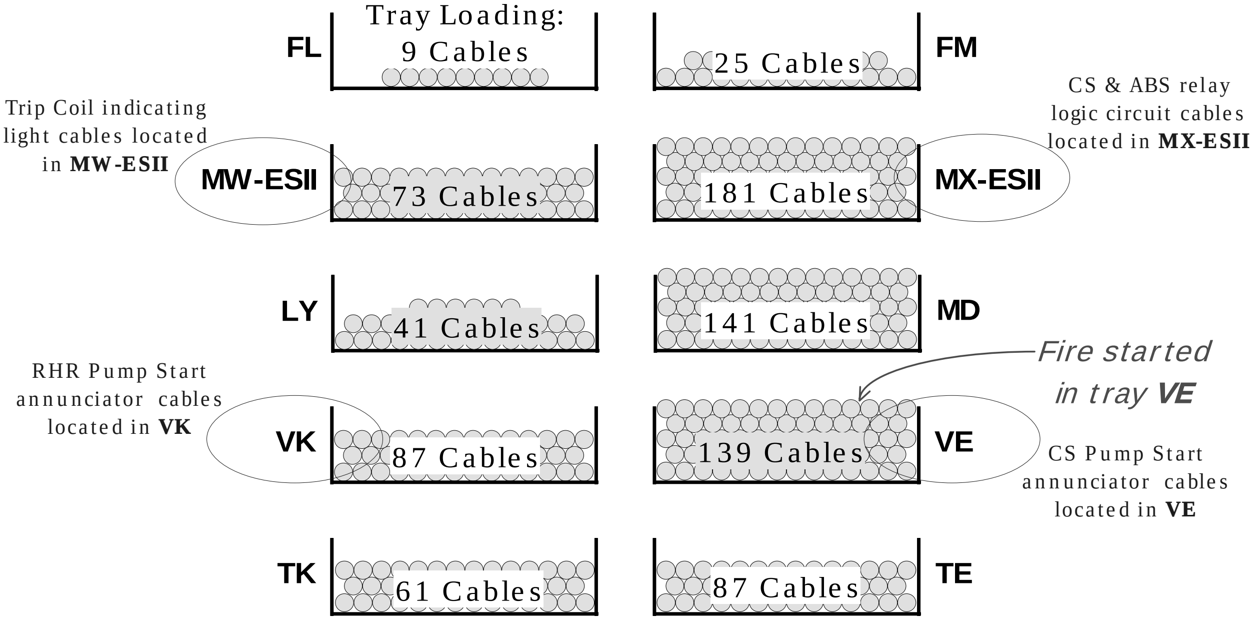


Figure C-9. Cable tray locations and contents. (Ref: Exhibit C1, pp. 30-32 of 69, *Physical Damage to Electric Cables and Raceways Involved in the Browns Ferry Nuclear Plant Fire on March 22, 1975*, contained in Regulatory Investigation Report Office of Inspection and Enforcement Region II.)

C.6 Findings And Conclusions

An analysis of the annunciator and pump control circuits, coupled with the identified fire-affected cables and conductors provided on the marked up drawings, indicates that at least some of the alarms and seemingly spurious component operations noted during the Browns Ferry-1 fire are explainable on an individual basis.

Could a single hot short or intra-cable short have caused these same events? The evidence available for this study does not fully support the single short theory. However, assume for the moment that one of the automatic blowdown system logic circuits, like those shown in Figures 1 and 2, were to have experienced shorting across the LIS contacts. This could explain some of the alarms (not all), however, the pumps (RHR 2A & 2C and CS 2A & 2C) are not automatically started by the relays indicated on those figures. On the other hand, spurious operation at nearly the same time for the four pumps is also difficult to explain. This would require us to make an assumption that multiple conductor-to-conductor shorts occurred simultaneously to start those pumps.

Electrically, these events can be explained (or strongly postulated) using the available documentation. To be certain though will require additional drawings/information that may or may not be available. Better quality drawings would certainly help improve this circuit analysis effort, perhaps supporting a different reason for these events or strengthening one or the other of the conclusions made so far.

APPENDIX D

EVALUATION OF THE EPRI/NEI MOTOR OPERATED VALVE CIRCUIT FAILURES - CABLE FAILURE MODE INFLUENCE FACTORS AND LIKELIHOOD

D.1. Introduction

For some time, the commercial nuclear power industry has been working to develop methods for addressing the regulatory issues related to circuit analysis and, in particular, fire-induced spurious equipment actuation. As a part of their efforts, industry (as represented by the Nuclear Energy Institute (NEI) and the Electric Power Research Institute (EPRI)) conducted a series of 18 fire tests designed to address specific aspects of the cable failure - circuit fault issue. The tests assessed the likelihood that cable failures might lead to spurious actuation of a surrogate motor-operated valve (MOV) circuit. Table D-1 shows the primary features of each of the eighteen tests conducted.

The testing was performed in cooperation with the USNRC which did participate in aspects of the testing. In particular, the USNRC and its contractors participated in the test planning, and sponsored the development and implementation by SNL of a cable failure mode monitoring system. The USNRC/SNL results are described separately in Appendix A and in NUREG/CR-6776. Under the terms of the RES/EPRI cooperative agreement, and per specific agreements relating to the tests, the USNRC reserves the right to make its own judgements regarding the test results and the implications of those results.

This Appendix D presents the viewpoints and opinions of SNL personnel who participated in the USNRC-sponsored portions of the test program based on their independent analysis of the data gathered under the EPRI/NEI-sponsored portion of the tests. EPRI/NEI have published their own description of the tests and results including their interpretation of the data and an assessment of the implications of those results with respect to the fire related risk at nuclear power plants. The reader should also review the industry test report (EPRI 1003326) and the EPRI expert panel report (EPRI 1006961) in developing their own views regarding cable failure modes and effects.

It should be noted that Tests #14 and 18 were designed and conducted in fundamentally different ways than the other sixteen tests. These two tests are not included in the discussions here. Also, note that the SNL analysis was completed prior to industry publication of their full test report. A review of the recently published industry report did not reveal areas of our own analysis requiring substantial revision, although some minor adjustments were made. Under the terms of agreements specific the joint test program, the USNRC and SNL were given full access to the data gathered by industry. Likewise, industry (and the public) has been given full access to the USNRC/SNL data. The original SNL analysis of the industry data also considered information presented by NEI and EPRI in various public forums (e.g., the NEI Fire Protection Information Forum), information provided by industry to an expert panel on spurious actuation likelihood estimation,[1] observations made by SNL and USNRC personnel during the actual tests, and interactions with industry participants subsequent to completion of the test program.

The industry portions of the test program focused on the observation of circuit fault behavior for a surrogate motor-operated valve (MOV) control circuit. The observations consisted primarily of fuse-blows (generally indicating that one of the energized conductors shorted to a grounded conductor or to an external ground) and spurious actuations (indicating a hot short energized a ‘target’ conductor). Voltage and current were also monitored and recorded for each circuit, along with temperature. Figures 1 and 2 show schematic drawings of the two MOV control circuits used in these tests.

The first circuit (Fig. 1) employed an effectively unlimited 120 Vac power source taken directly from the test laboratory’s facilities, and was used in tests 1-11. The second circuit (Fig. 2) was used in all of the

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[1] One of this report’s authors, S. Nowlen, was a participant on the EPRI expert panel.

other MOV circuit tests.[2] This second circuit differs from the first only in the use of a limited power output 150 VA step-down control power transformer (CPT). It should be noted that, in MOV control circuits in the U.S. nuclear industry, the use of a CPT powered from the MOV's three-phase ac motive power source is representative of typical practice. However, other control circuits may not utilize CPTs so care must be taken in the interpretation and application of the test results. Also note that the two energized single conductor source cables associated with each target cable bundle (bundles are described immediately below) were not connected to CPTs in any of the tests, rather, these conductors were always powered from the house power feeds.

In most case, each industry test involved 12 separate motor operator actuation devices, three connected to each bundle of four cable bundles. In most tests, each cable bundle comprised one multiconductor (seven-conductor) cable and three single-conductor cables taped together with fiberglass tape (the configuration shown in the Figures 1 and 2). There were generally three actuation target conductors present in each cable bundle: one connected to one of the three single-conductor cables, and two connected to conductors within the multiconductor cable. These are shown in Figures 1 and 2 as the conductors leading to devices A1, A2, and A3 respectively. These devices represent the actuation coils of the MOV circuit control relays. There were also four energizing source conductors in each bundle: two connected to the other two single-conductor cables, and two connected to conductors within the multiconductor cable (shown in the figures as conductors 1 and 2). Note that in the armored cable tests, the same general approach was used, but the three single-conductor cables were eliminated entirely.

Each of the MOV circuits in a given test was nominally identical except that the pattern of connections between the circuit and the multiconductor cable were unique. Figure 3 shows the four wiring schemes used during these tests (the conductor designations correspond to those used in Figures 1 and 2). In advance of the testing, it was nominally expected that the cable wired in accordance with Option 1, "Actuation Biased," would be most likely to lead to spurious actuations on cable failure. It was also nominally expected that the cable wired as indicted in Option 4, "Non-actuation Biased," would be least likely to cause spurious operations on cable failure. The other options are Option 2, "Center Ground," where the grounded conductor is located in the physical center of the cable, and Option 3, "Source Centered," where one of the two actuation source conductors is located at the physical center of the cable. These expectations were not fully realized as discussed in Section D.2.8.

Certain features are critical to the interpretation of test results. One such feature is room construction. The test room was constructed of uninsulated steel plate. Hence, wall and ceiling heat losses were much greater than would be expected, for example, in a concrete or gypsum enclosure. As a result, hot layer temperatures were lower for a given fire size than would be expected with a more conventional room construction. As a result, the typically applied correlations for estimating hot gas layer behavior will likely overestimate the temperatures as compared to the measured data unless the correlations are explicitly adjusted to reflect the much higher wall/ceiling heat losses.

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[2] Note that the NEI documentation contains a discrepancy regarding use of the CPTs in armored cable test 13. In the verbal descriptions it is cited that test 13 did not use CPTs. However, in the summary matrix, it is cited that Test 13 did use CPTs. Based on a discussion with W. Walker of Entergy on Nov. 5, Test 13 did use CPTs. The results are parsed accordingly.

Table D-1. Primary features of each test in the NEI/EPRI test matrix.							
Test No.	**Cable Type**	**Number of Conductors in Multi-Conductor**	**Race-way Type**	**Tray Fill (rows of cable)**	**Fire Intensity (kW)**	**Expo-sure Mode**	**CPTs Used?**
1	Armored	8	HT	2	350	HGL	No
2	TS	7	HT	2	70	Plume	No
3	TS	7	HT	2	145	Plume	No
4	TP	7	HT	2	145	Plume	No
5	TS	7	HT	2	200	HGL	No
6	TP	7	HT	2	200	HGL	No
7	TS	7	HT	2	350	HGL	No
8	TS	7	HT & C	3	145	Plume	No
9	TS	7	HT	1	145	Plume	No
10	TS	7	VT	1	200	HGL/Rad	No
11	TS	7	HT	4	145	Plume	No
12	TS	7	HT	1	145	Plume	Yes
13	Armored	8	HT	2	350	HGL	Yes
15	TS	7	HT & C	1	200 / 350 / 450 (variable)	HGL	Yes
16	TP	9	HT & C	2	145	Plume	Yes
17	TS & TP	9	VT	1	200	HGL/Rad	Yes

NOTES:

TS = Thermo-Set
TP = Thermo-Plastic
HT = Horizontal Tray
VT = Vertical Tray
C = Conduit
HGL = Hot Gas Layer
Rad = Radiative exposure
CPT = Control Power Transformer
(Tests 14 and 18 excluded from this analysis)

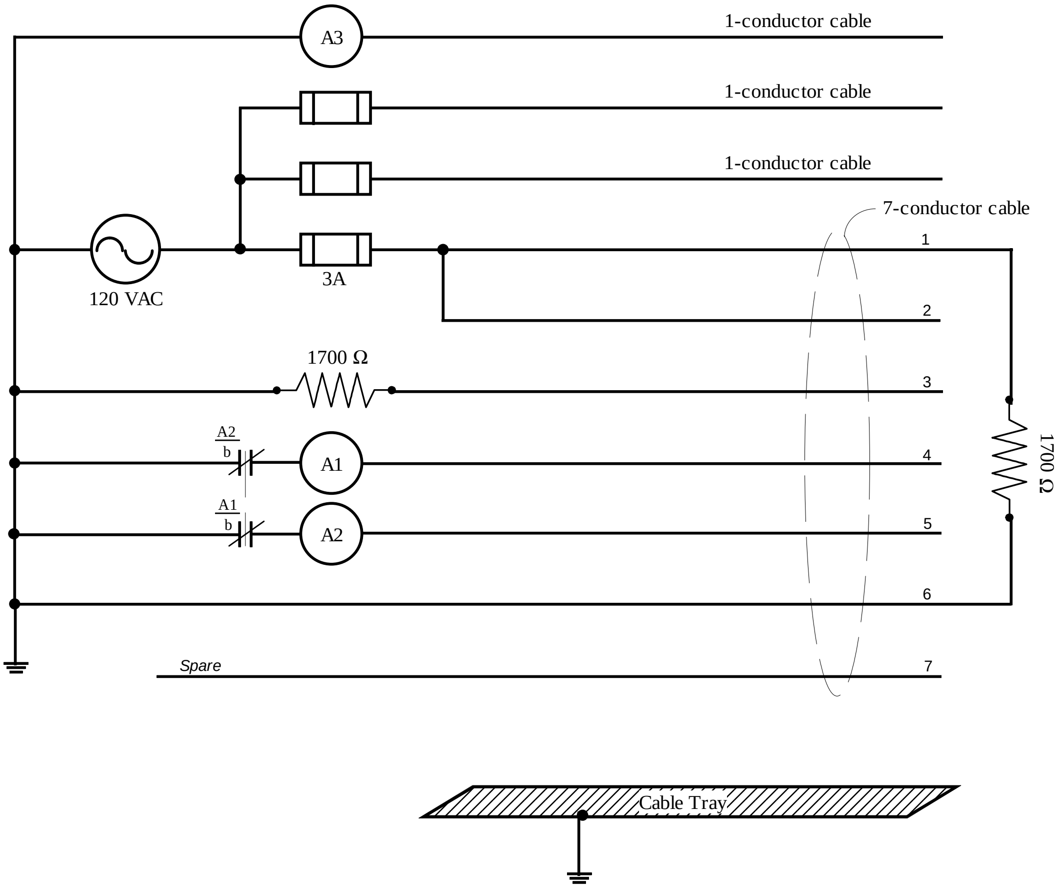


Figure D-1. EPRI-NEI MOV Test Circuit - Initial Configuration Employed in Tests #1-11.

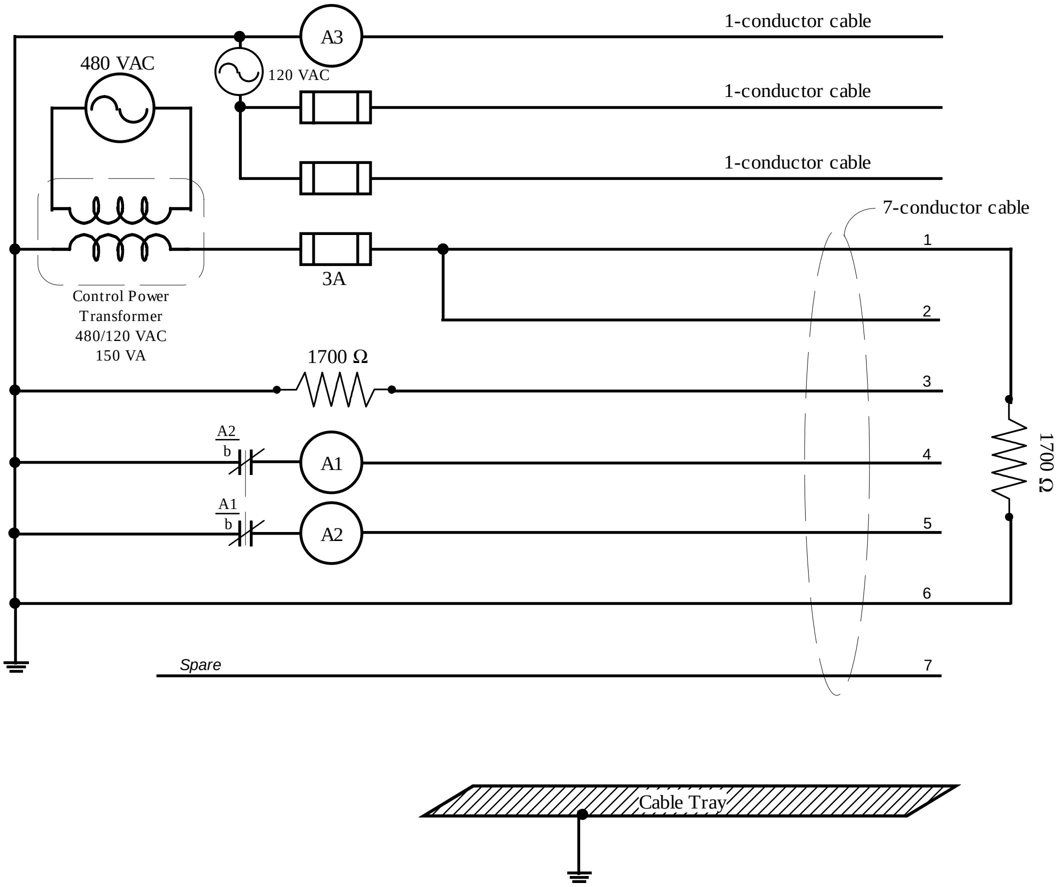
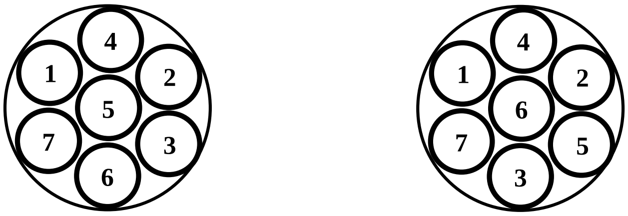
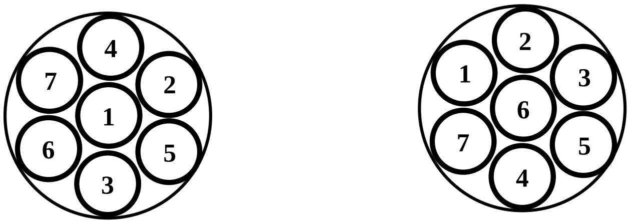


Figure D-2. EPRI-NEI MOV Test Circuit - Modified Configuration Employed in Tests #12, 13, and 15-17.



Option 1: Actuation Biased **Option 2: Center Ground**



Option 3: Source Centered **Option 4: Non-Actuation Bias**

Conductors:

1=Power Source
2=Power Source
3=Dummy Load
4=Actuating Device
5=Actuating Device
6=Ground
7=Spare

Figure D-3. Multi-conductor Cable Wiring Schemes Used During the EPRI-NEI Cable Tests.

A second feature of importance is directly related to the observations noted above regarding hot gas layer temperatures. The tests involved two cable tray exposure conditions as described further below; namely, plume and hot gas layer. During tests involving the hot layer exposure conditions, the temperatures generally hovered at or near temperatures typical of the failure thresholds typically assumed for, in particular, thermoset type cables. Hence, prolonged damage times, often in excess of one hour, were observed. The size/height of the open doorway (the only fresh air ventilation path) was adjusted during certain tests in an attempt to raise the hot layer temperature without adjusting the fire intensity (there was a practical limit to the fire intensity used). Such changes were not preplanned, but rather, were made when a need to increase the exposure temperatures became apparent during a test (e.g., after a prolonged exposure at relatively steady-state conditions with little or no apparent degradation of the cable integrity). The ventilation changes may not be well documented (e.g., time of change and nature of the change). The changes did impact hot layer temperature, but the tests still had difficulty in reaching higher hot gas layer temperatures, again, likely due to the high rate of heat loss through the wall.

A third factor is that it appears that some of the fires were burning in an under-ventilated condition. All of the pilot fires were provided by a propane gas burner. No burning outside the enclosure was observed, but there were indications of under-ventilated burning (e.g., heavy smoke, moderate hot gas layer temperatures, and temperature increase when ventilation was increased). Hence, the actual fire intensity may not have been as high as one might nominally estimate based on the propane gas flow rate, heat of combustion, and nominal burning efficiency for a gas burner. No measurements of the actual heat release rates were made.

A final factor to consider is related to inter-cable interactions. The four test bundles (and the USNRC/SNL IR bundle) were generally located at separated points within the test tray. There was little chance for interactions between bundles. The only exception is one test where one of the ERPI/NEI bundles was co-located with the USNRC/SNL IR bundle in a conduit. In this tests, there were interactions between the two bundles as described further below. For each of the individual cable bundles, there were cable-to-cable interactions observed including hot-short induced actuations. However, the bundling arrangement was rather contrived and would not be typical of actual practice in the nuclear industry. Hence, these results are likely subject to greater uncertainty than other data taken during these tests.

D.2. EPRI-NEI MOV Circuit Responses to Fire Damage

This analysis of the results from the EPRI/NEI MOV cable tests is intended to evaluate the type of circuit fault observed given cable failure. As a result, this analysis considers only those test cases where cable failures were observed. This analysis is not concerned with, and did not analyze, those tests or cables for which failures were not observed. Note, in particular, that the statistics presented in the various tables, and those shown in the corresponding figures, are all based on the relative frequency of the two primary circuit fault modes (noted immediately below) given failure of the exposed cables.

The circuit fault mode is identified as either “Fuse Failure” or “Device Actuation.” A fuse failure indicates shorting of the associated energized source conductor(s) to ground leading to an electrical over-current condition. Note that such circuit faults may be due either to a source conductor shorting to the external ground plane (e.g., the raceway), or to the one conductor in each multiconductor cable that is explicitly grounded (conductor 6 as shown in Figures 1 and 2). It is not possible to distinguish between these two cable failure modes given the available data. A device actuation is a clear indication of a hot short between one (or more) of the four energized source conductor and one (or more) of the four target conductors in each cable bundle (those conductors connected to the relay actuation devices).

The following discussions are based on the MOV circuit response given cable failure in terms of the eight principal influence factors studied during these tests (see Section 2.5 in the report's main body for a discussion of influence factors). The analysis focuses first on the actuators that are connected to the multiconductor cable. The determination of circuit fault mode for the multiconductor portion of each cable bundle is based primarily on whether or not a spurious actuation was observed prior to the failure of all fuses in a given circuit. Furthermore, the count of fuse failures and spurious actuations considers that each multiconductor cable presents one opportunity to produce either a spurious actuation or all fuse failures for that circuit.

That is, we do not count each individual fuse that blows, nor do we count multiple spurious actuations on a single cable bundle. In reality, each cable bundle had three actuation devices connected to it (two connected to the multiconductor, and a third connected to a single conductor cable). Hence, there is a nominal potential for spurious actuations impacting up to three devices. Indeed, in some cases a single device experienced multiple concurrent actuations through the course of a given test. However, in the counting scheme applied here, any bundle where the multiconductor cable fails will produce either one spurious actuation or one non-actuation data point (fuse failure). Our focus is on the initial failure mode in general, and hot-short induced spurious actuations in particular. Hence, each multiconductor cable contributes one yes/no spurious actuation failure mode data point to the analysis.

For example, if either of the actuators connected to the MOV circuit via the multiconductor cable experiences one or more spurious actuation signals at any time during the test, then this is counted as a single spurious actuation case. If the fuse powering the source conductors in the multiconductor cable fails with no observed actuations, then this is counted as a single fuse failure case. Similar analysis is performed independently for the actuator connected to one of the three single conductor cables. Note that most of the spurious actuations involved intra-cable hot shorts within the multiconductor cable. Any actuation on the actuator connected to the single conductor would by definition involve an inter-cable hot short. For most cases, an analysis of intra- versus inter-cable hot short induced actuations is also provided.

Also note that the use of CPTs has a significant impact on the observed circuit faults. Hence, the analysis will typically present results separately for tests with and without CPTs.

D.2.1. Cable Insulation Materials

The non-armored cables tested were classified as either thermoset (e.g., cross-linked polyethylene (XLPE) or ethylene-propylene rubber (EPR)) or thermoplastic (e.g., Tefzel, polyethylene (PE), or polyvinyl chloride (PVC)). Thermoplastic materials melt on heating and re-set on cooling, whereas thermoset materials will not melt, but instead will burn and/or char on heating. Circuit fault mode comparisons can be made according to these two broad material categories. It does appear that the insulation material type may have impacted the likelihood of certain types of cable failures.

Nominally, the thermoplastic cables showed a somewhat lower likelihood of intra-cable hot shorts leading to spurious actuation. However, the presence of a grounded conductor in the multiconductor cable was likely a significant factor in mitigating hot shorts within the cable, especially in the case of the thermoplastic cables. That is, given the melting behavior of the thermoplastic materials, these cables likely had equal if not more prevalent conductor-to-conductor intra-cable shorting behaviors as compared to the thermoset cables. However, the melting behavior also appears to have led to larger numbers of conductors being involved in the initial shorting behavior for the thermoplastics as compared to the thermoset materials. This result is confirmed by the corresponding USNRC/SNL data. Hence, it is likely that more prevalent involvement of the grounded conductor in initial intra-cable shorting may have mitigated the spurious actuation in at least some cases. This would easily explain the apparent differences in behaviors noted.

One difference between the two cable types that is clearly demonstrated is related to inter-cable shorting behaviors. The thermoplastic cables showed a significantly greater tendency toward inter-cable hot shorts leading to spurious actuation than did the thermoset cables. Inter-cable interactions involving the thermoset cables were detected by both the NEI and the USNRC/SNL data (see bullet lists below for details). These interactions appear to be dominated by interactions between two of the single conductor cables rather than between a single and multiconductor cable. In fact, for the NEI tests, all five of the inter-cable hot-short induced spurious actuations involving thermoset cables are attributed to interactions between two single conductor cables. (Note that interactions between the single and multiconductor cables were detected in the corresponding USNRC/SNL data in some cases.) In contrast, inter-cable shorting was somewhat common for the thermoplastic cables which also experienced a higher percentage of inter-cable hot shorts leading to spurious actuation. The inter-cable hot-short induced spurious actuations observed in the thermoplastic cable tests involve all three possible combinations; namely, a single conductor source and multiconductor target, a single conductor source and single conductor target, and a multiconductor source and single conductor target.

It would again appear that the melting behavior of thermoplastics, as compared to the charring behavior of the thermo-sets, was the primary factor in the observed differences in inter-cable shorting behaviors. During post-test examination of the thermoplastic cable bundles, the conductors of the different cables were largely co-mingled into a single solid mass of melted and cooled plastic with little to distinguish the conductors of one cable from those of another other than the size of the conductors. In contrast, the thermoset cable bundles retained a more distinct separation of the conductors in roughly their original configuration. One unaddressed uncertainty with regard to this difference is the fire intensity. As noted above, the exposure conditions generally hovered near what is generally assumed to be the damage threshold for thermoset cables. Given a more severe exposure, the thermoset cables may degrade more quickly and more thoroughly, and this might lead to a greater probability of inter-cable shorting. However, the validity of this supposition cannot be assessed based on the available data.

Both raceway type and the use of CPTs were found to be significant factors (as discussed further below). We have attempted to isolate cable type effects from effects related to raceway type and CPTs by considering only select subsets of the total test set rather than the test set as a whole. Consider first the behavior of the actuation targets connected to conductors in the multiconductor cable (i.e., the multiconductor targets which were typically sub-circuits 1 and 2 of each MOV circuit in the NEI test notation):

- The testing subset identified above includes 17 multiconductor thermoset cable failures (four each in Tests 3, 7, 9, and 10, and one in Test 11). Eight of these cable failures were manifested as device actuation circuit faults. In all eight of these cases, the spurious actuation is attributed to intra-cable short circuits within the multiconductor cable (i.e., both the source and target were in the multiconductor cable).

- The testing subset identified above includes eight multiconductor thermoplastic cable failures (four each in Tests 4, and 6). Three of these eight cable failures were manifested as device actuation circuit faults. In two of these three cases, the spurious operation is attributed, in part or in whole, to inter-cable hot shorts between an energized 1/C conductor and a target conductor in the multiconductor cables.

Next, consider the behavior of the actuation targets connected to one of the single conductor cables (typically sub-circuit 3 in the NEI test notation):

- The testing subset identified above includes 17 thermoset cable bundle failure cases (same as noted above). Of these 17 cases, five were manifested as a spurious actuation on the single-conductor target cable. In all five of these cases, the actuation was attributed to inter-cable shorting between two single-conductor cables (one source cable and the target cable). No cases are attributed to shorts between the single conductor target and a source conductor within the multiconductor cable.

- The testing subset identified above includes eight thermoplastic cable bundle failures (same test set as noted above). Of these eight failures, five led to spurious actuations on the single-conductor target conductor. At least one of these five cases (Circuit 4 in Test 3) and possibly a second (Circuit 2 in Test 6 - industry reporting contains a conflicting report of the actuation source) is attributed, in part or in whole, to contact between the single-conductor target cable and an energized conductor within the multiconductor cable.

Overall, the role of thermo-plastic versus thermoset materials does appear significant. For intra-cable interactions, the results are statistically similar: 8-of-17 cable failures led to device actuations for the thermoset cases, and 3-of-8 failures led to device actuations for the thermoplastic cases. However, for the inter-cable interactions, thermoplastic cables saw a much higher overall rate of inter-cable hot shorts than did the thermoset cables. Furthermore, hot short interactions between the single-conductor and multiconductor cables were observed only for the thermoplastic cables.

Table D-2 shows the number MOV circuit responses of each type (fuse failure and device actuation) observed based on the type of cable material tested for the expanded set of all tests. Thermoset cables without CPTs tended to initially fail equally by fuse failures and device actuations (9-to-8 respectively). With CPTs and thermoset cables, the ratio of fuse failures to device actuations increases to 5-to-1, a substantial decrease in the occurrence rate of spurious actuations. For thermoplastic cables, the data set is more limited, and somewhat contradictory compared to the results for thermo-sets. Without CPTs, thermoplastic cables failed more often by fuse failure than by device actuation (a 3-to-1 ratio). However, when CPTs were employed, the ratio decreases to 2-to-1 fuse failures to device actuations, indicating an increase in the rate of spurious operations versus fuse blows. Based on a more thorough analysis of the MOV circuit data by EPRI, it appears that the CPTs had little impact on cable failure mode (e.g., conductor-to-conductor shorting versus conductor-to-ground) but that the CPTs did substantially reduce the likelihood of spurious actuations. Recall that the CPTs limit the available power to the circuit. In these tests, the CPT provided approximately 150% of the power required to actuate a single device (based on the relay coil voltage-current characteristics). One unaddressed uncertainty in these results is the impact should the CPT provide a higher relative power output. Extrapolation of these results to a case where a relatively larger CPT is used is likely inappropriate (i.e., given a higher ratio between the power output of the CPT and the power needed to actuate the device).

Figure 4 shows the total number of failures associated with each multiconductor cable type. Figure 5 shows the relative probability of obtaining a fuse failure versus device actuation response for each type of multiconductor cable. Table D-3 and Figures 6 and 7 present the same type of information as above for the single-conductor cables bundled with the multiconductor cables in the tests.

Note also both the NEI and USNRC/SNL results reinforce the observation that thermoplastic cables are less robust than thermoset cables. In all cases, the thermoplastic cables failed far more readily than did the thermoset cables under similar exposure conditions. Past testing has demonstrated that the failure thresholds for thermo-sets are higher than those of thermoplastic. However, the results indicate that for intra-cable shorting, the cable insulation material appears to have relatively little impact on the initial failure mode, e.g., the likelihood of hot shorts and/or spurious actuation. In contrast, cable insulation type has a strong influence on inter-cable shorting. Unfortunately, in both cases there are a limited number of cases for which direct comparison between cable types is appropriate and this does leave some uncertainty in the robustness of these results.

Table D-2. Number of Fuse Failures and Device Actuations Attributed to Intra-Cable Hot Shorts Among the Failures for Cable Bundles in Cable Trays Based on Insulation and Jacket Material Types.

MOV Circuit Response	Thermoset Cables w/o CPTs	Thermoplastic Cables w/o CPTs	Thermoset Cables w/ CPTs	Thermoplastic Cables w/ CPTs
Fuse Failure	9	6	6	3
Device Actuation	8	2	1	2

Table D-3. Number of Fuse Failures and Device Actuations Associated with Inter-Cable Hot Shorts Based on Insulation and Jacket Material Types - Conduit Tests Excluded.

MOV Circuit Response	Thermoset Cables	Thermoplastic Cables*
Bundles that failed with no inter-cable hot short actuations	18	6
Bundles that failed with at least one inter-cable hot short interaction	6	6
A breakdown of inter-cable hot short actuations by source/target combination:		
1/C source -> 1/C target	5	3
1/C source -> 7/C target	0	3
7/C source -> 1/C target	1	2

* Note that in two cases (Test 4 - Circuit 4 and Test 6 - Circuit 1), a single cable bundle experienced two separate actuations attributed to different inter-cable hot shorts. Hence, there was a total of eight such actuations involving six test bundles.

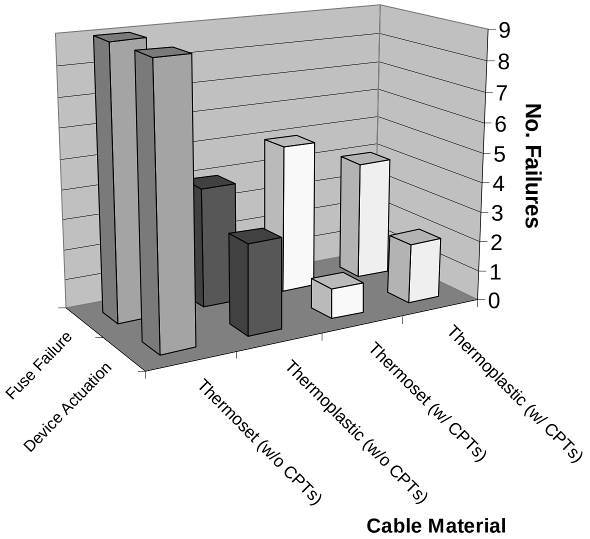


Figure D-4. Number of Fuse Failures and Device Actuations for Thermoset and Thermoplastic Multi-conductor Cables.

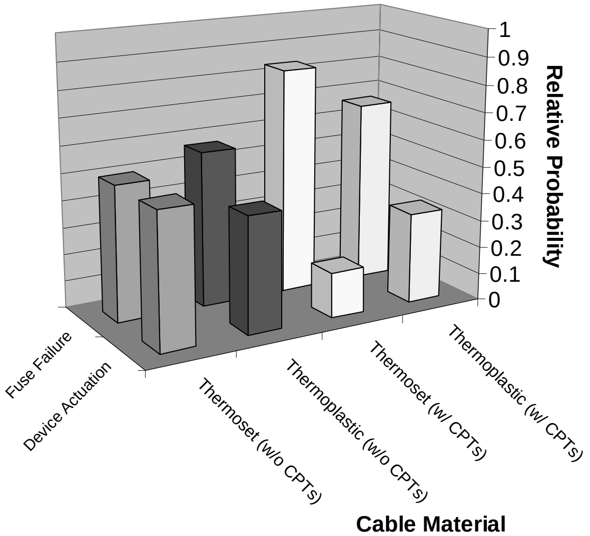


Figure D-5. Relative Probability of Obtaining Fuse Failure or Device Actuation for Thermoset and Thermoplastic Multi-conductor Cables.

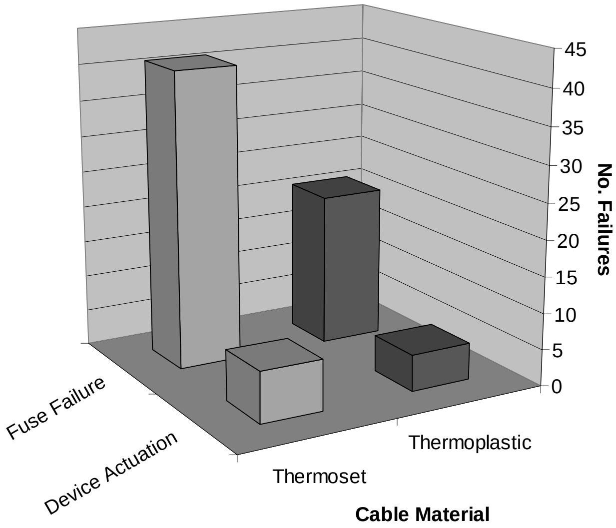


Figure D-6. Number of Fuse Failures and Device Actuations for Thermoset and Thermoplastic Single-conductor Cables.

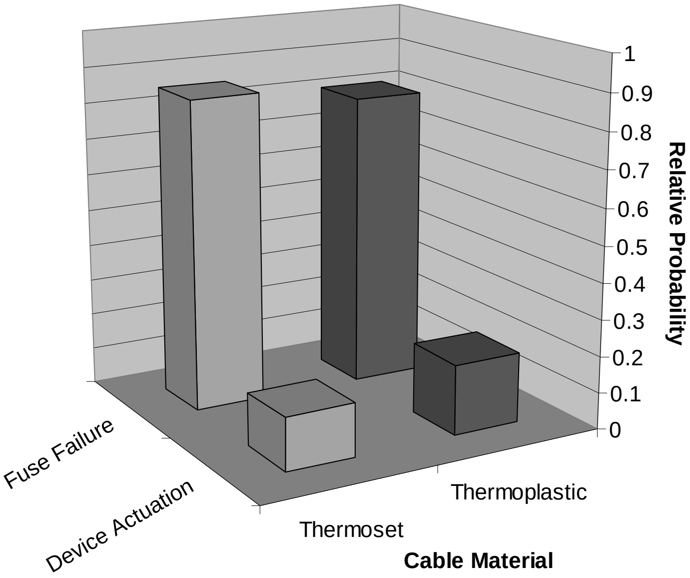


Figure D-7. Relative Probability of Obtaining Fuse Failure or Device Actuation for Thermoset and Thermoplastic Single-conductor Cables.

Overall, thermoplastic cables appear to show a slightly higher likelihood of spurious actuation due to intra-cable shorts than do thermoset cables. The EPRI test report (EPRI 1003326) shows approximately 38% of the failed thermoplastic cable bundles experienced spurious actuation events - at least one spurious actuation for a given bundle - versus approximately 28% of the thermoset bundles. However, this observation mixes all cases into a single statistic and may overstate the effects for intra-cable cases. The results more clearly indicate differences in the inter-cable hot short and spurious actuation behavior. In particular, the thermoplastic cables appear far more likely to experience inter-cable hot shorts and spurious actuations than do thermoset cables.

D.2.2. Number of Conductors

Seven-, eight- and nine-conductors cables (7/C, 8/C, and 9/C) were tested. Note that, the 8/C cables were all armored, whereas the 7/C and 9/C were not. Table D-4 provides the number and type of failures observed for each type of cable. Figures 8 and 9 present plots to show the relationship of failure mode to conductor count in the cables and the resulting relative probability of observing the particular failure mode.

It is clear that the behavior of the 8/C cables is substantially different from that of the 7/C or 9/C cables. In the author's judgement, the behavior of the 8/C cable reflects behaviors relating to armored versus non-armored cables (see section D.2.3) rather than behaviors relating to conductor count.

Considering only the 7/C and 9/C cables, the two cable types appear to demonstrate similar behavior regarding the observed circuit faults. In this case, the only 9/C cases available for comparison are CPT cases. Overall the data indicate that at least for this narrow range of conductors, that the conductor count is at most a weak influence factor. However, these results cannot be extrapolated easily (e.g., to a 3/C or 12/C cable) given that the 7/C and 9/C cables were rather similar in construction and layout.

Table D-4. Number of Fuse Failures and Device Actuations Attributed to Intra-Cable Hot Shorts for Multiconductor Cables Based on Number of Conductors.

MOV Circuit Response	7/C w/o CPT	8/C w/o CPT	7/C w/ CPT	8/C w/ CPT	9/C w/ CPT
Fuse Failure	13	2	5	4	4
Device Actuation	12	1	1	0	2

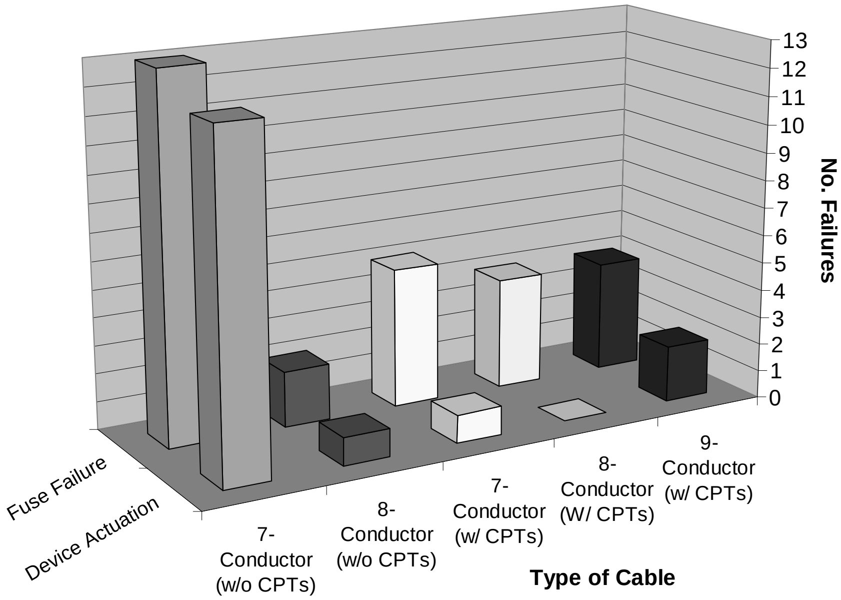


Figure D-8. Number of Fuse Failures and Device Actuations for Multi-conductor Cables as a Function of Number of Conductors.

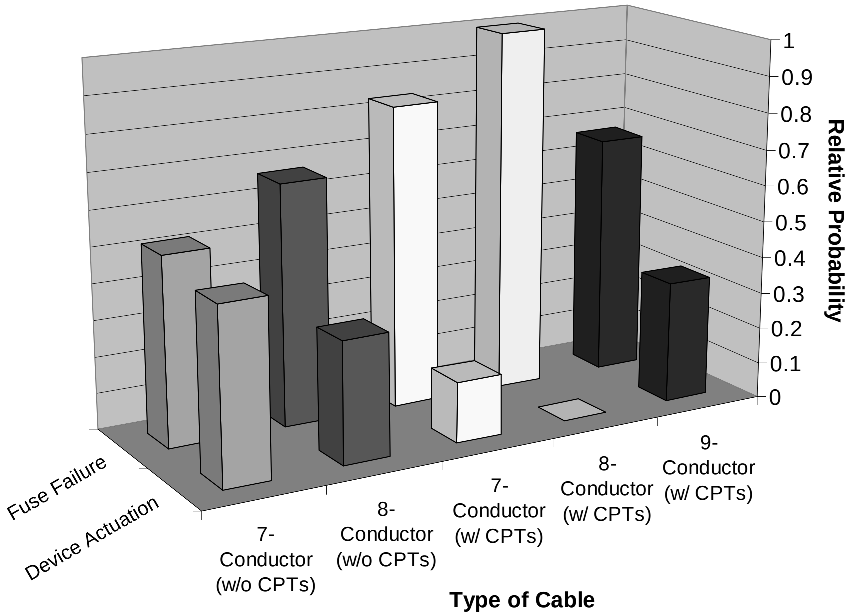


Figure D-9. Relative Probability of Obtaining Fuse Failure or Device Actuation for Multi-conductor Cables with 7-, 8- and 9-conductors.

D.2.3. Armoring

Armored cables were tested in two of the eighteen tests run (Tests 1 and 13). There is some conflict in the available information regarding use of CPTs in Test 13. Initial information from NEI indicated that CPTs were not used, but SNL notes taken at the time of testing indicate that CPTs were used. SNL confirmed with J. Walker, Entergy (a participant for NEI), that CPTs were used in Test 13. Recall that in the armored cable tests, the single-conductor cables are eliminated entirely. Table D-5 presents results for circuit fault mode observed for non-armored and armored cables considering only those device actuations associated with the multiconductor cables.

The circuit faults are nearly evenly distributed between fuse failure and device actuations for non-armored cables. However, armored cables experienced only one device actuation given a total of seven cable failures (one cable in Test 1 appears not to have failed - no fuse failure or device actuation is reported). The one case involving a device actuation also involved a circuit without the CPTs, and a cable where the minimum bend radius was violated when the cable was installed in the tray. While this violation of the bend radius may have had some impact on the test results, the industry analysis of the test data concluded that the bend radius violation was of limited impact.[3] (Also note that the armored cables were of an 8-conductor configuration and the exact wiring of the conductors is not known by the authors of this report.)

Overall, it would appear that armored versus non-armored cables is a strong influence factor with armored cables displaying a lower likelihood of spurious actuation as compared to non-armored cables. However, the data for armored cables remains somewhat sparse. Additional validation of these observations may be warranted.

Table D-5. Number of Fuse Failures and Device Actuations Attributed to Intra-Cable Hot Shorts for Multiconductor Cables Based on Armoring. (For non-armored cables, only the cable tray tests are considered.)

MOV Circuit Response	**Non-armored w/o CPT**	**Armored w/o CPT**	**Non-Armored w/ CPT**	**Armored w/CPT**
Fuse Failure	15	2	9	4
Device Actuation	10	1	3	0

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[3] Based on a comment provided by F. Emerson of NEI in a requested pre-publication review of this appendix.

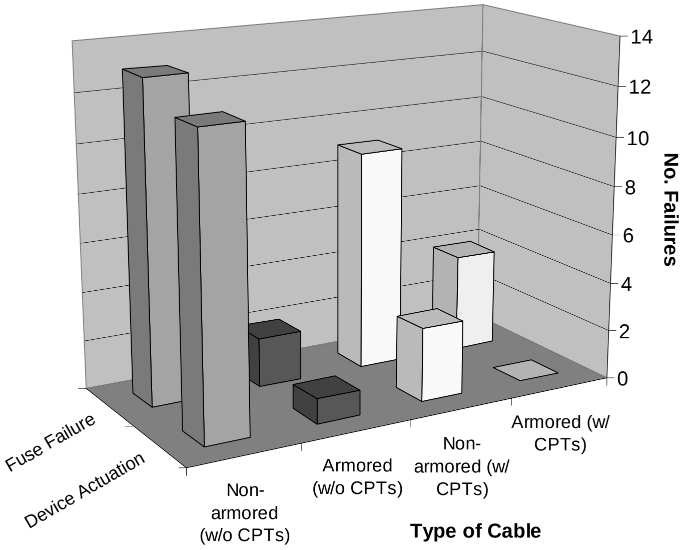

Figure D-10. Number of Fuse Failures and Device Actuations for Multi-conductor Cables Based on Armoring.

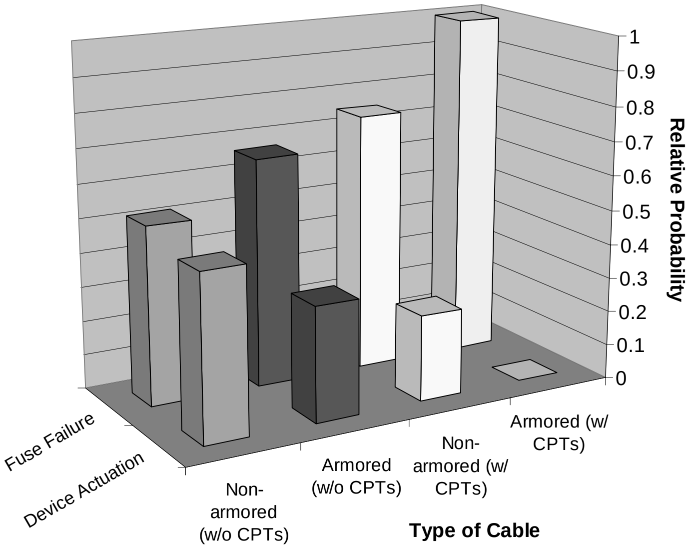

Figure D-11. Relative Probability of Obtaining Fuse Failure or Device Actuation for Multi-conductor Cables With and Without Armor.

D.2.4. Cable Trays vs. Conduit

Cable trays were used in all of the tests conducted. In addition, three tests also used a conduit. When a conduit was used, one of the four MOV circuit cables was routed in the conduit (the other three MOV bundles were routed in the cable tray). The fault mode results for cables tested in trays versus conduits, with and without CPTs, are provided in Table D-6. The corresponding data is also plotted in Figures 12 and 13.

For cables in trays the circuit faults are divided 11-to-13 (roughly 1-to-1) between device actuations and fuse blows without CPTs in the circuit. For cables in a conduit without CPTs, there is only one failure case, and this failure did cause a device actuation. With only one such case, the evidence must be judged as a weak indicator of any trends. When CPTs were included in the circuit, the number of circuit faults involving blown fuses increases significantly for both trays and conduits. However, for the cables in a conduit no spurious actuations were observed whereas for the trays the ratio of device actuations to fuse blows drops to 3-to-7 (or about 1-to-2).

Table D-7 illustrates the test results relating to inter-cable hot shorts. These cases can potentially be counted in many ways. Our count is based on the assumption that each failed cable bundle presents two opportunities for an inter-cable hot short induced spurious actuation; one opportunity possibly targeting the single conductor actuation device (i.e., A3) and one opportunity to target the multiconductor cable (i.e., either A1 or A2). Application of these data may require careful consideration of this approach. Figures 14 and 15 plot the data obtained for the single-conductor cables, based on raceway type, and the relative probability of fuse failures occurring compared to device actuations.

The NEI/EPRI data include only a small number of conduit failure cases (a total of three bundle failures). Hence, the results cannot be considered strong evidence. However, the results can be considered in light of the IR measurements taken by SNL in the same tests. In the IR tests, the conductors tended to short to the conduit when routed in a conduit and to other conductors when routed in a tray. Overall, we conclude that conduits are a potentially strong influence factor based on weak evidence. Spurious actuations appear less likely for cables in conduits than they are for cables in trays.

Table D-6. Number of Fuse Failures and Device Actuations Attributed to Intra-Cable Hot Shorts for the Multiconductor Cables Based on Raceway Type.

MOV Circuit Response	Tray w/o CPT	Conduit w/o CPT	Tray w/ CPT	Conduit w/ CPT
Fuse Failure	15	0	9	2
Device Actuation	10	1	3	0

Table D-7. Number of Fuse Failures and Device Actuations Associated with Inter-Cable Hot Shorts Based on Cable Tray versus Conduit.

MOV Circuit Response	Cable Trays*	Conduits
Bundles that failed with no inter-cable hot short actuations	24	2
Bundles that failed with at least one inter-cable hot short interaction	12	1
A breakdown of inter-cable hot short actuations by source/target combination:		
1/C source -> 1/C target	8	1
1/C source -> 7/C target	3	0
7/C source -> 1/C target	3	0

* Note that in two cases (Test 4 - Circuit 4 and Test 6 - Circuit 1), a single cable bundle experienced two separate actuations attributed to different inter-cable hot shorts. Hence, there was a total of 14 such actuations involving 12 test bundles.

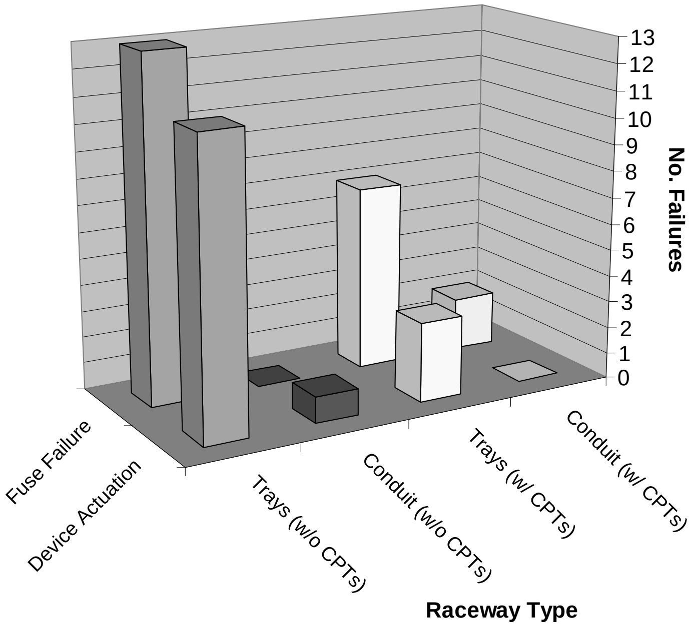

Figure D-12. Number of Fuse Failures and Device Actuations for Multi-conductor Cables Based on Raceway Type.

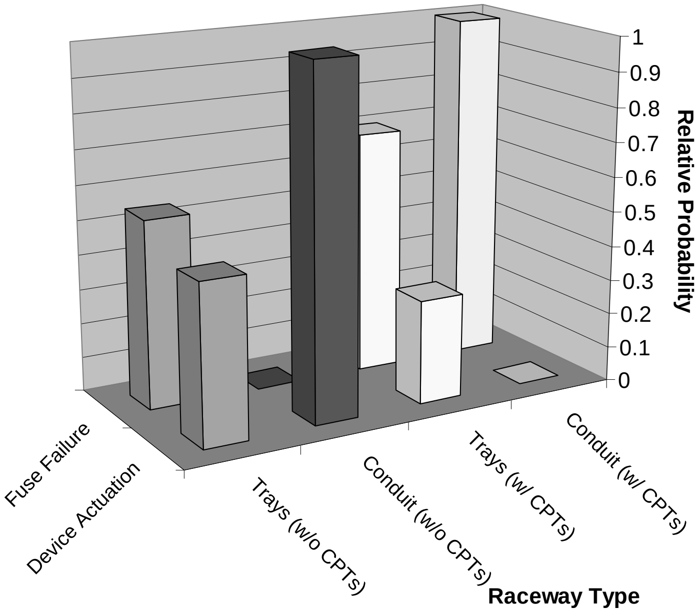

Figure D-13. Relative Probability of Obtaining Fuse Failure or Device Actuation for Multi-conductor Cables Based on Raceway Type.

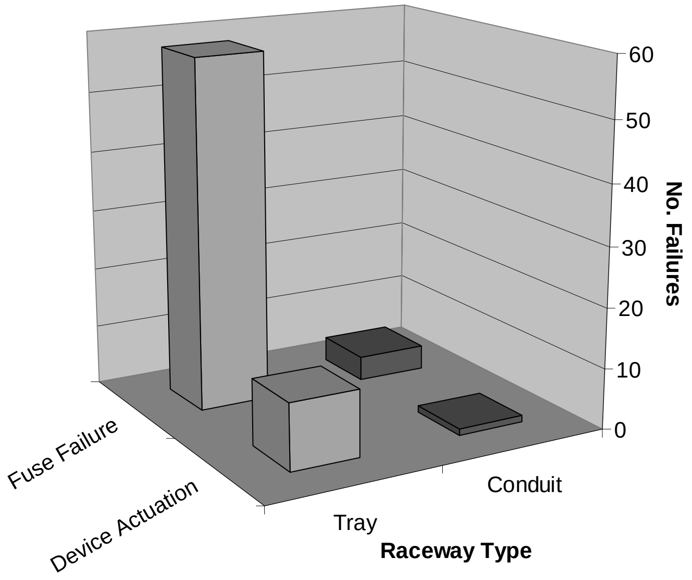

Figure D-14. Number of Fuse Failures and Device Actuations for Single-conductor Cables Based on Raceway Type.

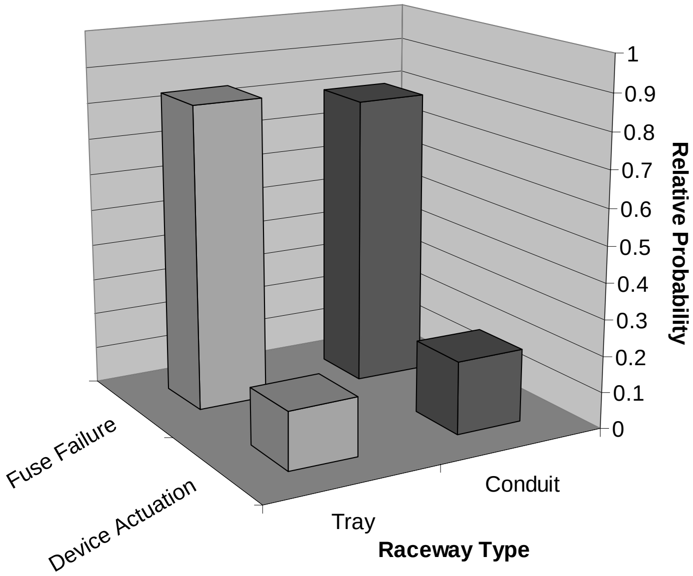

Figure D-15. Relative Probability of Obtaining Fuse Failure or Device Actuation for Single-conductor Cables Based on Raceway Type.

D.2.5. Cable Tray Loading

The cable trays used in these tests were filled with 1, 2, 3 or 4 rows of cables in order to assess the effect of raceway loading on the number and types of circuit faults observed. Table D-8 provides the results relating to the mode of failure for multiconductor cables. Figure 16 is a plot of the data in Table D-8 and Figure 17 shows the relative probabilities for fuse failures and device actuations depending on raceway fill. Table D-9 and Figures 18 and 19 show similar results for the single-conductor cables

As can be seen, for the multiconductor cables in circuits without CPTs, the frequency of fuse failures over device actuations increases as more cables are installed in the cable tray. As seen previously, when CPTs are included as part of the MOV control circuit, the relative number of fuse failures over device actuations increases significantly for all cases. For the single-conductor cables, fuse failures are the much more prevalent circuit response regardless of tray loading. In this case the results are also less clear-cut. The case with two rows of cables saw a much higher fraction of spurious actuations than were observed for either 1, 3, or 4 rows. The cases with 3 and 4 rows are rather limited, but no actuations were observed.

Overall, it would appear that the likelihood of spurious actuations is impacted by the tray fill. Nominally, it appears that the actuation likelihood is reduced for higher loadings. It would be useful to further parse the data to consider the location of the cable in the tray in addition to the tray loading, but as of this draft this parsing has not been completed.

Table D-8. Number of Fuse Failures and Device Actuations Attributed to Intra-Cable Hot Shorts for Multi-Conductor Cables Based on Rows of Tray Fill (Vertical Trays Excluded).

MOV Circuit Response	1-row w/o CPTs	2-rows w/o CPTs	3-rows w/o CPTs	4-rows w/o CPTs	1-row w/ CPTs	2-rows w/ CPTs
Fuse Failure	1	8	1	1	5	2
Device Actuation	3	7	0	0	1	1

Table D-9. Number of Device Actuations Associated with Inter-Cable Hot Shorts Based on Rows of Cables in Tray (Vertical Trays Excluded).

MOV Circuit Response	1 Row	2 Rows*	3 Rows	4 Rows
Bundles that failed with no inter-cable hot short actuations	8	11	1	1
Bundles that failed with at least one inter-cable hot short interaction	2	7	0	0
A breakdown of inter-cable hot short actuations by source/target combination:				
1/C source -> 1/C target	1	5	0	0
1/C source -> 7/C target	0	2	0	0
7/C source -> 1/C target	1	2	0	0

* Note that in two cases (Test 4 - Circuit 4 and Test 6 - Circuit 1), a single cable bundle experienced two separate actuations attributed to different inter-cable hot shorts. Hence, there was a total of nine such actuations involving seven test bundles.

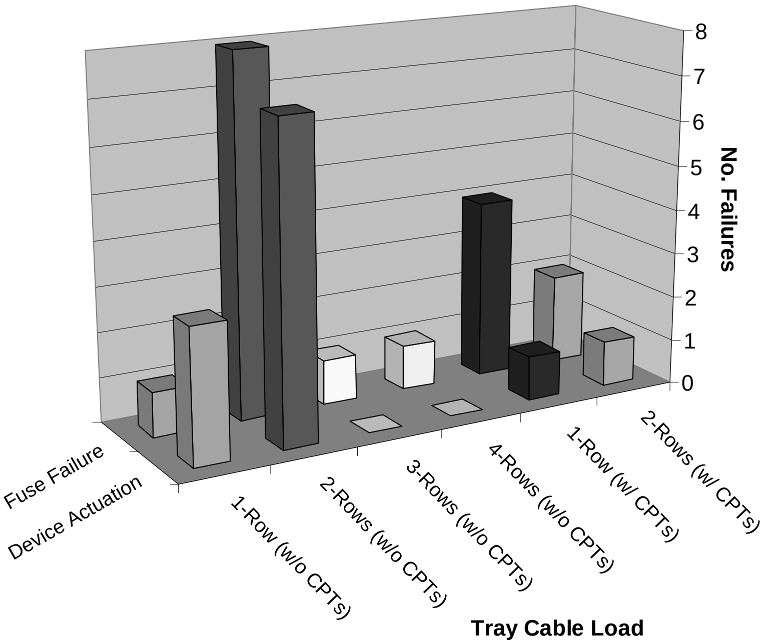

Figure D-16. Number of Fuse Failures and Device Actuations for Multi-conductor Cables Based on Raceway Loading.

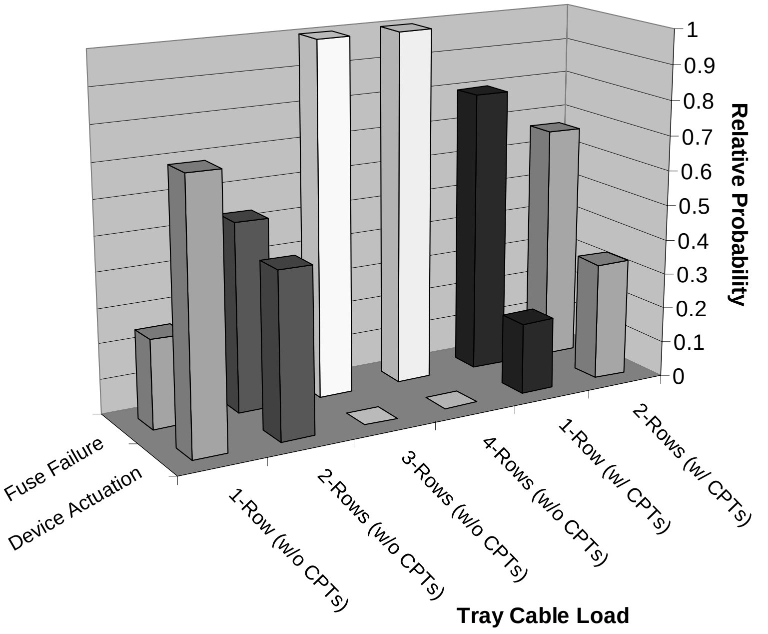

Figure D-17. Relative Probability of Obtaining Fuse Failure or Device Actuation for Multi-conductor Cables Based on Raceway Loading.

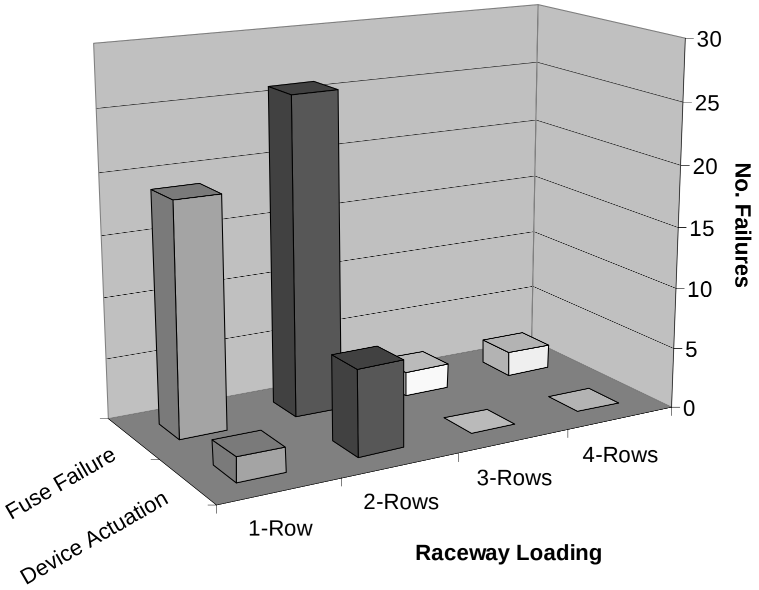

Figure D-18. Number of Fuse Failures and Device Actuations for Single-conductor Cables Based on Raceway Loading.

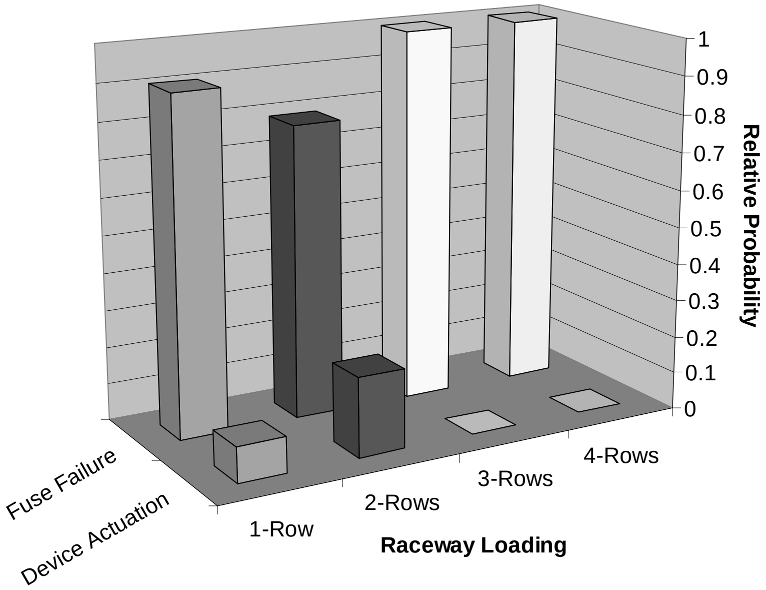

Figure D-19. Relative Probability of Fuse Failure or Device Actuation for Single-conductor Cables Based on Raceway Loading.

D.2.6. Cable Tray Orientation

Most tests were conducted with trays mounted horizontally in the test cell, however, vertical trays were installed for two of the eighteen tests (#10 and 17). These two tests led to a total of five cable failure cases (three without CPT and two with CPTs). Table D-10 provides the number of failures observed for the tests based on tray orientation. Figure 20 shows a plot of these results, and Figure 21 shows a comparison of the relative probability for each type of failure based on tray orientation. The results for single-conductor cables based on tray orientation are provided in Table D-11 and Figures 22 and 23, below.

The data show that without CPTs the number of fuse failures was very slightly more than the number of device actuations for both horizontal and vertical trays. When CPTs were used, the cables in horizontal trays tended to fail mostly by fuse failure rather than by device actuation. Cables connected to CPTs and routed in vertical trays saw one failure each involving a fuse blow and an actuation. Overall, the evidence would appear to indicate a weak influence due to raceway orientation on the failure mode likelihood.

One substantial factor in this assessment may be the role of the ground conductor in the MOV circuit cables. Recall that the NEI/EPRI MOV circuit cables always included one conductor that was explicitly grounded. One might speculate that with a vertical tray, conductor to tray shorts would be less likely due to the lack of a gravity force pressing the cables to the tray rungs. However, with a grounded conductor in each cable, short to ground behaviors are likely being dominated by internal cable behaviors (i.e., shorts to the grounded conductor). If the behaviors within the cable are predominant, then the impact of vertical versus horizontal trays may be minimal.

In the case of the single-conductor cables, those routed in horizontal trays tended to fail first by fuse failure much more often than by device actuation. The same is true when the single-conductor cables are routed in vertical trays. Hence, again, there appears to be no pronounced impact of tray orientation on failure mode likelihoods. Overall, the NEI/EPRI data appear to indicate that raceway orientation is a weak influence factor at least for cases where the cable in question includes an explicitly grounded conductor. However, caution is recommended in extrapolating these results to cases involving multiconductor cables in which there is no grounded conductor present.

Table D-10. Number of Fuse Failures and Device Actuations for Multiconductor Cables Based on Raceway Orientation.

MOV Circuit Response	Horizontal w/o CPTs	Vertical w/o CPTs	Horizontal w/ CPTs	Vertical w/ CPTs
Fuse Failure	11	2	6	1
Device Actuation	10	1	2	1

Table D-11. Number of Device Actuations Associated with Inter-Cable Hot Shorts Based on Cable Tray Orientation.

MOV Circuit Response	Horizontal Cable Trays*	Vertical Cable Trays
Bundles that failed with no inter-cable hot short actuations	21	3
Bundles that failed with at least one inter-cable hot short interaction	9	3
A breakdown of inter-cable hot short actuations by source/target combination:		
1/C source -> 1/C target	6	2
1/C source -> 7/C target	2	1
7/C source -> 1/C target	3	0

* Note that in two cases (Test 4 - Circuit 4 and Test 6 - Circuit 1), a single cable bundle experienced two separate actuations attributed to different inter-cable hot shorts. Hence, there was a total of 14 such actuations involving 12 test bundles.

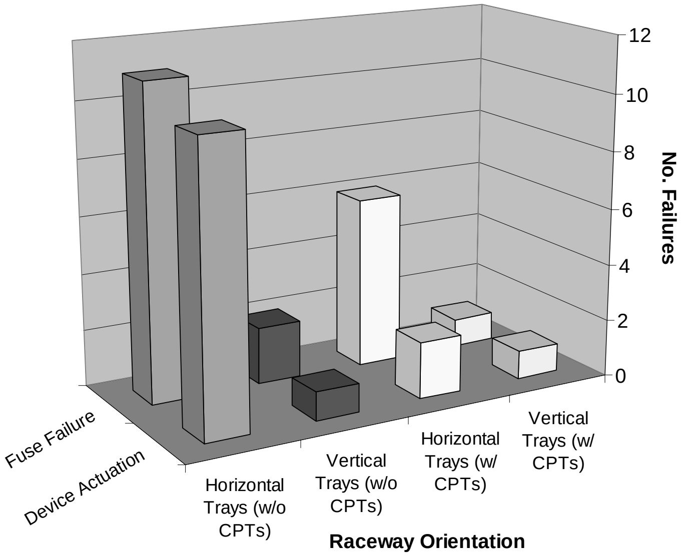

Figure D-20. Number of Fuse Failures and Device Actuations for Multi-conductor Cables Based on Raceway Orientation.

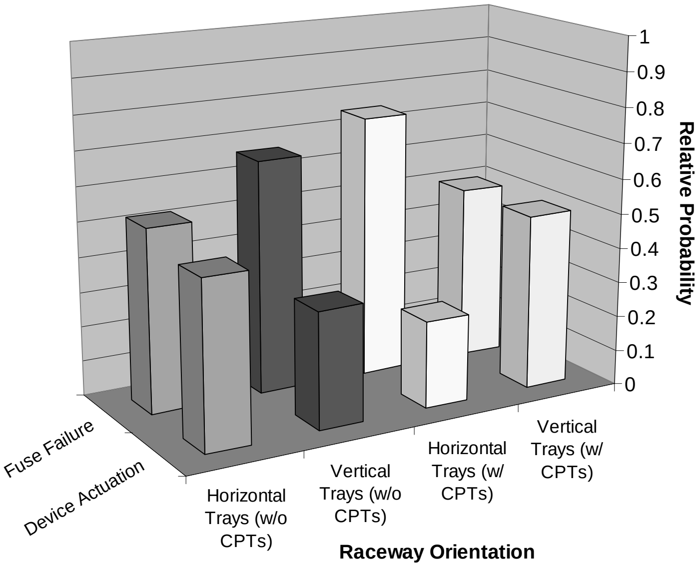

Figure D-21. Relative Probability of Obtaining Fuse Failure or Device Actuation for Multi-conductor Cables Based on Raceway Orientation.

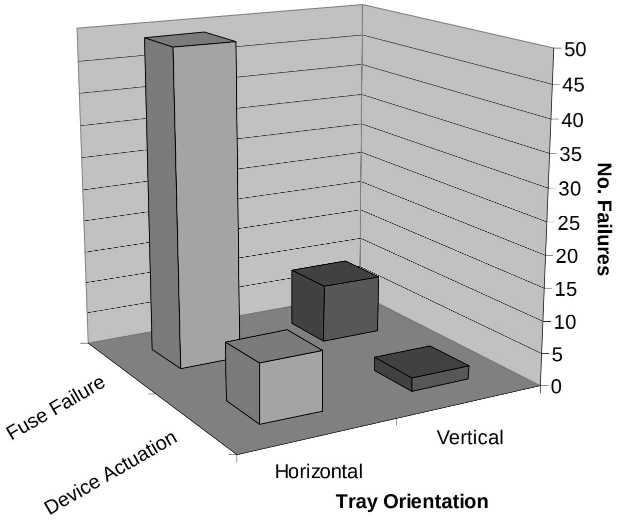

Figure D-22. Number of Fuse Failures and Device Actuations for Single-conductor Cables Based on Raceway Orientation.

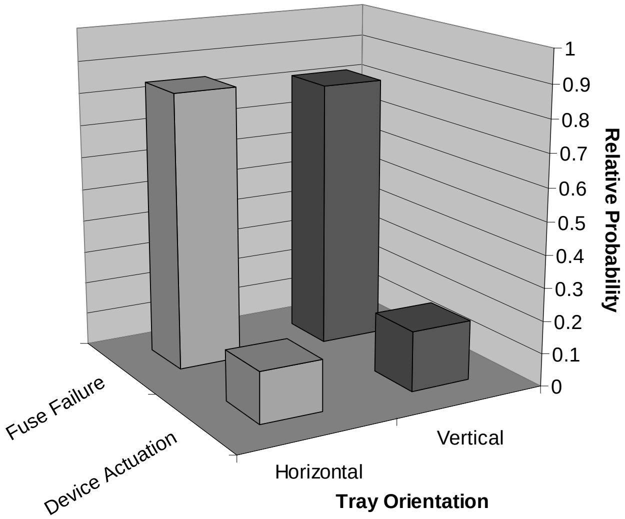

Figure D-23. Relative Probability of Obtaining Fuse Failure or Device Actuation for Single-conductor Cables Based on Raceway Orientation.

D.2.7. Exposure Mode/Intensity

Two fire exposure modes were used in testing; namely, fire plume (outside the flame zone), or hot gas layer. Note that the fire intensity is intimately tied to the exposure mode: for fire intensities of 145 kW or less, the cables were located in the plume, when fire intensities were 200 kW or greater the cables were exposed to the hot gas layer. It is clear that the exposure mode had a significant effect on the cable failure potential and times. That is, tests involving plume exposure saw a higher percentage of cable failures and saw cable failures in a shorter time period than did the hot gas layer exposure tests. This is consistent with anticipated fire behaviors given that the plume, in general, involves substantially higher temperatures than the hot gas layer.

However, the primary interest here is in the mode of failure given that a cable failure was observed. Table D-12 shows the mode of failure for those multiconductor cables that failed based on the coupled conditions of exposure mode and fire intensity. Figures 24 and 25 present this data graphically.

As noted previously, when the MOV circuits did not employ CPTs the failure modes of the multiconductor cables tended to be equally divided between fuse failures and device actuations, with a very slight edge toward fuse failures. This trend holds true in this parsing as well regardless of the exposure mode/intensity. When CPTs are included in the MOV circuits, a distinct tendency to fuse failure is evident, but again, there appears to be no direct correlation between failure mode and exposure mode/intensity. Similarly, the exposure mode/intensity did not have a significant effect on the way the single-conductor cables failed. Overall, the exposure mode/intensity appears to be a weak influence factor.

Table D-12. Number of Fuse Failures and Device Actuations Attributed to Intra-Cable Hot Shorts for Multiconductor Cables Based on Exposure Mode and Flame Intensity.

MOV Circuit Response	Plume-145 kW w/o CPTs	HGL-200 kW w/o CPTs	HGL-350 kW w/o CPTs	Plume-145 kW w/ CPTs	HGL-200 kW w/ CPTs	HGL-350 kW w/ CPTs	HGL-450 kW w/ CPTs
Fuse Failure	8	3	4	6	1	4	2
Device Actuation	7	3	3	1	1	0	1

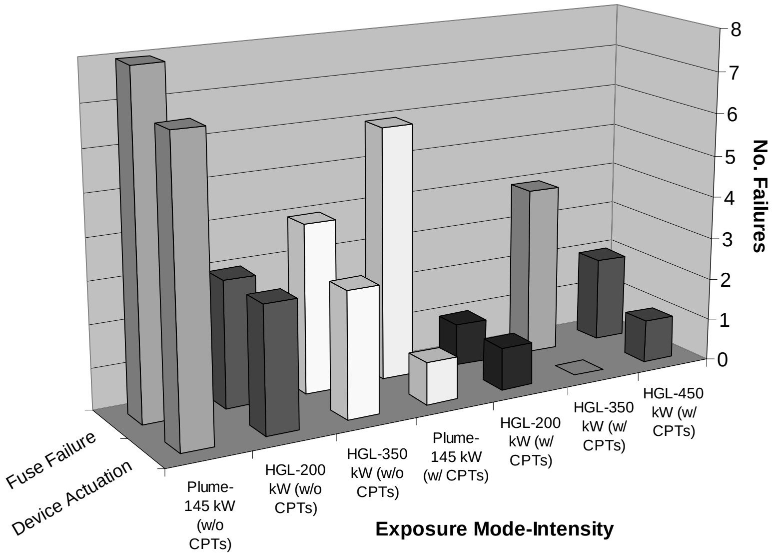

Figure D-24. Number of Fuse Failures and Device Actuations for Multi-conductor Cables Based on Exposure Mode and Flame Intensity.

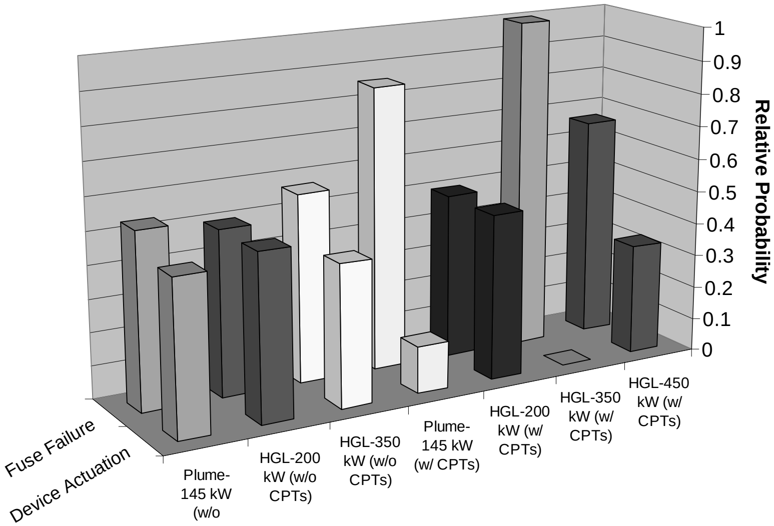

Figure D-25. Relative Probability of Obtaining Fuse Failure or Device Actuation for Multi-conductor Cables Based on Exposure Mode and Flame Intensity.

D.2.8. Cable-to-Circuit Wiring Configuration

This factor refers to the manner in which individual conductors were connected to various elements of the MOV circuit compared to the relative position of the conductors within the multiconductor cable. Four wiring schemes were used to connect the EPRI-NEI cables to the MOV control circuit components during these tests. Figure 3, above, provides the details of each wiring configuration. These configurations were recommended by SNL prior to the test program. Each configuration was named based on either on the predominant physical feature of the configuration (e.g., source-centered) or on SNL's nominal expectations regarding which configurations might be most likely to induce a spurious operation (e.g., actuation biased). As will be seen below, these expectations were not fully borne out in the testing.

Table D-13 shows the failure modes observed in testing parsed by how the wiring configuration. Figures 26 and 27 illustrate these same data graphically.

Consider first those tests that did not use CPTs as a part of the circuit. The configuration initially called "non-actuation biased" did indeed show the lowest relative number of actuations versus fuse blows (one actuation versus four fuse blows). However, the configuration originally named "actuation biased" actually showed next lowest ratio of actuations to fuse blows (three actuations to five fuse blows). The "source-centered" and "ground-centered" cases tended to show the highest likelihood of actuation with somewhat over half of the failures leading to actuation. The results for those cases involving CPTs are similar, although, across-the-board, fewer actuations are seen.

Overall, one can conclude that the cable-to-circuit wiring configuration is a strong influence factor. Overall, it would appear that the conductor located at the cable center was less likely to be involved in the shorting behavior, presumably due to the delay associated with heat conducting to the cable center. Configurations wherein the energizing source and the actuating target were in adjacent positions on the outer ring of conductors produced more actuations.

Table D-13. Number of Fuse Failures and Device Actuations Attributed to Intra-Cable Hot Shorts for Multiconductor Cables Based on MOV Circuit Wiring Scheme.

MOV Circuit Response	w/o CPTs				w/ CPTs			
	Actuation Bias	Cent. Ground	Source Cent.	Non-Act. Bias	Actuation Bias	Cent. Ground	Source Cent.	Non-Act. Bias
Fuse Failure	5	3	3	4	3	4	2	4
Device Actuation	3	4	5	1	0	1	2	0

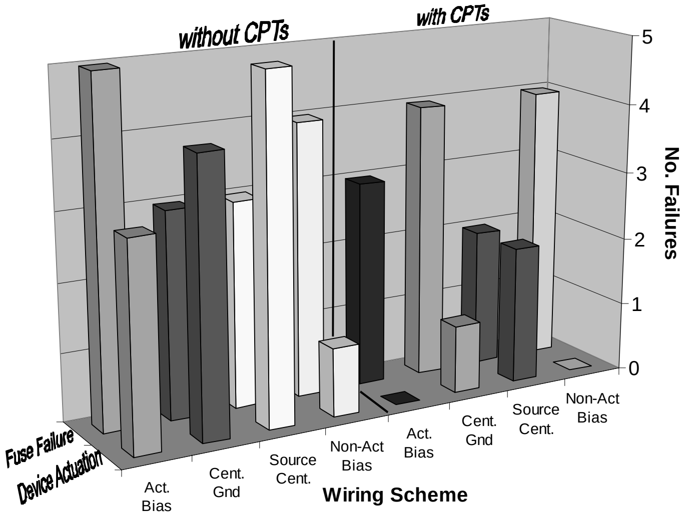

Figure D-26. Number of Fuse Failures and Device Actuations for Multi-conductor Cables Based on MOV Circuit Wiring Scheme.

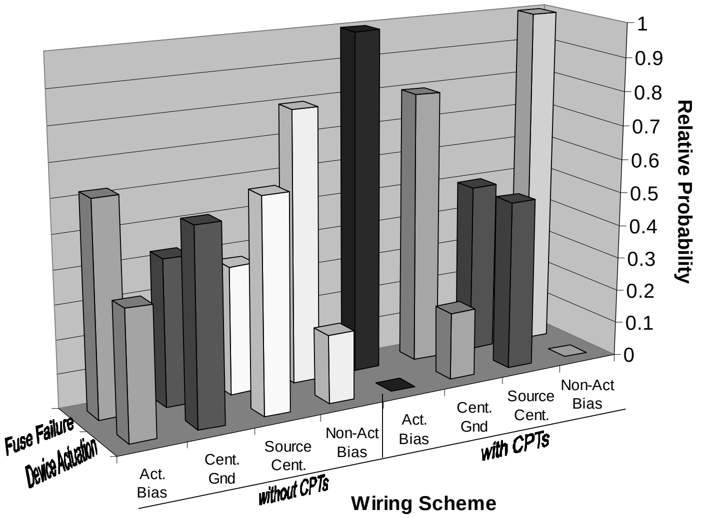

Figure D-27. Relative Probability of Obtaining Fuse Failure or Device Actuation for Multi-conductor Cables Based on MOV Circuit Wiring Scheme.

D.3. Conclusions

The NEI/EPRI Cable Failure Modes and Effects tests provided a great deal of useful data on the type of initial cable failure modes to be expected and the likelihood of spurious circuit actuation. The tests explored a number of potential influence factors, and have provided insights into the relative importance of many of these factors. The data analysis performed here has certainly not exhausted the potential insights that might be derived from these tests.

Note that in this analysis we have focused on the mode of cable failure given that a cable failure was observed. We have specifically chosen not to focus on the timing of cable failures nor on the relationship between fire intensity and room conditions. These tests were specifically designed to assess cable failure modes given failure. Comments provided by SNL during the test planning specifically did not consider factors related to fire type, fire intensity, or room construction. The intent of the tests was to create damaging fire conditions, not to create representative fire exposure conditions. The test fires were, in fact, not representative of actual fires to be anticipated in the plant. More important, the room construction was not typical of in-plant conditions. As noted previously, because the room was basically a relatively small, un-insulated, plate steel box, heat losses were far greater than would be expected in an actual plant situation. This almost certainly resulted in a substantial moderating of the room hot gas layer temperatures. In many cases, the hot gas layer temperatures hovered near what is nominally expected to be the failure threshold of a thermoset type cable (in the range of 350-400°C). Given such conditions, the prolonged failure times observed in many tests are not surprising, but rather, are fully consistent with previous cable failure testing results. It is not considered appropriate to generalize the observed failure times from these tests directly to a specific plant configuration of application.

The types of circuit faults observed given cable failure are identified as either “Fuse Failure” or “Device Actuation.” Fuse failures are interpreted as indicating a short to ground failure mode. For the NEI circuits, these may be shorts between an energized conductor and the grounded raceway, or they may involve conductor-to-conductor shorts involving the grounded conductor present in each of the multiconductor cables tested. A spurious actuation is a clear indication of a hot short between an energized conductor and one or the other of the conductors connected to the relay actuation devices. No loss of conductor continuity cable failures were observed in any of the tests performed.

In general, a significant number of spurious actuations were observed during the NEI tests. Indeed, in most of the tests where cable failures were induced, there was at least one spurious operation observed. In several tests, more than one spurious operation was observed and in some tests all of the cables that failed led to spurious actuations. Table D-14 provides an assessment of the relative strength of the influence factors evaluated in the tests.

One of the most important observed effects was that use of control power transformers (CPTs) had an overriding impact on the circuit response and likelihood of spurious actuation. Use of a CPT in control circuits appears relatively common, in particular, for MOV applications in the U.S. nuclear power industry. A CPT limits the total power available to the circuit. In these tests, the maximum power output of the CPT was approximately 150% of the power required to actuate one of the NEMA motor controller relay coils. As the current draw exceeds the available power, the voltage delivered by the CPT is degraded. If the voltage drops enough (in this case below about 87 VAC), then the relay coils cannot actuate regardless of the current flow. The CPTs appear to have had little impact on the cable failure mode; that is, hot shorts were still observed. However, because the CPT limits the available short-circuit power available, fewer of the hot shorts resulted in spurious actuations.

Based on the overall test results (e.g., including the USNRC/SNL results), degradation of the cables caused multiple current leakage paths, especially within the multiconductor cables. Each leakage path draws down some of the available power. Given the overall power limits imposed by the CPT, fewer source-to-target hot shorts retained sufficient power to sustain a spurious actuation. One unanswered question in this regard is the role of CPT power capacity in this behavior. It is likely that use of a relatively larger CPT (e.g., one that would supply 200% or more of the required actuation device power load) would substantially increase the spurious actuation likelihood. This behavior was not explored.

Given the overriding influence of the CPTs, it is difficult to draw conclusions regarding other influence factors when there was a CPT in the test circuit. That is, given the much smaller number of spurious actuations, it is difficult to discern trends related to other influence factors. Hence, the conclusions presented in Table D-14 are based largely on the results for circuits without CPTs. Nominally, one might anticipate a similar level of influence for circuits with CPTs, but would also expect a lower overall rate of spurious actuations.

The most important influence factors determining the likelihood of spurious actuation are raceway type (conduit or tray), raceway loading, armored versus unarmored cables, and the wiring scheme used to connect the MOV circuit elements (the way that the conductors are wired to the circuit). The cable material (especially for when considering the likelihood of inter-cable hot shorts), armoring, and raceway orientation were found to have a moderate impact on the outcome of the cable failures. The number of conductors and exposure mode (plume versus hot gas layer) were found to be weak influence factors.

Note that the evidence in some cases remains weak. For example, the industry tests included very few tests with armored cables, conduits, and vertical trays. Rankings that are accompanied by a notation '(?)' indicate that the evidence available from the industry MOV circuit tests is limited or inconclusive.

Another effect that was illustrated in the industry tests is the circuit-to-cable wiring configuration. In particular, the configuration initially identified as non-actuation biased did indeed experience a lower proportion of spurious actuations than the other configurations. However, for the other three configurations the data are quite comparable. In particular, the configuration originally labeled "actuation biased" proved to be poorly named, showing approximately the same rate of spurious actuations as the "source centered" and "center ground" configurations. Additional testing would be needed to further elucidate this factor. Two insights that can be taken from these results are as follows:

- embedded conductors are likely to fail later than conductors located in the outer layer of conductors for a multiconductor cable with seven or more conductors, and
- a given conductor is most likely to short first to one of its nearest neighbors among the sibling conductors - failures involving other more remote conductors are also likely, but with some time delay.

A final point of note that has not been explicitly discussed above relates to the duration of the observed spurious actuation signals. The tests report that spurious actuation signals persist for a wide range of times. Some signals were of momentary duration (e.g., less than one second). The maximum observed duration was ten minutes (circuit 2-3 in test 6). Several actuations that lasted for greater than one minute were observed. The duration of a hot short condition is expected to be a function of the fire exposure intensity, although this has not been explored in detail for this test set.

Table D-14: Summary of influence factor insights from NEI/EPRI tests.			
	Level of Influence on Spurious Actuation		
Factor	**Strong**	**Moderate**	**Weak**
Insulation/Jacket Material		X (?)	
Number of Conductors			X (?)
Armoring	X (?)		
Cable Tray vs. Conduit	X (?)		
Raceway Loading	X		
Raceway Orientation		X (?)	
Exposure Mode/Intensity			X
Wiring Scheme	X		

D.4 Supplemental Data Summary Tables

The following tables (S-1 through S-6) provide the raw information developed by SNL in our analysis efforts. These tables provide base test characteristics, identify those tests and circuits for which failures were observed, and identify the failure mode of each failed circuit. The source cable which led to each spurious actuation is also identified per the information provided to SNL by NEI and EPRI.

Supplemental Table Notes:

- Recall that sub-circuits 1 and 2 for a given circuit (i.e., cable bundle) were connected to the multiconductor target conductors, and sub-circuit 3 was connected to one of the three single conductor cables.
- Wiring configurations are described above - the abbreviations used here should be obvious.
- A notation '??' means the appropriate value or entry is unknown.
- The column "Source if actuated" refers to the source conductor that energized a device actuation if known. 'Intra' refers to intra-cable hot shorting; 'inter' refers to inter cable hot shorting.
- Under "source if actuated," for cases involving inter-cable hot shorting behaviors, whether the short was from a single conductor (1/C) or the multiconductor (7/C) is indicated. In some cases, inter-cable hot shorts involved multiple sources impacting a single circuit.
- Tests 14 and 18 are excluded from this analysis. These tests were, in reality, the last two tests conducted in the test series. These tests were of a fundamentally different nature, and the full data for these tests was not available at the time this report was drafted.[4]

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[4] Author's note: as of the final editorial changes on this report, the data are now available - see EPRI 1003326. However, due to scope and time limitations, it was not possible to revised this analysis to reflect the additional test data.

Table S-1. Circuit fault results for industry tests involving thermoset cables in cable trays

Test	CPTs (y/n)	Circuit	Wiring Config.	Failures (y/n)	Sub-circuit target	Actuation (y/n)	Source if actuated	Notes
2	n	1		n	1			No Failures
					2			
					3			
		2		n	1			
					2			
					3			
		3		n	1			
					2			
					3			
		4		n	1			
					2			
					3			
3	n	1	AB	y	1	y	intra	
					2	y	??	
					3	y	inter - 1/C	
		2	CG	y	1	n		
					2	n		
					3	n		
		3	SC	y	1	y	??	
					2	y	intra	actuated during spray
					3	y	inter - 1/C	actuated during spray
		4	NAB	y	1	n		
					2	n		
					3	n		
5	n	1		n	1			No Failures
					2			
					3			
		2		n	1			
					2			
					3			
		3		n	1			
					2			
					3			
		4		n	1			
					2			
					3			

Table S-1 (cont). Circuit fault results for industry tests involving thermo-set cables in cable trays

Test	CPTs (y/n)	Circuit	Wiring Config.	Failures (y/n)	Sub-circuit target	Actuation (y/n)	Source if actuated	Notes
7	n	1	SC	y	1	y	intra	
					2	y	??	
					3	n		
		2	CG	y	1	n		
					2	n		
					3	n		
		3	AB	y	1	n		
					2	y	intra	
					3	n		
		4	NAB	y	1	n		
					2	n		
					3	n		
8	n	2		n	1			(circuit 1 in conduit)
					2			
					3			
		3	AB	y	1	n		
					2	n		
					3	n		
		4		n	1			
					2			
					3			
9	n	1	SC	y	1	y	??	
					2	y	intra	
					3	n		
		2	CG	y	1	y	??	
					2	y	intra	
					3	n		
		3	AB	y	1	y	??	
					2	y	intra	
					3	n		
		4	NAB	y	1	n		
					2	n		
					3	y	inter - 1/C	
10	n	1	SC	y	1	n		
					2	n		Vertical Tray
					3	n		
		2	CG	y	1	y	intra	
					2	n		
					3	y	inter - 1/C	
		3	AB	y	1	n		Circuit 4 was an Air Drop Cable
					2	n		
					3	n		
		4	NAB	y	1	n		
					2	n		
					3	y	inter - 1/C	

Table S-1 (cont). Circuit fault results for industry tests involving thermo-set cables in cable trays

Test	CPTs (y/n)	Circuit	Wiring Config.	Failures (y/n)	Sub-circuit target	Actuation (y/n)	Source if actuated	Notes
11	n	1		Partial	1			Only failure was fuse blow on one of two single-conductor source cables
					2			
					3			
		2		n	1			
					2			
					3			
		3		n	1			
					2			
					3			
		4	NAB	y	1	n		All circuit fuses blew by end of test
					2	n		
					3	n		
12	y	2	CG	y	1	n		
					2	n		
					3	n		
		3	AB	y	1	n		7/C to 1/C inter-cable hot shot - chatter only
					2	n		
					3	y	inter - 7/C	
		4	NAB	y	1	n		
					2	n		
					3	n		
15	y	1	SC	y	1	n		
					2	n		
					3	n		
		2	CG	y	1	n		
					2	y	intra	
					3	n		
		3	AB	y	1	n		
					2	n		
					3	n		
17	y	3		n				Vertical Tray
		4		n				

Table S-2. Circuit fault results for thermo-plastic cables in cable tray

Test	CPTs (y/n)	Circuit	Wiring Config.	Failures (y/n)	Sub-circuit target	Actuation (y/n)	Source if actuated	Notes
4	n	1	AB	y	1	n		
					2	n		
					3	n		
		2	CG	y	1	n		1/c to 1/c hot short
					2	n		
					3	y	inter - 1/c	
		3	SC	y	1	n		1/c to 1/c hot short
					2	n		
					3	y	inter - 1/c	
		4	NAB	y	1	y	inter - 1/c and intra	possible 1/c to 7/c hot short
					2	y	??	
					3	y	inter - 1/c and 7/C	possible 7/c to 1/c hot short
6	n	1	SC	y	1	y	??	
					2	y	inter - 1/c	1/c to 7/c hot short
					3	y	inter - 1/c	1/c to 1/c hot short
		2	CG	y	1	y	intra	
					2	n		
					3	y	inter - 7/C	7/C to 1/C hot short
		3	AB	y	1	n		
					2	n		
					3	n		
16	y	1	AB	y	1	n		
					2	n		
					3	n		
		2	CG	y	1	n		
					2	n		
					3	n		
		3	SC	y	1	y	intra	
					2	y	intra	
					3	n		
17	y	1	SC	y	1	y	intra and inter - 1/C	1/C to 7/C inter-cable hot short after fuse blow on intra-cable source caused second actuation on 1-1 Vertical Tray
					2	y	??	
					3	n		
		2	CG	y	1	n		
					2	n		
					3	n		

Table S-3. Circuit fault results for thermo-set cables in conduit

Test	CPTs (y/n)	Circuit	Wiring Config.	Failures (y/n)	Sub-circuit target	Actuation (y/n)	Source if actuated	Notes
8	n	1	SC	y	1	y	intra	
					2	n		
					3	y	inter - 1/C	
12	y	1	SC	n				no failure
15	y	4	NAB	y	1	n		no actuation
					2	n		
					3	n		

Table S-4. Circuit fault results for thermo-plastic cables in conduit

Test	Circuit	CPTs (y/n)	Wiring Config.	Failures (y/n)	Sub-circuit target	Actuation (y/n)	Source if actuated	Notes
16	1	y	AB	y	1	n		
					2	n		
					3	n		1/c target

Table S-5. Circuit fault mode results for the two armored cable tests

Test	CPTs (y/n)	Wiring Config.	Circuit	Sub-circuit	Cable Fail (y/n)	Device Actuation	Actuation (source)	Notes
1	n	SC	1	1	y	n		
				2				
		CG	2	1	y	y	intra	Cable installation violated bend radius
				2		y	intra	
		AB	3	1	y	n		
				2				
		NAB	4	1	n			
				2				
13	y*	SC	1	1	y	n		
				2				
		CG	2	1	y	n		
				2				
		AB	3	1	y	n		
				2				
		NAB	4	1	y	n		
				2				

* conflicting information in NEI documentation - use of CPT verified per discussion with J. Walker, Entergy, 11/5/01.

Table S-6. Summary of overall test results - this matrix identifies each test in one of three categories : tests with no cable failures observed, tests with at least one cable failure but no device actuations, and tests with at least one device actuation observed (Tests 14 and 18 excluded)

Test	CPTs (y/n)	No Failures	Failures but no device actuations	At least one device actuation
1	n			X
2	n	X		
3	n			X
4	n			X
5	n	X		
6	n			X
7	n			X
8	n			X
9	n			X
10	n			X
11	n		X	
12	y			X
13	y		X	
15	y			X
16	y			X
17	y			X