Circuit Analysis - Failure Mode And Likelihood Analysis

A Letter Report to the USNRC

Final Report

May 8, 2000

Prepared by:

Jeffrey LaChance
Steven P. Nowlen
Frank Wyant
Vincent Dandini

Sandia National Laboratories
Albuquerque New Mexico 87185-0747

Prepared for:

Probabilistic Risk Assessment Branch
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington DC 20555
USNRC JCN Y6037

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.

TABLE OF CONTENTS

APPENDICES

1.0 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: open circuit, short to ground and hot short. (See Section 2.2 for definitions of each failure mode.)

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 is 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 fire modeling tools. The modeling tools themselves may be relatively simple (e.g., closed form equations) or may involve the use of an integrated compartment fire model. The most common approaches apply a single-valued damage threshold to predict the onset of cable failure. That is, when the cable reaches a pre-determined temperature, and/or is exposed to a threshold heat flux, failure of that cable is assumed.[1] A transient calculation results in the prediction of the time that damage occurs relative to the time of fire ignition. The predicted damage time is then weighed against assessments of the likelihood of suppression before damage occurs (the second process). Under current methods, an independent assessment is made of the response of fixed fire suppression systems (if available) and the manual fire brigade to predict the likelihood that the fire will be suppressed within a given time. The result of folding these two pieces of information together, time to damage and time to suppression each potentially given as distributions, is the conditional probability that the cable (or set of cables) is damaged given the postulated fire.

At this stage the analyst can combine the fire frequency with the conditional probability of damage to estimate of the frequency with which fires will cause damage to a specific cable or set of cables. The next piece in the PRA quantification process that must be assessed is the consequences of those 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 is discussed 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 of fires that occur within the plant on plant operations. The discussions presented immediately above have 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 potentially 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.

---

[1] Many studies independently consider both temperature and heat flux damage criteria. There are also many variations to this general approach. For example, some studies will 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.

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

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 (NUREG/CR!4832, [Ref. 3]). 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 alternate cable failure modes (hot shorts) and circuit fault modes (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 scenarios explicitly. The earliest known documentation of this approach is presented in NUREG/CR!2258 [Ref. 10]. This particular study has been widely cited, and is discussed in detail in Section 5.1.

NUREG/CR!2258 makes a number of points that remain valid today and have not been contradicted by the current study. The general conclusion that initial faults involving conductor-to-conductor hot shorts are relatively likely for multi-conductor cables is supported by the current study (see Section 5.2 below), albeit the current study will cite a somewhat higher conditional probability of such faults (approximately 0.7). 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 is required to cause an actuation. Hence, directly equating the nominal hot short failure probability to the spurious actuation 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. The original objectives of this task, as described in the USNRC fire research plan [Ref. 22], were as follows:

---

[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.

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

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.

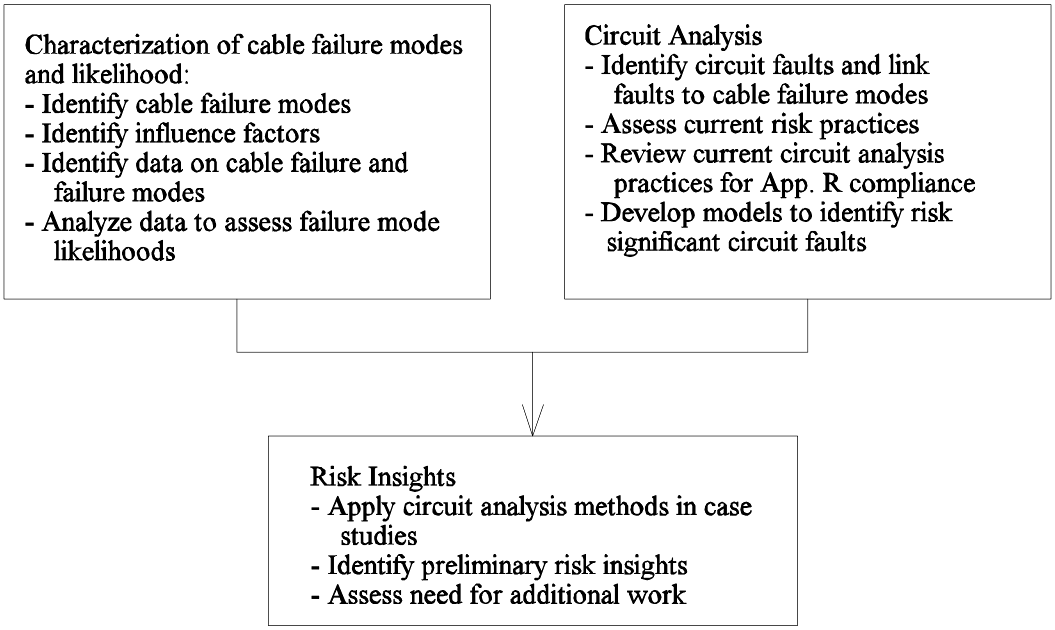


Figure 1-1: Overall structure of the circuit analysis task.

Section 2 provides a discussion of 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 assessment of the conditional probability that, given a cable failure, a particular mode of failure will be observed. This is also supplemented by the information provided in Appendix A which documents a review of current test data relevant to the estimation of cable failure modes and likelihoods.

Section 3 of this report discusses some circuit fault modes that can result from the different types of conductors failures and also identifies particular 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 uses Failure Modes and Effects Criticality Analysis (FMECA) [Ref. 2].

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-intensive process, screening methods are needed to appropriately limit the scope of the circuit analysis to those components important to fire risk. This screening can be performed as part of the fire PRA process including the application of qualitative screening steps that can utilize existing circuit analyses performed for Appendix R and additional assessments as required using an FMECA approach.

Section 5 provides a follow-up to the discussions in Section 2. In particular this section documents the current state of knowledge regarding cable failure modes and likelihood based largely on the data review documented in Appendix A. This section 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 of this report summarizes the results and conclusions of this task and provides recommendations for further work needed to support circuit analysis efforts including uncertainty reduction. As discussed in the research plan [Ref. 22], Task 1 of the NRC fire risk research program represents a first step in a detailed study of the issue of circuit faults and their treatment in fire PRA.

2.0 CABLE FAILURE MODES

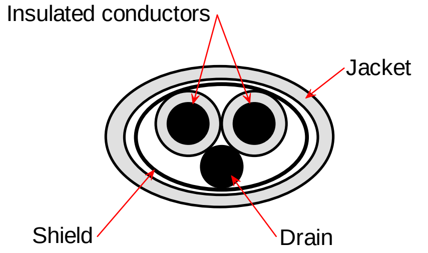
Fires can cause cable failures, and cables can fail in more than one way. Different modes of cable failure can, in turn, produce different circuit faults. The risk implications of a given circuit fault are dependent upon the associated component function. This section provides a description of the types 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 functional types of cables in a nuclear power plant: power, control, and instrumentation cables. Virtually every system in the plant is dependent on the continued operation of one or more electrical cables. Any cable is comprised of one or more electrical conductors generally either aluminum or, more commonly, copper. 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.

Power cables may be single-conductor, multi-conductor, or triplex. Control and instrumentation cables are generally of a multi-conductor design. 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 un-insulated core wire. The core wire may be connected to the circuit ground. Triplex cables are common, in particular, in three-phase power applications.

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



2-Conductor with Shield and Drain

3-Conductor

7-Conductor

12-Conductor

Figure 2-1. Illustration of common multi-conductor cable arrangements.

A cable's size is generally expressed as the number of conductors and the American Wire Gage (AWG) of the individual conductor. 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 diameter can approach or even exceed one inch (note that a higher gage number indicates a smaller conductor). For power cables the size selection is generally based on the ampacity (current carrying capacity) required in a specific application. Control cables are generally of a smaller gage, commonly ranging from 16 AWG up through 10 AWG with some exceptions on the upper end of the size range. Instrumentation cables are generally of 16 AWG or smaller.

Voltage levels will also vary with the application. Instrument circuits generally use low voltages (50 volts or less). Control circuits are commonly encountered in the 120-250 volt range. 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.

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 instrumentation) but cables of various voltages and functions can be found together in some plants (generally older plants). High-voltage power cables are typically routed by themselves and may use " maintained spacing" due to ampacity concerns. Under maintained spacing, there is no stacking of the cables, and each cable is individually strapped down to the electrical raceway. Gaps between cables ensure that they do not come into physical contact with each other. 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

Fire-exposure of an electrical cable can cause a loss of insulation resistance, a loss of insulation physical integrity (i.e., melting of the insulation), and electrical breakdown or short-circuiting. Fire-induced damage to a cable can result in one of the following electrical conductor failure modes:

- Open Circuit - The loss of electrical continuity of an individual conductor (i.e., the conductor is broken and the signal or power does not reach its destination).

- Shorts to Ground - A condition that is experienced when an individual conductor comes into electrical contact with a grounded conducting medium such as a cable tray, conduit, or a grounded conductor resulting in a low-resistance path that diverts current from a circuit. The fault may be accompanied by a surge of excess current to ground, particularly in higher voltage circuits, that is often damaging to the conductor.

- Hot Short - Electrical faults that involve an energized conductor contacting another conductor of either the same cable (a conductor-to-conductor hot short) or an adjacent cable (a cable-to-cable hot short). The hot short has the potential to energize the affected conductor or to complete an undesirable circuit path.

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 (conductor-to-conductor hot short) while a fourth conductor has shorted to ground.

Note that both shorts to ground and hot shorts may be manifested in the form of a low-impedance fault (often referred to as a “bolted-“ or “dead-short”) or as a high-impedance fault between the conductors. These two modes of shorting are distinguished because:

- a high-impedance fault 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 would likely trip the lowest level of upstream circuit protection whereas multiple high-impedance faults may trip a higher level circuit protection feature (if circuit protection coordination is not provided) leading to loss of a higher level electrical bus; and

- high-impedance faults 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 situation (e.g., complete loss of indication or an indication at the extreme high- or low-scale).

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 Appendix A. This section of the report focuses on the question of factors that may influence the 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, approximately 45 reports and papers (totaling over 2000 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 modes 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 fire simulation tests where cable 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 objective of this effort 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.

Several factors concerning the nature of the cable were identified. These include the number of conductors in the cable, the cable type including whether it has been qualified to IEEE 383 standards, the cable function, and the cable aging condition. A second general class of factors is related to cable routing and protection. These factors include whether the cables are routed in conduits or cable trays, the raceway orientation, raceway fill, and the use of fire-retardant coatings. A third general class of factors are related to the fire exposure. These factors include the type of exposure (e.g., direct flame impingement, convective heating as in a hot layer or plume, or radiant heating), the exposure intensity, and the exposure duration. A final class of factors are those associated with the electrical circuit. This includes circuit voltage, cable ampacity, circuit protection features, and circuit function. 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 [Ref. 4].

This fire damaged over 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 NRC report on the fire [Ref. 5] 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 V dc 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 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 NRC report on the fire [Ref. 5]:

> “*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. Circuits such as these are either designated as “associated circuits” and under Appendix R requirements are required to meet the same separation criteria as safety circuits or they must be isolated from the safety circuits.

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 spurious operation of ECCS pumps, and
- the pump and valve indicating light behavior.

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 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 appear to support the theory that multiple hot shorts and spurious actuation 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 was 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 configuration will always remain unanswerable, as will the uncertainty associated with whether certain systems actually did operate spuriously or only indicated a spurious operation.[4]

2.5 Factors Influencing Cable Failure Mode Likelihood

There are a range of factors that 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 only a very 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 with the objective of seeking both information regarding 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 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 factors' 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

---

[4] 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.

associated with the fire 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 multi-conductor cable
- armoring
- shielding of conductor pairs
- presence of an un-insulated ground conductor
- aging condition
- cable size
- cable qualification status

Routing factors:
- cable tray types versus conduits
- overall raceway fill
- maintained spacing installations
- protective coatings
- raceway orientation
- bundling of cables

Electrical function factors:
- circuit function (instrumentation, indication, power, control)
- cable ampacity load for power cables
- circuit voltage

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. Included is a discussion of the current evidence available regarding each of the factors from both experiments and actual experience. Finally, 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. For example, various factors may influence the timing of failures but may have little influence on the mode of failure once failure occurs. These would be listed as of little potential importance in this study, again, because the mode of failure is not impacted. Those factors that are expected, or have been shown, to be of primary importance to the failure mode likelihood are ranked as “significant” influence factors. Those factors that are expected, or have been shown, to have only a very weak influence on failure mode are ranked as “weak” influence factors. Two intermediate ranking categories identify those influence factors whose importance is poorly understood. In these cases judgement has been used to identify such factor 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 insulation material will largely determine the vulnerability threshold for internal failures in a multi-conductor cable, as well as the failure threshold for single conductor cables. This may influence cable failure mode likelihoods, but most likely only in cases where there is a mixture of cable insulation types present. 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 are degrading more quickly than others. In cases where cables are primarily of a common insulation type, the influence of the insulation type on failure modes is likely to be weak. The experimental evidence relating to this factor appears to indicate no clear trends regarding failure modes. However, it is also noted that most tests were performed using only a single type of cable in a given test (all the cables in a given test would be identical). Furthermore, because cable type strongly influences fire behavior, comparisons between tests are not fruitful. No useful insights were gained from event reviews.	Poor	Likely Weak
Jacket properties	The jacket material and thickness may influence the timing and likelihood of cable-to-cable failures. In particular, jackets are generally considered sacrificial, and damage to jackets during installation is not considered problematic. Also, jackets tend to age and degrade more quickly than insulations materials. However, the presence of a robust and intact jacket material may delay the onset of short circuits outside of a multi-conductor cable and make internal cable failure modes (conductor-to-conductor shorts) more likely at the expense of external failure modes. No direct experimental or experience based information on this factor was identified. A number of different jacket materials have been tested. However, the effect of jacket material cannot be sorted out from that of other factors.	Very poor	Likely weak
Number of Conductors	The number of conductors will almost certainly influence the likelihood that any two or more conductors within a cable might short together. It is also likely that the total conductor count may impact the relative likelihood of internal versus external failure modes. For cables with more than six conductors, the configuration will be such that at least one of the conductors will be fully surrounded by sibling conductors. In general, the focus of PRA circuit analysis concerns will be on instrument and control	Good	Significant

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

Factor:	May influence failure mode likelihood because:	Evidence	Ranking
	(I&C) cables. Hence, cable self-heating and self-ignited cable fires are not the primary concerns. For I&C cables, fire heating occurs from the outside of the cable inward. Hence, conductors located on the outer edges of the cable will likely fail before embedded conductors. As the number of conductors increases, more layers of conductors are present. Some experimental evidence is available for comparison. In most tests, three-conductor cables have been used. In these cases it is common for the initial fault mode to involve two of the three conductors, although it is also common for the third conductor to become involved shortly thereafter(i.e., within several minutes). In three test programs, seven-conductor cables were tested, and two provide some interesting insights. In one (EPRI NP-1881), the seven conductors all shorted to one-another concurrently. In the second (EPRI NP-1675) a very complex behavior was observed with conductors shorting to one-another in two groups of three. This evidence indicates that as the conductor count increases the failure behavior can become quite complex. Hence, the evidence indicates that conductor count will be a significant influence factor.		
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 influence the likelihood and duration of non-grounded conductor-to-conductor shorts within the cable. In effect, the armor represents a readily accessible ground plane (the armor is typically grounded). The ready availability of a strong ground plane would increase the likelihood of ground shorts. This is especially true for I&C cables because the heating during a fire will occur from the outside in. Hence, conductors (or insulation) nearest the cable surface will likely fail first. Some experimental evidence regarding armored cables is available, in particular, from testing by EdF (EF.30.15.R/96.442, see Appendix A and Section 5 for details). In this program several samples of various armored cables were tested. Most showed evidence of the initial failures involving one conductor and the armor, and relatively few showed conductor-to-conductor shorts independent of the shield. Hence, the experimental evidence indicates that in comparison to non-armored multi-conductor cables, the likelihood of conductor-to-conductor hot shorts (not involving the armor) is substantially reduced.	Good	Significant

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

Factor:	May influence failure mode likelihood because:	Evidence	Ranking
Shield wraps	Shield wraps may be encountered in multi-conductor 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 may increase the likelihood of ground shorts and substantially decrease the possibility of hot 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. Conductor-to-conductor shorting within the shield may also be substantially reduced given the intimate availability of a strong ground plane. Some limited experimental evidence to support this supposition. In testing by SNL (NUREG/CR!5546) 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. This indicates a conductor-to-conductor hot short probability much smaller than that noted for general multi-conductor cables.	Good	Significant
Drain wires	A drain wire is an un-insulated conductor within a multi-conductor 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 differently, but ultimately cables are relatively simple constructions. The physical aging behaviors of cable materials are well characterized. The impact of aging on electrical properties, at least at room-temperature, are also well known. High temperature behaviors are largely based on simple pass-fail thresholds, and do not consider cable failure mode. While a number of studies on cable aging are available [e.g., ref. 23, 24] how aging might impact the relative likelihood of various failure modes has not been examined in any study known to the authors. In terms of fire-induced cable failure modes, the general stiffening of an originally flexible cable may make certain modes of failure less likely. In particular, cable-to-cable hot shorts may be less likely as 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 increase in the conductor-to-conductor hot short likelihood. It is not clear that a mechanism for such behavior exists.	Very limited	Likely weak

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

Factor:	May influence failure mode likelihood because:	Evidence	Ranking
	Experimental evidence regarding aging effects on fire-induced cable failure modes is relatively poor. Testing of aged and unaged cables in NUREG/CR-5546 revealed little impact on failure thresholds, but the tests did not directly explore failure mode. 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 actual wire gauge of the cables will impact the rate of heating, and hence, the timing of failure onset. In cases where all of the collocated cables are of similar size, this is likely to have little impact on cable failure modes. However, in cases with mixed large and small cables, the likelihood of certain failure modes may be impacted. In particular, smaller cables are likely to degrade more quickly. Hence, for the probability of a cable-to-cable hot short between a large and small cable may be substantially smaller than the probability of the same failure mode for cables of like size. There is no direct experimental or experience based evidence available for this factor. Almost all tests have been conducted using only a single cable type (i.e., all cables in a given raceway are typically identical).	Poor	Likely significant
Cable qualification status	Cable qualification status (rated or un-rated) in this context refers specifically to the cables status with regard to <u>all aspects</u> of the IEEE-383 qualification standard [Ref. 7] (both flame spread and harsh environments). An IEEE-383 rated cable has been shown to be 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. However, qualification status may not influence the relative likelihood of any given failure mode. While the robust cable may last longer than the less robust cable, but once the cable fails, it may fail in the very same ways. The one exception to this may be in cases where a raceway contains a mixture of rated and un-rated cables. Here, the un-rated cables will almost certainly fail before the rated cables. This may imply that the likelihood of cable-to-cable hot shorts between a rated and un-rated cable would be reduced. No experimental or experience based evidence is available for this factor. No tests were identified in which a monitored raceway contained a mixture of qualified and unqualified cables.	Very poor	Likely weak for raceways with only one cable type. If types are mixed then likely significant for cable-to cable hot shorts

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

Factor:	May influence failure mode likelihood because:	Evidence	Ranking
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 without rungs versus ladder type cable trays will likely impact the potential for ground shorts to be observed, although some competing effects may need to be considered. For example, the rungs of a ladder type tray represent points of high loading perpendicular to 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 cable tray type importance 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.	Very poor	Likely significant
Conduits	Similar to the above discussion regarding solid bottom trays, there are competing effects when one considers conduits. The conduit itself will represent a very strong ground plane. However, because the conduit supports the cables evenly along their entire length rather than at discrete points the localized loading forces associated with a ladder tray are absent. 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. Factors that further complicate the potential influence of a conduit include the fact that conduits may be made of either plastic or metal (metal is by far more common in nuclear plant applications), conduits may be either flexible or rigid, and conduits may be routed in a range of configurations. Further, moisture may accumulate in a conduit and that water may provide a path for ground shorting (through what would by then be a superheated steam environment). Finally, conduit transitions including locations with bends, may place physical loads on the cable that might also impact the failure mode. Experimental evidence for conduits is poor. In one test series (EPRI NP-1881) several cables in conduits were functionally monitored during large scale tests. However, only three failures were	Poor	Likely significant

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

Factor:	May influence failure mode likelihood because:	Evidence	Ranking
	observed. One of the three involved shorting to the conduit, one showed an intermittent conduit short that later healed leaving only a conductor-to-conductor hot short, and one showed only a conductor-to-conductor hot short. This evidence does tend to indicate that the support loading effect may be predominant and may result in an increased probability of hot shorts within the conduit.		
Air Drops	Air drops are situations where cables drop out of an overhead tray or conduit and down to a panel or electrical component. Air drops may be quite short (on the order of one foot or so) or may be several feet in length. Air drop length is likely to be a significant factor in determining the failure mode impact. Very short air drops will likely expose the entire length of the drop including the point of exit from the tray/conduit. The weight of the air drop is supported at that exit point, and that exit point therefore is likely point for a short to ground to occur. That is, the weight loading on this point may accelerate the shorting. For longer air drops, the loading point may not come into play. In these cases many common fires, such as panel fires, are likely to threaten only the unsupported section of cable. For individual cable air drops, the initial mode of failure is almost certainly limited to conductor-to-conductor hot shorts in multi-conductor cables because of the absence of a ground plane and other cables. For bundled air drops, the possibility of cable-to-cable hot shorts would also likely increase substantially. However, the duration of a hot-short failure may also be reduced provided the fire damage is not interrupted. 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. Examples include NUREG/CR-5546 and NUREG/CR-4638. These tests clearly show that in the absence of a raceway, sustained conductor-to-conductor hot shorts are the dominant failure mode with a probability approaching 1.0. The only exceptions would be cables with grounded shield/drain arrangements, armored cables (two cases where routing is likely unimportant as discussed above), and cables that contain a grounded conductor. No experiments where the exit/support point was directly threatened by fire were identified. One study, NUREG/CR-2927, did investigate air-drop loading effects, but the results provide no useful insights because only post-test measurement of conductor-to-conductor insulation resistance were taken and shorts to the support were not monitored. Overall, there is substantial evidence to suggest that the likelihood of conductor-to-conductor hot shorts	Good for some aspects, very poor for others	Significant

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

Factor:		May influence failure mode likelihood because:	Evidence	Ranking
		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.		
	Raceway loading	A cable tray or conduit may contain as few as 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 probably be substantially reduced, unless the cables are bundled (see next item). Also as the cable load exceeds a single layer of cables and some depth of fill is developed, the loading on the bottom cables increases. This is likely to increase the likelihood of cable-to-tray shorts, particularly for ladder type cable trays where the load is supported at discrete points (see related discussions on cable tray type above). The 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, cable trays were loaded with nearly 100 passes of a single length of cable. Hence, the one cable actually made several passes through the fire zone in direct contact with the tray, and those contact points were under considerable load. In the majority of cases, a cable-to-tray ground short was the first fault mode observed. This is in contrast to various other tests where only one or a single layer of cables was tested. In these cases the conductor-to-conductor hot short probability increased substantially.	Fair	Significant
	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 plastic 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. In this case, nylon ties will likely release before the cable insulation fails, and the effect may be minimal. There is no experimental or experience-based evidence regarding this factor.	None	Likely Significant

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

Factor:		May influence failure mode likelihood because:	Evidence	Ranking
	Protective coatings	A protective coating is generally a mastic material sprayed directly onto the cables in a cable tray or air drop. The coatings are not designed to prevent thermal damage, but rather, to reduce cable flammability and minimize fire growth potential. The 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, since the coatings are applied only after installation of the cables, there is no impact on raceway contact. It would appear likely that protective coatings would have a limited impact on failure mode, and that impact may mirror the impact of exposure type and intensity factors (see discussion below). There is some evidence regarding cable coating provided in early SNL/USNRC tests. However, the data is limited to reports of the relative time to shorting with and without coatings and no failure mode information is available. The data do show failure delays with most coatings.	Poor	Likely weak - may be able to use fire exposure type and intensity as surrogates for coating impact.
	Raceway orientation	The orientation of a raceway may also influence the likelihood of certain failure modes. In particular, with 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) if 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. In particular, a vertical orientation for conduits may increase the likelihood of conductor-to-conductor shorts within a multi-conductor, and decrease the likelihood of ground shorts. In most vertical cable tray installations the cables will be strapped to the trays using some type of wire ties. This practice might mitigate the potential differences for cable trays. However, the loss of the localized loading forces 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. There is only one test available where failures were observed in a vertical cable tray (NUREG/CR!0596). In this one case the failure observed was a conductor-to-conductor hot short. However, this may have been influenced by the test configuration and is considered unreliable.	Very poor	Likely significant

Table 2-1: 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. This may occur in trays, but is more common in conduit (so that cables can be pulled through the conduit as a single group) 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 multi-conductor cable than like several individual cables. There is no experimental or experience based evidence for this factor.	None	Likely significant
Basic circuit factors			
Circuit function / type	The function of the circuit (instrumentation, indication, control, power) will almost certainly influence the nature of the circuit faults that might be observed. The circuit function will also determine the cable failure and circuit fault modes that are of interest to the risk assessment. Various tests have been performed to simulate power, control, or instrument circuits, and failure behavior is clearly impacted. Indeed, in the proposed likelihood estimation framework (see Section 5.3) circuit type is proposed as a primary factor in selection of the “:base cases”.	Good	Significant
Base ampacity for power circuits	The base current imposed on a cable determines a cable’s normal operating temperatures. In this case the most important factor would be how heavily the cable is actually loaded in comparison to its allowable current limits (or ampacity). The cable ampacity 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. First, failures may occur at lower temperature and at earlier times for cables that carry a significant fraction of their allowable current loads simply because these 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 (in comparison to the cable ampacity limits) will likely fail first, and this may increase the probability of cable-to-cable hot shorts to the more heavily loaded cables. Second, as the potential energy (current load and voltage combined) available increases, there is a substantial increase in the likelihood that no faults will be sustained for any substantial time period.	Good for some aspects	Significant in particular for open circuit likelihood

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

Factor:	May influence failure mode likelihood because:	Evidence	Ranking
	Rather, once the insulation does breakdown, 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 faults ultimately followed by an open circuit faults. Indeed, the only open circuit faults observed in any of the experiments or incidents reviewed involved cables with relatively high current carrying potential (on the order of 50 A or more). This was clearly shown in the Hinsdale fire investigation (Illinois), and in testing by LLNL (UCRL-ID-110598) (see Appendix A). Note that ampacity loading is only an issue for cases involving the exposure of normally loaded power cables. Instrument and control cables generally carry either very light or intermittent ampacity loads so that the heating effect is quite minimal.		
Circuit Voltage	The impact of circuit voltage is in part related to the discussions of circuit ampacity provided immediately above. Cable insulation thickness is typically determined based on the dielectric properties of the insulation and on the rated voltage of the cable. In this case, we presume that all cables are energized well within their rated voltage. Even in this case the actual conductor voltage of the cable is one factor in determining the available energy that might be discharged in a short-circuit situation. If voltage is high enough (a level not yet clearly defined) then the likelihood of open circuit failure increases substantially. In a faulting situation, a cable with sufficient voltage may experience a series of very short duration intermittent faults that are ultimately followed by open circuit failure.	Good	Significant
Fire/exposure factors			
Direct flame impingement	This exposure mode if generally associated with close proximity to the fire source, and will lead to very rapid and severe localized cable damage. It is not clear how this will impact cable failure modes because of the competing effect this brings about. For larger fires that expose a substantial length of cables, the rapid and severe degradation will increase the likelihood of ground shorts and may make sustained hot shorts unlikely. However, it is not clear that the initial failure mode will change substantially. Hence, in some circuits (those involving latching relays) the impact may not be significant. There is not clear evidence associated with this factor because for the large-scale tests one cannot tell if individual cables failed due to a given failure mode.	Very poor	Likely significant
Convective exposures	Convective heating will generally be associated with cables remote from the fire source, at the least, outside the fire’s flame zone. Hence, the heating is likely to be somewhat slower to cause damage than	Very poor	Likely significant

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

Factor:		May influence failure mode likelihood because:	Evidence	Ranking
		direct flame impingement This may make failure modes that do not involve shorts to ground more likely to last for longer times. Many of the small scale fire cable tests have simulated convective heating conditions. Unfortunately, these tests typically sought information on cable failure thresholds, and little data on failure mode is available. Hence, the experimental evidence regarding failure mode is very poor.		
	Exposure duration/ intensity	Long duration or very intense short duration fire exposures would be expected to lead to higher levels of damage that would inevitably lead to the conductors shorting to the local support structure (the raceway) and to ground. Shorter duration or lower intensity long duration fire exposures may lead to more modest damage states that might be associated with sustained conductor-to-conductor and cable-to-cable hot shorts. 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. Unfortunately, these tests typically sought information on cable failure thresholds, and little data on failure mode is available. Hence, the experimental evidence regarding failure mode is very poor.	Very poor	Likely Significant
	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. In general, fires tend to impact 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 were begun with exposure fires from below the trays. Ultimately, while the factor may be significant, it is also ultimately of very little interest because most fires will be exposing cables from below. Certainly in virtually all fire risk assessments known to the authors, fire scenarios are postulated in which cables are threatened only from below.	None	Likely significant (but ultimately of little interest)

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

Factor:		May influence failure mode likelihood because:	Evidence	Ranking
	Application of suppressants	The application of suppressants may impact failure mode likelihoods in several ways. Suppressants will cool the exposed cables and this may lead to either “freezing” a given damage state into place, or to “healing” of cable shorts. (The healing effect was observed in various tests, e.g., NUREG/CR-5384, and involves a recovery of some substantial insulation resistance upon cooling even though a short circuit may have been detected during the fire exposure.) If water is applied, electrical shorting may be sharply aggravated and a number of both high and low impedance shorts may be created where none previously existed. The application of a hose stream will likely lead to movement of the impacted cables. This might also enhance the likelihood of cable-to-cable shorts being observed (this has been noted in at least one fire incident in Armenia). There is no experimental evidence associated with this factor as no cable damage tests have been conducted where both suppressants have been applied and cables have been functionally monitored.	Poor	Likely significant

3.0 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, the 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 conductor fault on circuits, the resulting impact on component operation, and some parameters that can affect the circuit fault mode.

3.1.1 Open Circuit

An open circuit failure of a power cable will result in loss of power to components. 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 those components that are in standby, loss of power will prevent the component from starting and operating as required. Other 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 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 not impact the current function of the associated system. However, the loss of power will prevent the component from functioning if required for accident mitigation. In this situation involving components such as motor-operated valves, manual operation of the valve can sometimes be performed remotely. Finally, it is important to recognize that since open circuits in electrical distribution cables can result in loss of power to multiple components, power distribution cables represent important targets to consider in fire assessments.

The impact of open circuits in component control circuits is dependent upon where they occur in the control circuit. Open circuits in the portion of the circuit controlling power to breakers, relays, and contactors that must be closed for power to reach the component are of the most concern and generally have the same impact as open circuits to the power cables as described above. Open circuits in the portion of the control circuit used to shut off a component or change its position will eliminate this capability. Open circuits in the indicating portions of the circuits could lead to loss of status indication which could influence operator actions in a negative manner. Finally, it is important to note that the individual conductors for a given component control circuit are generally routed via the same multi-conductor cable. Thus, if an open circuit were to occur in one conductor of the cable due to a fire, the remaining conductors also would likely experience open circuits leading to all of the failure modes listed. However, the review of experimental data performed in this study indicates that open circuits in individual conductors are less likely than shorts to ground (which can effectively result in open circuits) and hot shorts. Indeed, the data review revealed no cases where an open circuit failure was the first failure mode observed for a cable, and open circuit failures were only noted in very limited circumstances (see Section 5.2).

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 a form of 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, may result in a complete loss of indication or a degradation of accuracy.

No circuit design features that would reduce the potential of a fire-induced open circuit were identified. However, the voltage of the cable may impact the potential for an open circuit (as discussed in Table 2.2, higher voltages may lead to a higher potential for open circuit cable failures). It is also worth noting that common practices such as separation of redundant components on different power supplies do reduce the impact from such open circuits.

3.1.2 Shorts to Ground

The impact of shorts to ground in power and control circuits is dependent upon whether the circuit is grounded. A short to ground at a grounded portion of a circuit will have no impact since the circuit is already grounded. However, a short to ground in an ungrounded circuit can result in large currents that may actuate circuit protective features such as circuit breakers or fuses. Thus, this type of short to ground can have the same effect on a circuit and component operation as do open circuits which was described above. Random failure of the circuit protection device for the faulted circuit can result in opening of circuit protection devices upstream that can result in loss of power to multiple components required for accident mitigation. Although the probability of a circuit breaker failing to open when required is approximately 1E-3 per demand [Ref. 26], manual actions to remotely open a failed breaker and then reclose the upstream breaker would reduce the risk significance of such a scenario. The random failure of circuit protection devices can also result in a secondary fire in a faulted cable at a location different than the initiating fire location.

The only other circuit design feature that can influence the impact of a short to ground is proper breaker coordination. Breaker coordination requires that the circuit breaker immediately upstream of a short to ground trips before any breakers upstream of that breaker. Improper 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 power plants, breaker coordination is typically done for higher voltage power circuits (i.e., greater than 480 Vac). Breaker coordination at lower voltage levels is less typical except when specifically required by Appendix R compliance.

A short to ground in an instrumentation circuit may generate faulty indications or a complete loss of signal. Another concern, especially in a fire, is a progressive reduction in insulation resistance between separate signal conductors, or between a signal conductor and ground. As the insulation degrades, 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, thus allowing shorts to ground or conductor-to-conductor shorts.

3.1.3 Hot Shorts

The potential for hot shorts in control circuits is dependent in part upon whether the circuit is grounded. For grounded control circuits, the energized conductor for the hot short can be from any energized conductor. However, for ungrounded circuits (less typical in nuclear power plants), the energized conductor must be from the same source (e.g., the same control power transformer or battery). For un-grounded dc circuits, a hot short can also occur from a different dc source but this would require contacting two wires of the proper polarity. A hot short on an ungrounded dc 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). Also note that 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.

Concurrent hot shorts on all 3-phases of an ac power source are generally required to energize a component such as a motor-operated valve (MOV) or pump (it may be appropriate to verify that hot shorts on two phases is 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 fire assessments (Appendix R or PRA analyses) except for high/low pressure interfacing valves. The contacting of a higher voltage conductor can result in the application of destructive voltages to a lower voltage circuit. This is possible in some plants where mixed voltage cables are routed in the same cable trays. Note that in Appendix R assessments, hot shorts between different voltage conductors are not explicitly considered.

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. 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.

Instrumentation circuits might also suffer degradation due to a hot short, but the resulting systems effects might be unique. For example, while various cable failure modes might render the instrumentation system unavailable, 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. A bias of this nature can certainly be anticipated to occur during a fire and thus accounted for in the recovery procedures. However, the question remains of the effect that the loss of a particular signal will have on the operator's knowledge of plant conditions and their response to the loss or degradation of the signal readout. Another, related concern is the potential for hot shorts to cause spurious operation of a pump or valve if the instrument governs the switching on of auto-start (automatic initiation) contacts in the component's control circuit. Ultimately, essential instrumentation circuits should be analyzed for the specific cases of open circuits, shorts to ground and hot shorts in order to predetermine the potential effects on the signal accuracy/availability due to fire. A third area of concern is instrumentation circuits that are tied to component start/stop logic. For example, rotating equipment (such as a pump) is commonly dependent on the operation of lubrication systems. Hence, there is commonly a permissive tie to, for example, an oil pressure instrumentation 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.

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 [Ref. 9] 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 an MOV open or closed and power will not be disconnected from the motor after it is completely open or closed since the limit and torque switches have been bypassed. The motor will stall and the current and torque may be high enough to fail the motor windings and possibly cause mechanical failure of the valve. Any mechanical damage may prevent an operator from manually operating the valve using a handwheel.

Other open contacts in the control circuits can also affect the potential for a hot short at a certain location impacting the operation of a component. Examples of open contacts in a control circuit include 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 in between these contacts 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.

Experimental and anecdotal experience with hot shorts indicates that given a sufficiently severe and prolonged fire exposure, the affected conductors eventually short to ground. 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 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 (e.g., by the use of a latching relay) into the circuit and another signal is needed to reverse the action (e.g., energization of an MOV). In other cases, the effect of the hot short can be reversed. The best example of this is an 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 non-essential systems. Fire damage to these non-essential circuits may negatively impact the operation of required mitigating systems whether they be 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:

- 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
- Circuits of equipment whose spurious operation or mal-operation may adversely affect mitigating systems

These concerns are described in the following subsections.

3.2.1 Circuits That Share a Common Power Supply

It is not uncommon in nuclear power plant design to include non-essential equipment on the same electrical bus as safety-related equipment. This raises a concern that a fire that causes a short in these non-essential 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 non-essential 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 non-essential 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 non-essential loads and then reloading required loads. Such actions could be credited in a fire PRA provided sufficient procedural guidance and time is 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 non-essential 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 special concern related to common power supplies is the issue of multiple high-impedance faults. High-impedance faults on cables may involve arcing between conductors rather than direct contact or may be associated with severe, but not total, degradation of insulation resistance. In either case, high impedance faults may not generate fault currents of sufficient magnitude to trip the circuit protection feature associated with the circuit. The occurrence of multiple high-impedance faults on circuits powered by the same bus can result in an accumulative fault current sufficient to trip the bus supply circuit breaker upstream, causing a loss of power to the entire electrical bus. The method for protecting against multiple high-impedance faults is also to properly coordinate breakers not only for the occurrence of shorts to ground, but also for multiple high-impedance faults.

It is not possible to tell whether or not multiple high impedance faults have ever been a factor in an actual fire. Indeed, in post-fire analysis 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. One factor that would reduce the likelihood of this scenario developing is that each of the high impedance faults must progress at nominally the same rate, and the faults must be of just the right impedance so as to not trip the first up-stream fuse or breaker, and yet the combination of faults on multiple cables must be sufficient to trip the second (or third) up-stream fuse or breaker. Based on the available data and experience, no clear probability of occurrence for such scenarios can be established. However, historically the probability of high-impedance faults has been assumed to be low and thus, to the authors knowledge have not been considered in fire PRAs (see Section 5.1 for further discussion).

3.2.2 Circuits That Share a Common Enclosure

It is not unusual for cables of non-essential 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 non-essential cables that share a common enclosure with safe shutdown equipment. The electrical protection must be such that the non-essential 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 non-essential 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.

4.0 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.

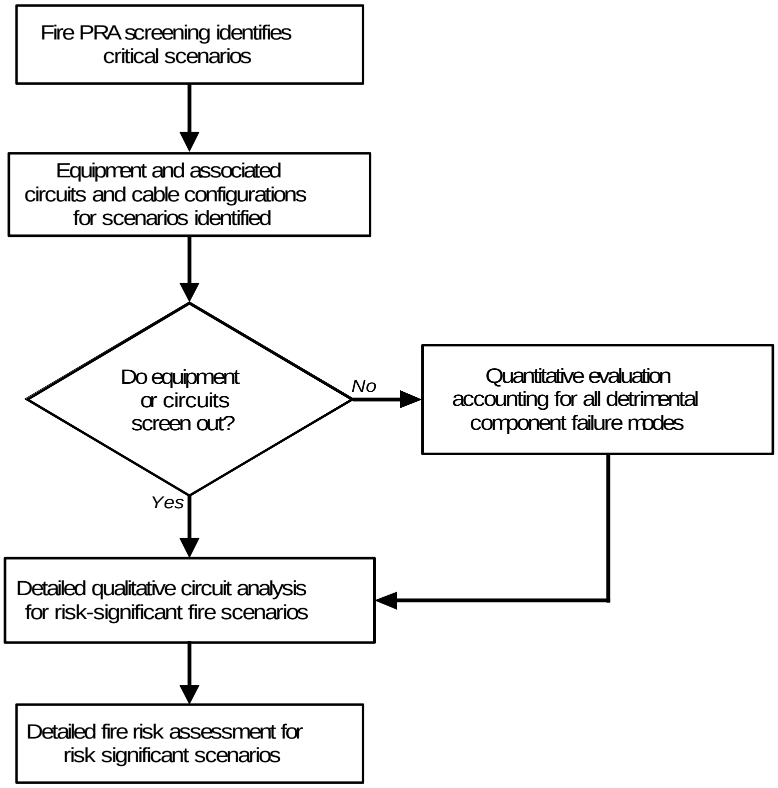


Figure 4-1. Circuit analysis process for fire risk assessment.

Since circuit analysis is a time-intensive process, screening methods can be used to appropriately limit the scope of the circuit analysis to those components important to fire risk. This screening can be performed as part of the fire PRA process. A typical example of a PRA screening method involves assuming all essential components with cables known to be located in a fire area fail due to any fire that can occur in the area. The fire PRA must assume mitigating components fail in this screening process when it is not known if cables associated with the operation of those components are located in the area. Note that some components may be capable of failing in different ways, only some of which may be detrimental to the plant and where the impact may 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 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.

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 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. Note that some component and system faults that can be induced by cable failures during a fire are not typically included in PRA models. These may include failures that arise through associated circuit issues (see Section 3.2.2 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 non-essential 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.

Some level of circuit analysis is required to perform this screening assessment. 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 is more prudent not to screen fire areas based only on the potential for a scram mechanism particularly since there may be a reasonable probability that a manual plant scram would be performed as a result of a significant fire.

The result of the PRA screening process is the identification of fire areas that contain components whose failure can initiate plant transients and also contain components required to mitigate those transients. The identified fire areas may be susceptible to risk-significant fire scenarios. For unscreened fire areas, analysis of specific fire scenarios involving specific fire sources and equipment can be performed. Fire scenario evaluation does require that the cables involved in the fire scenario and components served by those cables be identified. These fire scenario analyses would include the potential for fire growth to additional cables before suppression can occur. If non-Appendix R equipment located in the fire area is credited at this point in a fire PRA, then additional circuit analysis of that equipment is required to identify the possible component and system faults that can occur in each of the identified fire scenarios. This includes evaluation of associated circuit issues pertaining to the non-Appendix R equipment. Alternatively, a fire scenario screening process can be performed where only Appendix R equipment is credited . The results of this fire scenario screening process would be the identification of potentially risk-significant fire scenarios .

For those fire scenarios that are shown to contribute significantly to fire risk, non-Appendix R equipment can be credited for accident mitigation where justified. An analysis of the circuits for any non-Appendix R equipment in the fire area including evaluation of associated circuit issues in the area is required to fully justify the operation of this equipment. One method that can be used to perform this additional circuit analysis is discussed in the following section. The circuit analysis would identify what circuit and associated component faults are possible as a result of different fire-induced failures of the cables involved in each risk-significant scenario. Using established probabilities for each fire-induced cable failure mode and knowledge of the circuits, the unscreened scenarios can be re-quantified 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. 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 used in circuit analysis performed to meet Appendix R requirements. This method includes some conservatisms 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 allow for a systematic analysis of a circuit. 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 a circuit analysis of the safe shutdown equipment. 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 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 Appendix R safe shutdown equipment. 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, circuit analysis will have to be performed. 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 3.2.2, 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) and excludes mechanical devices such as manual valves, tanks, heat exchangers, and pressure relief valves. The list does include valves in flow paths that can result in flow diversion. Flow diversion paths can include lines where multiple valves have to open and multiple small lines whose total flow can result in significant flow diversion. For each of these components, all associated cables are reviewed to determine if their failure can prevent the component from performing their required safe shutdown function. This review includes consideration of the potential for 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 master actuation relays are included (master actuation relays are energized or de-energized when the required number of instrumentation signals are obtained; the relays then actuate emergency equipment such as the ECCS pumps and valves). Each leg of the initiating logic circuits is generally not included 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 action. Such indications that may affect the operator 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. Although, 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 from conductors within the shield or to open circuits. 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 open circuits, shorts to ground, and short circuits. However, some nuclear power plant licensees have interpreted the guidance in GL 86-10 as inferring that only one hot short at a time has to be assumed for components that are not 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 [Ref. 13] 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, hot shorts involving cable-to-cable proper polarity faults 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 relative 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 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. Currently there is little data on the duration of a hot short.

Electrical coordination in nuclear power plants is typically done 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 electrical 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 (which is available) 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 fault modes resulting from different cable failure modes can be examined and documented using a FMECA approach [Ref. 2] 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 open circuits, 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 circuit fault modes resulting from the identified cable failures. Examples of circuit fault modes 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 mode can result in different component faults that are dependent upon the system design. For example, an air-operated valve can be designed to fail either 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 solenoid-operated valve (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 motor-operated valve 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 an 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 circuit fault on the component's or system's operation. 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 provided in Table 4-1. The FMECA addresses all possible conductor faults for the SOV control circuit external to control cabinets (i.e., an open circuit, a short to ground, and hot shorts to both internal circuit conductors and external conductors). A criticality ranking for each conductor fault 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 location 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: open circuit, short to ground, and hot short to power source. 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 un-grounded dc source).
- The valve is assumed normally de-energized and closed.
- All conductors in the SOV circuit are in the same cable.

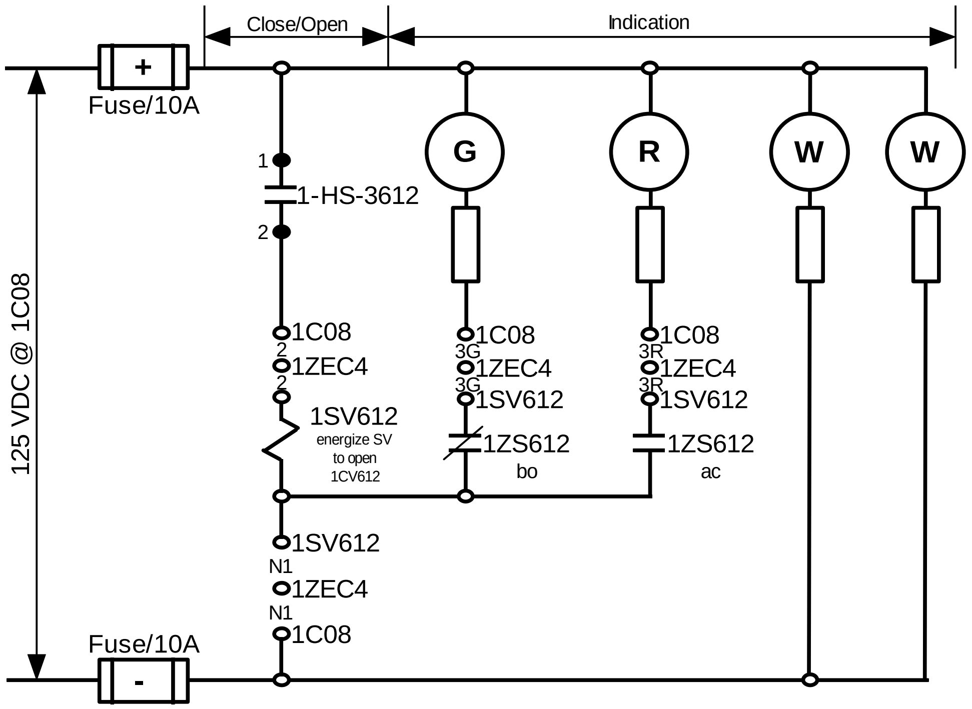
A review of Table 4-2 provides the following insights relative to the SOV circuit analysis:

- many of the identified conductor faults result in the inability to open the SOV,
- only faults to external conductors would lead to spurious opening of the SOV,
- many of the identified conductor faults would result in some indication prior to attempts to open the valve,
- some of the identified conductor faults would result in some indication after attempts are made to open the SOV,
- some of the conductor faults would not provide indication at any time, and
- many of the identified circuit faults are dependent on the duration of the postulated hot short.

Additional FMECAs were performed for a typical motor-operated valve (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 internal conductor shorts as well as open circuits, shorts to ground, and shorts to external energized conductors were evaluated. The results of these FMECAs are presented in Appendix B. The benefit of the FMECA method is illustrated by the some of the significant insights obtained from utilization of this approach in this study.

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.



Scheme 1CV612

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

Motor-Operated Valve

Several unusual findings resulted from the MOV control circuit FMECA. They include the following 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 [Ref. 9].
- 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 re-open 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).

Table 4-1. FMECA for SOV.

Item	Identification	Description	Failure Modes	Effects	Criticality
1	Conductor 2	Positive dc power lead	1) Open circuit	- 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) Open circuit	- 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	Wire 3G	Valve CLOSED status indication	1) Open circuit	- 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	Wire 3R	Valve OPEN status indication	1) Open Circuit	- 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. FMECA for SOV.

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

Pump Motor

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 FMECA 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 shows 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 three-conductor cables, shorting of multiple conductors can be expected with a significant probability. The behavior of cables with more conductors is unknown at this time.

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 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 may be important to identify in other circuit analysis techniques. For example, one method for identifying hot shorts 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 a conductor in the circuit. This method could be expanded to identify if contacting another “cold” conductor would mitigate the hot short.

Table 4-3. FMECA Summary Results - MOV

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

5.0 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 open circuits, shorts-to-ground, and 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 the existing probabilities for fire-induced conductor failure modes used in fire PRAs. Available experimental data is also presented and used to provide an indication as to what the probabilities for each failure mode might be. The parameters that significantly affect these estimates are identified. 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 [Ref. 10]. The authors of this report used empirical data from the Browns Ferry fire and information from three cable test programs[5] that were available at the time to generate a single distribution for the probability of a hot short for a multi-conductor 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 is 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 multi-conductor 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 multi-conductor 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 was expressed as a log-normal distribution with the 5th and 95th percentiles 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.

---

[5] 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).

A review of the fire assessments in the Individual Plant Examinations of External Events (IPEEE) indicates that when the potential for hot shorts 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. That is, if a spurious opening of a valve was the worst consequence of the conductor damage, that failure mode was assumed to occur with a probability of 1.0. Under the second method, some IPEEE fire assessments assigned a probability for the occurrence of a hot short leading to spurious component operation. The assigned probability was typically 6.8E-2, the mean value from NUREG/CR-2258, or an assumed value of 0.1. The potential for multiple hot shorts was often calculated by assuming that each hot short was conditionally independent of the other given fire damage to the cables of interest. Thus, the probability for two 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.

The duration of a hot short was also addressed in NUREG/CR-2258. Citing the opinion that hot shorts eventually become open circuits due to the further deterioration of cable insulating materials under the continued presence of a fire and the fact that spurious signals during the Browns Ferry fire occurred during the first half hour, the time for a hot short to become an open circuit was expressed as being normally distributed with 5th and 95th percentiles of 5 and 35 minutes, respectively. The duration of the hot shorts was typically not addressed in the IPEEE fire assessments. Appendix R assessments will generally assume that the hot short remains active until actions are taken to clear it, and it would appear that this same assumption was used in most IPEEE assessments.

The authors of NUREG/CR-2258 state that open circuits are the dominant conductor failure mode during a fire. The definition of open circuit in this report includes both physical discontinuities in the conductor and opening of circuit protection features due to a short-to-ground. Thus there was no attempt in that report to establish separate probabilities for those two failure modes. Instead, the probability for either one was established as the complement of the probability for a hot short as a distribution with 5th and 95th percentiles of 0.8 and 0.99, respectively, and a mean probability of 0.932.

The occurrence of high-impedance faults are not generally considered 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 as the potential result of such faults, they 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 or alternatively, be designed out of the plant by including their potential in breaker coordination schemes. 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. Probably the most important factor contributing to this perception is that there must be concurrent high-impedance faults, on multiple conductors connected to the same power supply, to result in loss of multiple equipment due to a single fire.

Furthermore, each of the individual line faults must fit within a narrow range of impedance. This is because the faulted conductors must have specific fault current magnitudes such that they don’t trip the load breaker for each of the faulted circuits, but collectively, result in a fault current sufficient to cause the supply breaker feeding all of the faulted circuits to open. If the impedance is too low, then the nearest up-stream 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 fault 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 mega-ohms are commonly encountered), and changes of this magnitude may be associated with only very modest temperature differences (on the order of 20-30EC 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) resulting in generation of a fault current sufficient to open the load breaker for that circuit and eliminate its contribution to the fault current on the upstream breaker. Overall, it would appear reasonable to assume that, from a PRA perspective, multiple highimpedance 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 occurredduring 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.

Measured data directly relevant to quantifying the relative probability of different fire-induced cable failure modes was obtained from ten reports. A detailed discussion of the tests and results presented in these reports is provided in Appendix A. The data is grouped and discussed here according to the type of cables tested. Three groups of data are presented:

- Multi-conductor cables (without shield, drain wires, and armor)
- Armored multi-conductor cables without shields and drain wires
- Multi-conductor cables with shield and drain wires

The data was grouped in this fashion since the presence of a shield and drain wire present a ground plane within the cable which will significantly affect the potential for a short to ground versus a conductor-to-conductorhot short. Similarly, the armor in armored cable can also be grounded and thus also affect 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.

5.2.1 Multi-Conductor Cable Data

The data obtained for multi-conductor 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 [25] from Underwriter's Laboratories (UL) which represents 161 of the186 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 individual testsinvolving eight different types of cables (including types typical of both qualified and unqualified cables), three fire exposure intensities were used, both vertical and horizontal trays were tested, and each of the horizontal tray tests 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

Table 5-1. Measured data on multi-conductor cable failure modes.

Reference	Type of Cable[1]	Size (AWG)	Number of Conductors	Number of Failures[2]			Comments
				Shorts to Tray or Conduit	Conductor-to-Conductor Shorts	Open Circuits	
NUREG/CR-0833 (Reference 11)	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 14)	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 19)	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
EPRI NP-1881 (Reference 17)	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	
ENS-IN-99-00412 (Reference 16)	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.

Table 5-1. Measured data on multi-conductor cable failure modes.

Reference	Type of Cable[1]	Size (AWG)	Number of Conductors	Number of Failures[2]			Comments
				Shorts to Tray or Conduit	Conductor-to-Conductor Shorts	Open Circuits	
UL File NC555 (Reference 25)	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				52/186	134/186	0/186	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.

were tested and are described in the report, the data results are obscured such that individual results cannot be tied to specific cable types. 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 (the core conductor at the center of the cable) was grounded along with the cable tray.

Of the remaining sources, the majority of the data is from two series of tests performed by Sandia National Laboratories under USNRC sponsorship and pertains to three-conductor cable. The method for measuring electrical integrity in the tests reported in NUREG/CR-0833 [Ref. 11] was not provided. Although the report provides data stating that both conductor-to-conductor and conductor-to-tray shorts occurred in 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.

The data shows that for multi-conductor 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 an open circuit failure in any of the reports referenced in Table 5-1.

Only the UL tests provide some nominal indication relating to the potential for multiple hot shorts. In the other tests, there was typically only a single length of instrumented cable in each test. However, in UL the horizontal tray tests there were four trays exposed during each test. Most of these tests did record conductor-to-conductor hot shorts 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 hot shorts in a single test would be expected.

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 that requires 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%). The data that provided these observations are shown in Table 5-2. Note that a sensitivity evaluation is included in the table in which the data from NUREG/CR-5546 [Ref. 15] 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. In summary, if shorting of a third conductor will mitigate a hot short (e.g., if the third conductor was grounded), the data reviewed in this study indicates that this would be a likely scenario since the majority of the test data (approximately 90%) shows all three conductors shorting together. However, if only a momentary conductor-to-conductor short is required (e.g., in a circuit involving a latching relay), then the likelihood of just the two required conductors shorting together is also high (>40%).

There is very little data in the reports reviewed here that can be used to characterize the likelihood that specific conductors might short, and in particular, for cables with more than three conductors. Most of the tests reviewed in this study used three-conductor cables. While the UL tests involved seven conductor cables, the conductors were energized in two groups of three conductors each plus a single grounded conductor (see Appendix A, Figure A-10). Hence, it is not possible to say which individual conductors shorted when. In fact, only two data points for seven-conductor cables were identified where individual conductor behavior could be discerned. In one case (EPRI NP-1881 [Ref. 17]) all seven conductors shorted together simultaneously while in the other case (EPRI NP-1675 [Ref. 21]) a more complex behavior occurred. The cable with the more complex behavior included several conductors which shorted together, then healed to some extent, and shorted together again. One conductor shorted to ground while yet other conductors not involved in the initial shorting later shorted to other conductors. The trend in the cable behavior suggests that continued exposure of this cable to fire may have eventually resulted in all of the conductors shorting together and also to ground (see Appendix A and Figure A-2). However, no conclusions can be reached from this limited information on the relative probability of certain combinations of conductor shorts in seven conductor cables or their duration. Furthermore, this data is insufficient for judging the appropriateness of any combinatorial models that could be used to establish the probability of certain conductor-to-conductor shorts.

Finally, there is very little information from the tests represented in Table 5-1 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. 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 hot shorts observed in these tests.

Of the available data, only EPRI NP-1881 and a French test reported in ENS-IN-99-00412 [Ref. 16] provided some information pertaining to the duration of conductor-to-conductor shorts. The two ungrounded cables in conduits that experienced conductor-to-conductor shorts in the tests reported

Table 5-2. 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 15)	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 22)	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 11)	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 parenthesis 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

in EPRI NP-1881 did not experience shorts to the ungrounded conduit during the duration of the fire (if the conduit had been grounded, low-impedance shorts to it would have terminated the conductor-to-conductor hot short). However, it should be noted that these tests involved relatively small pilot fires that lasted for approximately 6 and 10.5 minutes, respectively. The ignited cables self-extinguished by 9.25 and 11 minutes, respectively (i.e., 3.25 and 0.5 minutes after the pilot fire extinguished). In contrast, the pilot fire in ENS-IN-99-00412 was relatively large and the duration of the initial conductor-to-conductor short was approximately 1 minute before the cable shorted to ground. In conclusion, there is insufficient information available from these test reports to establish distributions for the duration of a conductor-to-conductor hot short.

5.2.2 Armored Cable

Two of the tests reviewed in this study involved 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 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 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 an open circuit as the initial cable failure mode.

5.2.3 Shielded Cables with Drain Wires

One series of tests reported in NUREG/CR-5546 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 cables 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 in NUREG/CR-5546 shows that the majority (38 out of 40) of the initial conductor-to-conductor 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 an 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

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	Open Circuits		
EPRI NP-1881 (Reference 11)	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 18)	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.

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 Cable-to-Cable Shorts

The reviewed data contained very little information on cable-to-cable failures. This is because only two of the reviewed reports were instrumented to specifically identify the occurrence of cable-to-cable shorts. The tests performed by Lawrence Livermore National Laboratories (documented in Reference 12) were specifically instrumented to detect cable-to-cable shorts, cable-to-tray shorts, and open circuits. 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 is not likely. In addition, it is noted that this was the only test to record electrical open circuits. The open circuits occurred after the occurrence of many shorts between cables and the tray. The occurrence of these open circuits in these tests and not in any of the others reviewed in this study indicates that open circuits 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 test that contains information on cable-to-cable shorts is the French test performed in cooperation with the Nuclear Energy Institute [Ref. 16]. This test, which is described in detail in Appendix A, involved one two-conductor “source” cable surrounded by seven “target” cables. The results of this single test shows 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 cable tray which was grounded 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.)

In conclusion, there is insufficient data in the reviewed reports to establish the relative likelihood of a cable-to-cable hot short developing.

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 1.1 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 indicates 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 occurring in a multi-conductor cable than the value implied in NUREG/CR!2258. The earlier study cited that the hot short probability for a multi-conductor was “on the order of 0.1 or larger.” The current review has found the hot short probability to be on the order of 0.3 to 0.8 (i.e., given failure of a general multi-conductor cable this is the conditional probability that the initial failure mode will be a non-grounded conductor-to-conductor short circuit). This still leaves open the question of the likelihood that the hot short that forms will lead to a spurious actuation. Overall, however, 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 multi-conductor 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 multi-conductor 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.[6] 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.

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 multi-conductor 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. It is also reasonable to postulate that initial failure is 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). Finally, shorts are most likely to occur first in conductors near the outer surface of the cable 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.

---

[6] This is simply an example and is most certainly not universally true. Cases were identified in the FMECA examples where spurious actuations would occur even given shorting between several conductors within a multi-conductor cable. This is a case-specific factor that must be confirmed and cannot be assumed.

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 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 pre-selected 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 2.4 above. 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 co-existence 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 consensus on the base case likelihood distributions, and (4) seek consensus on the methods and values for addressing the influence factors in a given application.

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 factors.

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 as being critically important to failure mode likelihood. One example taken from the data review would be cables with shield/drain arrangements as distinct from general multi-conductor 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 multi-conductor. 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.

– 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.

<u>Example 1: Un-shielded, un-armored multi-conductor cables:</u>

<u>In conduit:</u> 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 multi-conductor in a conduit. Influence factors would likely include circuit voltage, cable size, total conduit fill, total conductor count, and potentially factors associated with the fire exposure (intensity, duration, etc.)

<u>In horizontal trays:</u> 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.

Un-grounded 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 re-surface. 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:[7]

Grounded armor: Similar to the cases involving shield wraps, armored cables are unique in that cable-to-cable interactions independent of the armor wrap are presumed to be highly unlikely. In the case were 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

---

[7] A typical armored cable is similar to a general multi-conductor cable. However, in addition to the normal polymeric jacket, a metallic armor sheath is added. This sheath is typically either braided metal strands (wire mesh) or a spiral wound metal band (similar to flexible conduit). In either case, the armor itself may be exposed, or may be further covered by a polymeric sheath, generally applied for moisture and physical protection rather than for any electrical purpose.

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.

6.0 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, and insights from the review of the 1975 Browns Ferry fire. 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 hot 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 hot shorts include the following:

    - For general multi-conductor cables without armor, shields, or drain wires, the test data demonstrate that the likelihood of an initial fault being a conductor-to-conductor hot short ranges from 0.3 to 0.8 depending on the test set analyzed. The value for all of the available data taken together is about 0.7.

    - In multi-conductor 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 hot 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 multi-conductor 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 hot short probability was estimated at 0.05 (as compared to 0.3 to 0.8 for general multi-conductors as noted above).

- The data on conductor-to-conductor hot shorts for multi-conductor cables indicates that any number of conductors may be involved in the shorting behavior. That is, conductor-to-conductor shorts between conductor pairs is not the only potential concern. Rather, it was clear that conductors may short in individual pairs or in larger groups. Hence, the circuit analysis must consider the possibility of conductor faults involving any number of conductors.

- There is very little experimental data on the duration of conductor-to-conductor shorts in multi-conductor cables. What little data is available suggests that given a severe and sustained fire exposure, all conductors will eventually short to ground. However, shorter or less intense exposures may lead to sustained hot shorts. 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 open circuit 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 open circuit 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 (open circuited) in post-test examinations. However, the open circuit 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 an open circuit.

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

- 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
    - routing in conduits
    - 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. The available tests clearly demonstrate that meaningful cable failure monitoring circuits, including high energy cable circuits, can be implemented safely during both large- and small-scale fire tests. None of the approaches reviewed was found to be “ideal” from the standpoint of cable failure mode determination, and some were of questionable merit even in detecting the onset of failure (e.g., the post-test examination approach).

Recommendations arising from these conclusions include the following:

- A framework for performing cable failure mode likelihood estimation using a pre-defined 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 on 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 NRC and contractor experts in the design and planning of future test programs.

- It is recommended that an expert panel be convened to address both immediate and long term needs with regard to cable failure likelihood analysis. The proposed analysis framework is recommended as a potential starting point for panel deliberations. The charter of the panel should include (1) development of likelihood estimation methods, (2) seeking consensus opinions on mode likelihood, (3) seeking consensus opinions on influence factors, and (4) developing recommendations for needed testing.

- 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 has 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.

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.

- 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 scenarios 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 deterministic 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, multiple hot shorts 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. Since experimental data indicates that hot shorts can short to ground in a relative short time frame, this is a conservative assumption 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 up-stream breaker and a loss of power to multiple components. This would not be captured by either a typical Appendix R analysis, nor by 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 use of FMECA for performing circuit analysis was found to provide information that can be used to advance both the circuit analysis and human factors portions 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 have not 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 need to be addressed in a fire PRA include those related to associated circuits for systems credited in the PRA. The associated circuits are those (safety or non-safety related) circuits whose fire-induced 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).

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.

- 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.

- 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-intensive; 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.

- Additional investigation is needed to assess the merits of combinatorial models that purport to estimate the likelihood of a hot shorts involving specific combinations of conductors within a multi-conductor cable. The available data provide no direct evidence supporting or refuting such models.

7.0 REFERENCES

1. The Code of Federal Regulations: Title 10 - Energy, Part 50 - Domestic Licensing of Production and Utilization Facilities, Appendix R - Fire Protection Program for Nuclear Power Facilities Operating Prior to January 1, 1979.
2. *Guidelines for Hazard Evaluation Procedures,* American Institute of Chemical Engineers, New York, (1985).
3. J.A. Lambright, et.al., "Analysis of the LaSalle Unit 2 Nuclear Power Plant: Risk Methods Integration and Evaluation Program (RMIEP) - Internal Fire Analysis," NUREG/CR-4832, Volume 9, U. S. Nuclear Regulatory Commission, March 1993.
4. R.L. Scott, "Browns Ferry Nuclear Power-Plant Fire on Mar. 22, 1975," *Nuclear Safety*, Vol. 17, No. 5, September-October 1976.
5. Harold J. Collins, et al., "Recommendations Related to Browns Ferry Fire," NUREG-0050, U. S. Nuclear Regulatory Commission, February 1976.
6. S. P. Nowlen, "An Investigation of the Effects of Thermal Aging on the Fire Damageability of Electric Cables," SAND90-0696, NUREG/CR-5546, Sandia National Laboratories, May 1991.
7. "IEEE Standard for Type Test of Class 1E Electric Cables, Field Splices, and Connections for Nuclear Power Generating Stations," ANSI/IEEE STD 383-1974, The Institute of Electrical and Electronic Engineers, April 30, 1975.
8. S.P. Nowlen, "A Summary of Nuclear Power Plant Fire Safety Research at Sandia National Laboratories, 1975-1987," NUREG/CR-5384, Sandia National Laboratories, Albuquerque, NM, December 1989.
9. NRC Information Notice 92-18, "Potential for Loss of Remote Shutdown Capability During a Control Room Fire," February 28, 1992.
10. M. Kazarians and G. Apostolakis, "Fire Risk Analysis for Nuclear Power Plants," NUREG/CR-2258, University of California at Los Angeles, Los Angeles, CA, September 1981.
11. L. J. Klamerus, "Fire Protection Research Program Corner Effects Tests," SAND79-0966, NUREG/CR-0833, Sandia National Laboratories, December 1979.
12. H.K. Hasegawa, K.J. Staggs, and S.M. Doughty, "Fire Tests of Wire and Cable for DOE Nuclear Facilities," UCRL-ID-110598, Lawrence Livermore National Laboratory, Livermore, CA, September 1992.
13. "Implementation of Fire Protection Requirements," Generic Letter 86-10, U, S. Nuclear Regulatory Commission, April 24, 1986.
14. D. D. Cline, W. A. von Riesemann, J. M. Chavez, "Investigation of Twenty-Foot Separation Distance as a Fire Protection Method as Specified in 10 CFR 50, Appendix R," SAND83-0306, NUREG/CR-3192, Sandia National Laboratories, October 1983.
15. S. P. Nowlen, "An Investigation of the Effects of Thermal Aging on the Fire Damageability of Electric Cables," SAND90-0696, NUREG/CR-5546, Sandia National Laboratories, May 1991.

16. “Loss of Insulation Test on an Electric Cable During a Fire,” ENS-IN-99-00412, Electricite’ de France, April 16, 1999.
17. “Categorization of Cable Flammability: Intermediate-Scale Fire Tests of Cable Tray Installations,” EPRI NP-1881, Factory Mutual Research Corporation, Norwood, Massachusetts, August 1982.
18. J. M. Such, “Probability Study Program on Fire Safety, EF.30.15.R/96.442, Electricite’ de France.
19. L. J. Klamerus, “A Preliminary Report on Fire Protection Research Program Fire Barriers and Suppression (September 15, 1978 Test),” SAND78-2238, NUREG/CR-0596, Sandia National Laboratories, December 1978.
20. W. T. Wheelis, “Transient Fire Environment Cable Damageability Test Results, Phase I,” SAND86-0839, NUREG/CR-4638, Sandia National Laboratories, September 1986.
21. J. S. Newman and J. P. Hill, “Assessment of Exposure Fire Hazards to Cable Trays,” EPRI NP-1675, Factory Mutual Research Corporation, Norwood, Massachusetts, January 1981.
22. N. Siu and H. Woods, “NRC Fire Risk Research Plan: Fiscal Years 1998-2000,” USNRC/RES, attachment to USNRC internal memorandum from T.L. King to G.M. Holahan, June 28, 1999.
23. EPRI TR-103841, “Low-Voltage Environmentally-Qualified Cable License Renewal Industry Report,” Revision 1, July 1994.
24. R. F. Gazdzinski, et.al., “Aging Management Guide for Commercial Nuclear Power Plants - Electrical Cables and Terminations,” Sandia National Laboratories contractor report, SAND96-0344, Sept. 1996.
25. “Flame Propagation Tests of Power and Control Cables,” Underwriters Laboratories, UL File File NC555, Project 74NK8900, 23 Aug. 1976, placed in the NRC Public Document Room (PDR) by memorandum dated May 31, 2000 from Hugh W. Woods (NRC) to Mark A. Cunningham (NRC), including written permission from the copyrighted document’ s sponsor for its reproduction (ADAMS Accession # ML003721765).
26. “Reactor Safety Study: An Assessment of Accident Risk in U.S. Commercial Nuclear Power Plants,” WASH-1400, NUREG-75/014, Nuclear Regulatory Commission, 1975.

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 faulting. 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 behavior 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 cable failure, a particular mode of cable faulting 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: this is a short circuit between two (or more) conductors within a multi-conductor cable independent of either a cable-to-tray or cable-to-cable short circuit and without the involvement of a ground connection.

- Cable-to-cable: this is a short circuit between conductors in two (or more) separate cables without a simultaneous interaction with ground.

- Ground faults: this is a short circuit between one (or more) energized conductors and a ground plane. In this case several source of the ground plane may be of interest. Hence, a further subdivision of these faults is necessary as follows:
  - Cable-to-raceway: this is a fault between one (or more) energized conductors and the supporting cable raceway. Typical raceways include cable trays and conduits.
  - Conductor-to-grounded conductor: this is a unique subset of the conductor-to-conductor fault where one of the conductors in a multi-conductor cable is explicitly grounded and is involved in the fault.

    - Conductor-to-shield/drain: this is a unique fault 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 ground fault 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 may be grounded either explicitly or through ground contact somewhere along the length of the cable.

- Open circuit: this is a failure that results in the loss of conductor integrity, that is, breaking of the conductor.

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 fault modes. Note that it is not the objective of this appendix to discuss the impact of a given fault 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 faulting 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 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 fault 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]

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.

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

---

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

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 EPRI-Sponsored Tests

This section describes the publically available information from test programs sponsored by the EPRI. The tests described were all performed by Factory Mutual Research Corporation (FMRC) and took place 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.

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 continuos 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 faulting 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 fault retains some impedance. The fault 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 faulting groups described above.

<u>Summary of Results:</u> 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 fault behaviors. The data appear to show that two groups of three conductors each formed interacting faults, 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 faults were not dead-shorts because the various conductor voltages remained distinct. This test illustrates that faulting behavior for multiconductor cables can be

complex, and than not all conductors are likely to experience the exact same faulting 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 faults. The cable monitoring circuit is shown in Figure A-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 faults. 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 faults 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 fault 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 fault 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 fault occurred between two of the three cable conductors. Within approximately 1 additional minute, the third conductor appears to have faulted to the conduit while the hot-short between the other two conductors was maintained independently. It would then appear that the fault 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 faults 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 fault 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.

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 discusses. 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 cite times to electrical shorting observed in each test. However, it is not known what mode, or modes, of faulting were monitored. There is no discussion of fault 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 fault mode was; namely, either conductor-to-conductor of 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 faults 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 fault 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 faults. Further, the first fault in any of the 56 cable segments in a given tray would be the only fault detected. Subsequent faults 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 fault transitions are, however, noted.

Conductor-to-conductor failure was detected and confirmed for one of the five trays (tray 3). The fault 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) fault 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 faults. 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 faulting 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 faults were detected. A second tray (tray 1) experienced intermittent fault indications during the burn test. However, in post-test analysis no faults 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.

<u>Summary of Results:</u> This test indicates that one-of-one observed initial failures was a conductor-to-conductor fault within a multi-conductor cable. The fault was sustained, and was also confirmed after completion of the test. No transition of the fault to a ground or tray fault 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 fault. 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.

<u>NUREG/CR-0833:</u> 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 faults were detected, the report does cite independent times for “cable to cable” and “cable to tray” faults noted during testing. It would appear, however, that “cable to cable” shorts as used in the original report would correspond to “conductor-to-conductor” faults 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” faults as that term is used in the current report. In the discussions that follow, reports of a “cable to cable” fault in the original document are interpreted here as conductor-to-conductor faults.

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, cite failures in all of the tested cable trays. For the 6 qualified cables tested (2 cables in each of three tests), the initial fault 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 faults. Of the 6 unqualified cables tested, 4 report an initial cable-to-tray fault followed one minute later by a conductor-to-conductor fault. The remaining two samples report simultaneous occurrence of both conductor-to-conductor and cable-to-tray faults. The installation of the cables as a single length of cable looped repeatedly through the fire zone likely influenced the mode of faulting. 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.

Summary of Results: 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.

NUREG/CR-2927 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 over, 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 faults. Hence, these tests provide some information regarding cable failure thresholds, but no information on the relative likelihood of one fault 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 fault (which would drive the AC current to zero) while the DC current was intended to detect cable-to-tray faults (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 faults. Many failures were detected, all involving cable-to-tray faults. No open circuit faults were detected.

Results Summary: The air-oven tests provide no data whatsoever regarding the relative likelihood of a given fault mode. In the radiant heat tests, cable-to-tray faults were detected in most of the experiments. However, the predominance of cable-to-tray faults is not meaningful with regard to the relative likelihood of a given fault mode because that is essentially the only fault mode that was sought. At most the tests illustrate that open circuit faults 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 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 criteria 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 faults 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 fault 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 fault following a conductor-to-tray fault: In this case, the conductor to tray fault would dominate the circuit and a subsequent conductor-to-conductor fault may not be indicated. Hence, reports of conductor-to-conductor faults after the onset of a conductor-to-tray fault are considered unreliable.

- Cable-to-cable faults: These faults 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 fault would either lead to no indication of faulting (if one of the three conductors faulted to itself at a crossing-point) or the same indication that would result from a conductor-to-conductor fault.

- Conductor-to-tray following a conductor-to-conductor fault: In this case, the circuit may have provided indication of a conductor-to-conductor to conductor-to-tray fault transition, but only if the conductor-to-tray fault 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 fault in the lower tray, what this means is ambiguous. Lower tray faults as reported in NUREG/CR-3192 should be interpreted as follows:

- A reported conductor-to-ground or conductor-to-tray fault represents two fault 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 fault is indicated by the light for the energized conductor going out. No distinction between which of these two fault 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 amp-meters reading identical current values rather than the original different values and the indicating lights remaining illuminated.

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

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

For the Lower Trays:*

- In Experiment 2 (unqualified cable) a conductor-to-ground fault was detected at 614s
- In Experiment 4 (unqualified cable) a conductor-to-ground fault was detected at 735s
- In Test 1 (unqualified cable) a conductor-to-ground fault was detected at 262s
- In Test 3 (unqualified cable) a conductor-to-conductor fault was detected at 1043s
- In Test 5 (unqualified cable) a conductor-to-conductor fault was detected at 775s

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

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.

These 1983/84 tests were documented originally in an unpublished letter report to the USNRC dated July 14, 1984. The primary test results (damage time versus exposure temperature) have been published in NUREG/CR!5384.[2] This review is based on consideration of both documents.

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 12AWG.

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 course 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 faults were monitored. Conductor-to-conductor shorting was monitored.

---

[2] Ref: Nowlen, S.P., *A Summary of Nuclear Power Plant Fire Safety Research at Sandia National Laboratories, 1975-1987*, NUREG/CR-5384, Dec. 1989, see pp. 92-99, section 6.2.4.

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

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

---

[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.

[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.

the others would remain at elevated voltage. If all three conductors faulted together, the conductor-to-ground voltage on all three conductors simultaneously drops to the same level, and if the fault 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 faults, 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 fault in some discrete order, the nature of both initial and subsequent faults 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.

- In some experiments faults 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 faults 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 ground faults. 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 faults.

- 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 faults at the location of the thermocouple, and indeed, increase the likelihood of faults 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 faults 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 faulting behavior to that presented for the two conductors known to have faulted to the thermocouples. Further, all of the initial faults occur at very similar times during each test (between 245 and 294 seconds). Secondary faults 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 faults 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 faults were anticipated. Indeed, the failures that did occur (in tests 7 and 9) were conductor-to-conductor faults.

<u>Summary of Results:</u> 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 faults. In two tests (A and B) cable faults 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 tray or ground fault to occur. Hence, these tests provide little or no useful information on the relative likelihood of one failure mode as compared to another.

<u>NUREG/CR-5546:</u> 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-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 faults.

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 16AWG 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 fault tripping the circuit, but up until this time, the three conductors each displays 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 faulting was generally associated with the drain conductor. That is, in only two cases out of 40 observed faults 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 faulting monitored was conductor-to-conductor faults. The rather interesting behavior of the BIW samples illustrates the potential importance of shield and drain arrangements in the faulting behavior. As noted above, in only two cases out of 40 observed faults 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 faults that would exclude the drain conductor are of low probability (nominally on the order of 0.05 per fault).

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 faults), “circuit-to-ground” (conductor-to-ground) faults, and two circuits monitoring “circuit-to-circuit” (conductor-to-conductor) faults. The tests involved low-voltage (28 VDC) power sources and simple indicating lights that would either light or extinguish upon a detected fault. In the SNL tests an additional voltage monitoring circuit was installed across the indicating lamps to provide a digitally recorded record of any faults that might occur. However, the detection circuits were largely of a “pass/fail” design. The circuits used are illustrated in Figure A!8.

---

[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.

Summary of Results: 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 faults such faults were detected. In the one circuit designed to detect conductor-to-ground faults, a ground fault was detected. Unfortunately the data provides no indication of the relative likelihood of one fault mode versus another because each circuit was designed specifically to detect one and only one mode of cable faulting. Comparison of fault 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.

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 faults. However, there was no raceway. All faults 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 faults (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 faults 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 faults

---

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

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, an 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 fire 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 faults and conductor-to-tray faults for those tests involving cable trays. It is also not clear if any monitoring of cable-to-cable faulting 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 faults that occured within a given cable. However, the circuit could not independently detect a conductor-to-conductor fault from a conductor-to-tray fault 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 faults 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 faults independent of cable-to-tray faults. 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 faulting. 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 fault 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 fault 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 faults that occurred subsequent to a phase-to-phase fault would not be detected. Phase-to-phase faults that occur subsequent to a phase-to-ground fault 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 faults as cable-to-ground short circuits 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%).

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.

Table A.1: Summary of test results from UL NC555.

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

Summary of Results: 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.

Boeing: 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 faulting 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 faults 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 faults. Hence, the results are no real interest because 100% of failures for these cables are, by design, conductor-to-conductor faults.

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 faults. However, in all cases the tests simply illustrate the transitions between faults involving groups of conductors rather than actual transitions in fault 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.

<u>Summary of results:</u> 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 faulting that was monitored. Hence, there is no data that would help quantify the relative likelihood of one fault mode as compared to another.

<u>Illinois:</u> *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 fault 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 faults involving either the energized cables or the ignition source cable. Hence, even given faults it would not be possible to distinguish between cable-to-cable and cable-to-tray faults.

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 faults 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 fault 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 fault 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 faults in the multi-conductor cables.
- The circuit is unable to detect any faults 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 fault, no fault currents will be measure in either the tray or the other cables. Specifically, unless the welding wire is actively involved in the fault the arrangement cannot detect:Cable-to-cable faults between the multi-conductor and/or coaxial cables and any other cables that filled

---

[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.

the tray,Cable-to-tray faults involving the multi-conductor and/or coaxial cables or any of the other cables that filled the tray, orAny faults involving the general mass of cable fill that was not energized or monitored.

The circuit can detect the following fault modes:

- Cable-to-cable faults involving the welding wire and any of the other monitored cables,
- Cable-to-tray faults involving the welding wire, or
- Open circuits in the welding wires only.

The tests did result in numerous cable failures in virtually all of the tested cable bundles. Faults included cable-to-cable, cable-to-tray, and ultimately open circuit faults. It is not possible from the test data to clearly discern which modes of faulting were observed first. In general, the open circuit faults were observed only after repeated faults 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 fault 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 faults between the welding wires and the tray were observed, it can be concluded that multiple cable-to-cable faults were also observed. Again, the relative timing of these faults 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 faults. 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 faulting/shorting. In these tests the faults are characterized by very intense but short-duration spikes in the measured currents.

Discussions with one of the report authors revealed that the faults 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 faults. 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 fault 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 faults would open shortly after being initiated.

Most of the faults appear to involve the cable tray as an active element of the faulting. 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 faults 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 faulting 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 faults are possible. However, the results provide no specific insights regarding the onset of conductor-to-conductor faults, nor can the results be assumed to accurately characterize the initial onset of cable-to-tray faults.

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

This 1997 report documents one cable fire test (PEPSI 1) performed in France by Electricite de France (EdF). 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:[11]

- 3-conductor 16 mm^2 armored power cables (equiv. to 8 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).

---

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

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. 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 faults are summarized as follows.

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/470O). 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.)

Faults 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 faults, four appear to be one phase shorting to ground (presumably the grounded armor). This is apparent in that one of the three phases jumps up in current quite suddenly resulting in a circuit trip. One of the six faults appears to be a phase-to-phase (conductor-to-conductor) fault. This is apparent in that two of the three phases simultaneously jump up in current resulting in a circuit trip. The sixth fault is somewhat uncertain. Two of the three phases appear to be involved in the fault, hence it is classified as a conductor-to-conductor fault. 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.

2/C Control Cable:

The 2-conductor (2/C) control cable in each tray was energized using a 125 VAC, single phase 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 faulted 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 VAC single-phase 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 faults. However, in this specific case, the length of cable involved in the test (estimated at in excess of 500 feet) introduced sufficient internal resistance so that conductor-to-conductor faults 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 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 fault is indicated followed in 1 to 14 minutes by a conductor-to-ground fault.

<u>2/C Instrument Cable:</u>

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 faulting.

Three of the four circuits showed failure during the test. All illustrated a sharp faulting 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 faults. Both of the other two are classified as conductor-to-conductor fault, although one of these two shows some unexplained behavior following the initial fault. For the 7-conductor control cable, three of three failures involved initial conductor-to-conductor faults. These faults 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 faults in all three cases. Recall that all of the faults 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 fault 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 fault only after cycle 54 or 9:00.

Summary of Results: 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 fault mode was indeed the conductor-to-conductor fault 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.

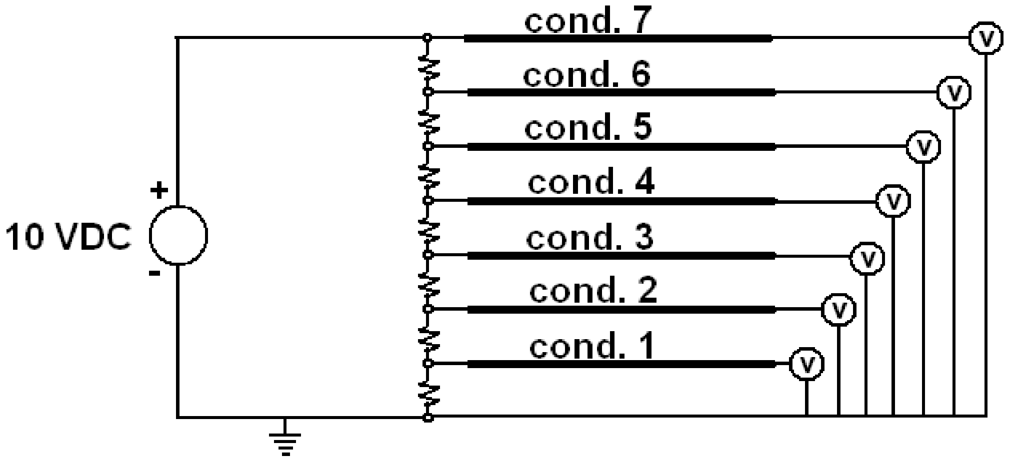


Figure A-1: Schematic representation of the FMRC cable functionality monitoring circuit as inferred from the description provided in the test report EPRI NP-1675.

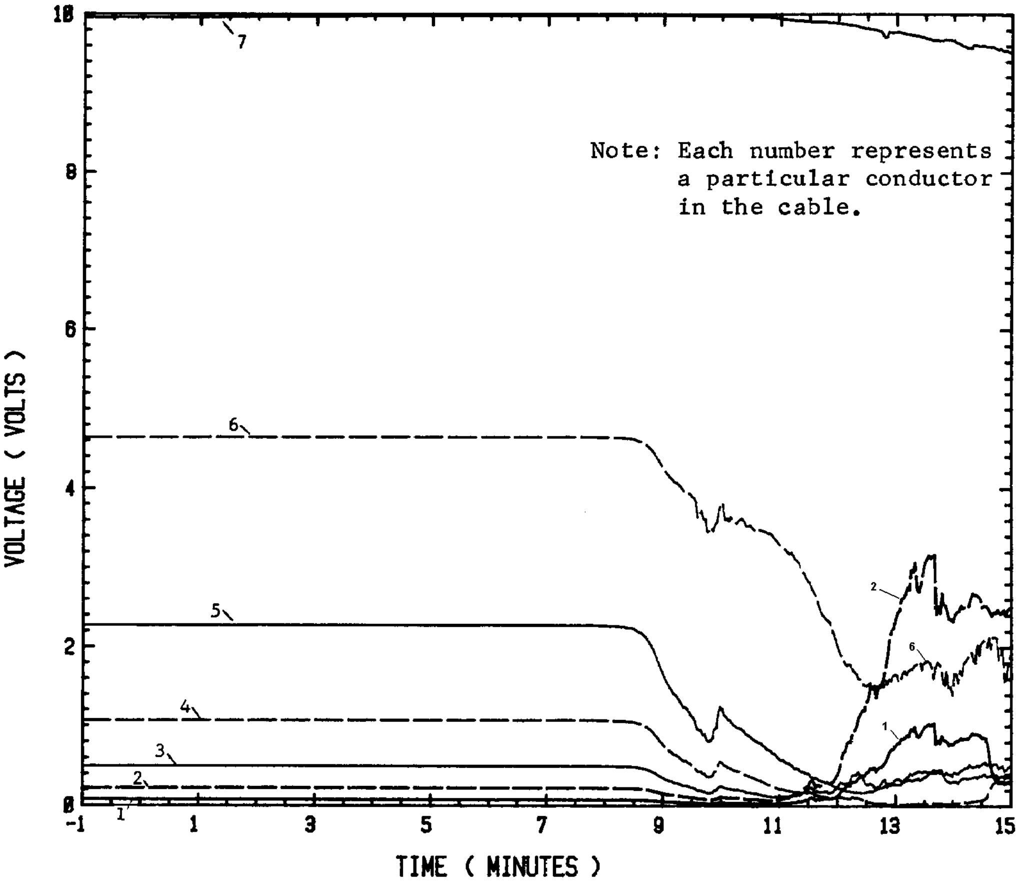


Figure A-2: Figure 3-11 from EPRI NP-1675 illustrating cable functionality measurements during FMRC Test 28.

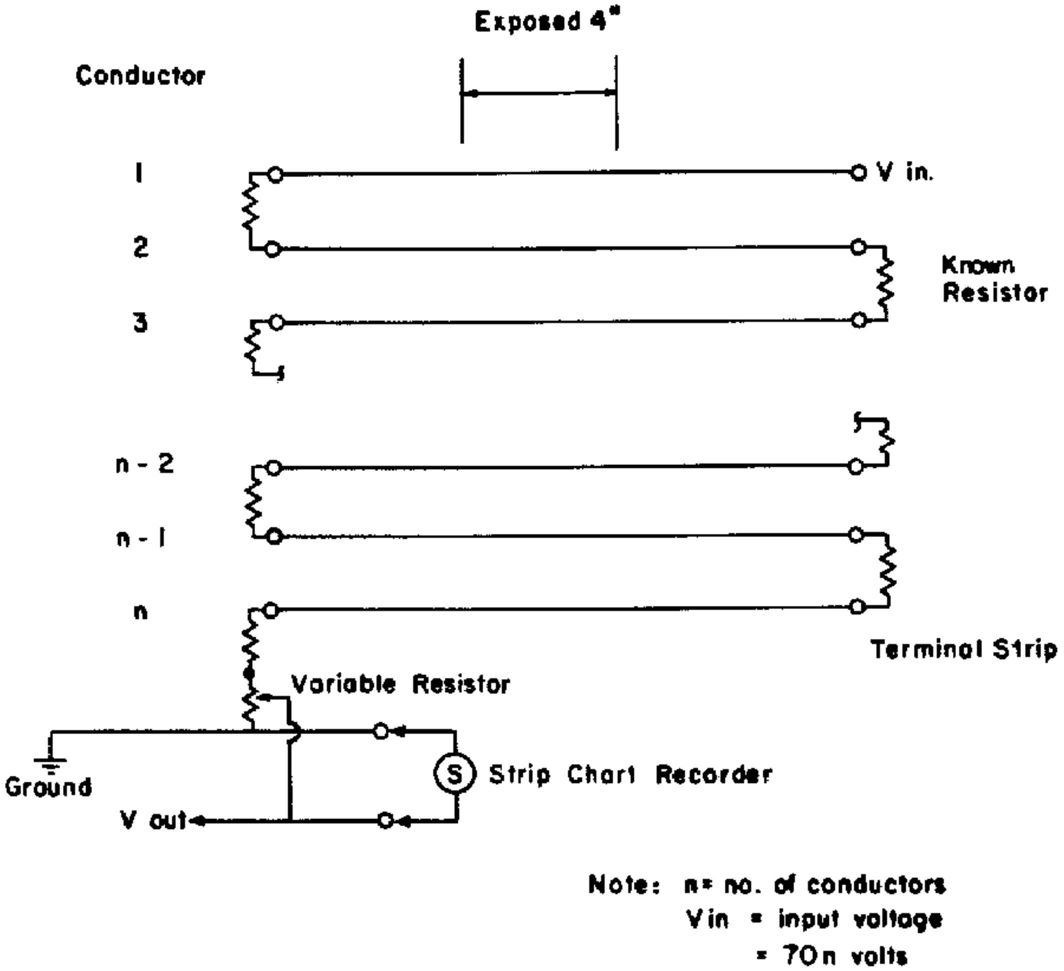
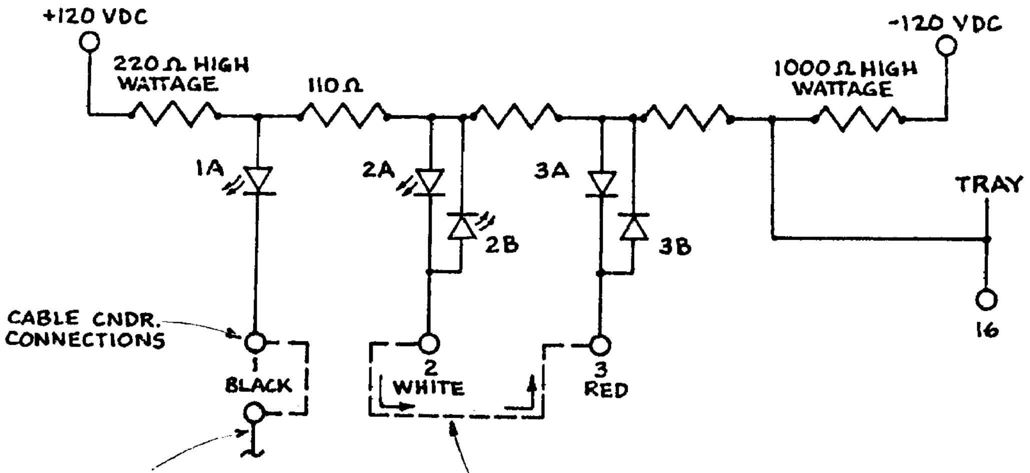


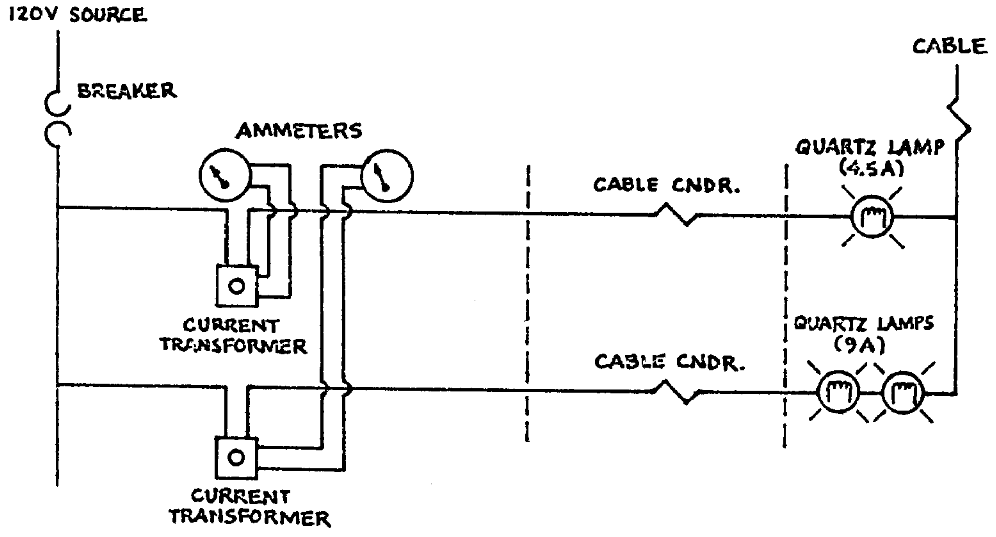
Figure A-3: Circuit used in FMRC tests as documented in EPRI NP-1767 (a reproduction of figure 2-3 from that same report).



ANY CNDR. TOUCHING THE CABLE TRAY CONN. 16 WILL CAUSE CURRENT FLOW THROUGH YELLOW LED TO NEG. OF SUPPLY.

IF TWO CNDRS. SHORT TOGETHER CURRENT WILL FLOW THROUGH THE YELLOW LED (2A) AND RETURN THROUGH THE RED LED (3B), INDICATING A SHORT BETWEEN CNDRS.

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 faults. Bottom circuit used for lower tray and detects open circuit faults.

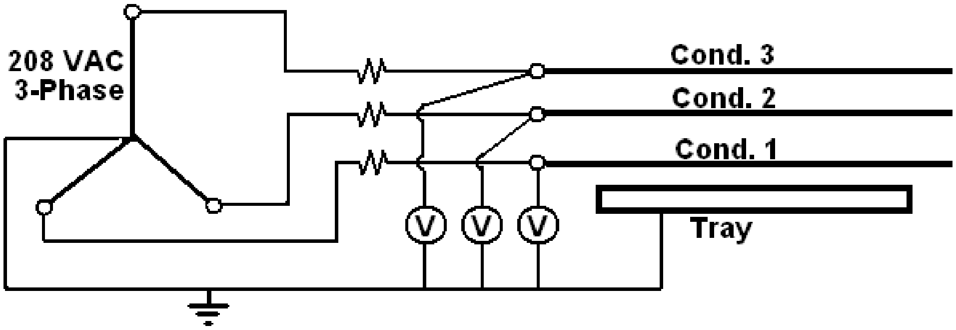


Figure A-5: Cable monitoring circuit used in NUREG/CR-4638. Note the voltage monitors placed on each conductor.

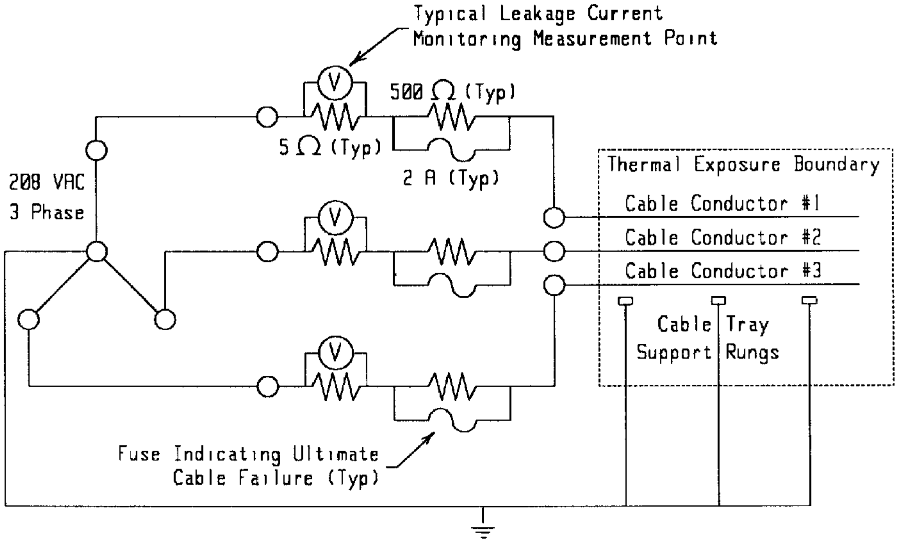


Figure A-6: Circuit used in NUREG/CR-5546 tests.

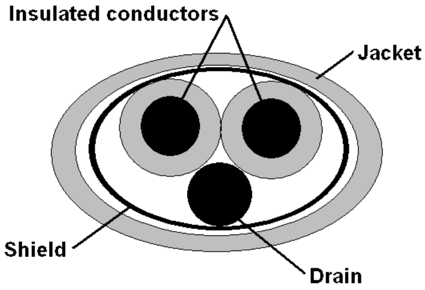
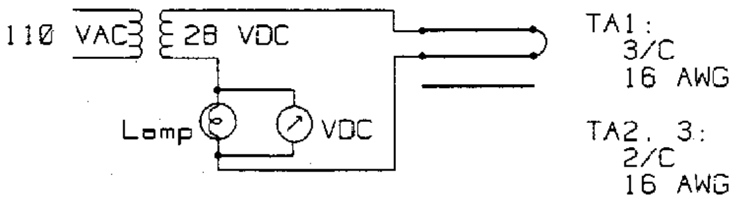
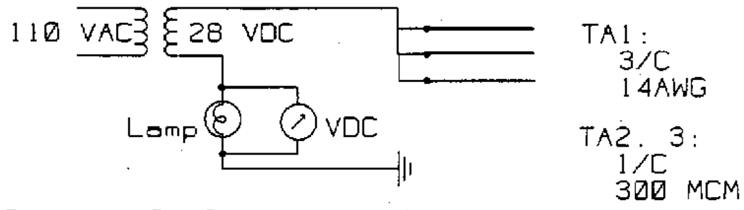


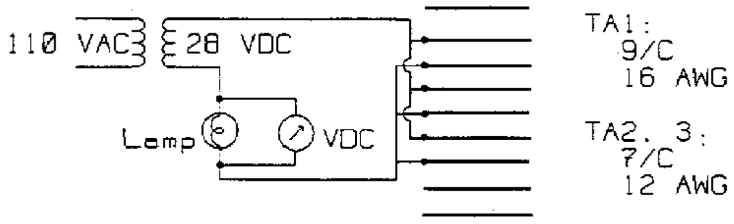
Figure A-7: Schematic representation of the 2/C BIW wire tested by SNL.



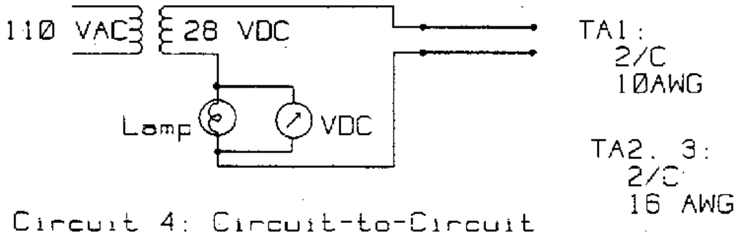
Circuit 1: Circuit-to-System



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.

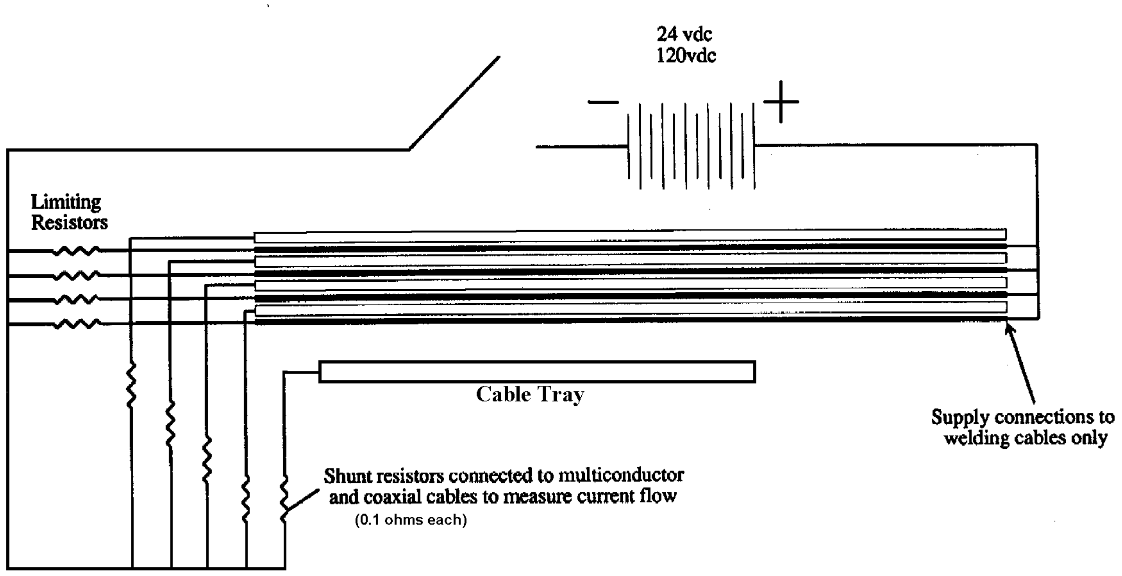


Figure A-9: Circuit used in LLNL/DOE cable fire tests. This is essentially Figure 26 from UCRL-ID-110598, but note that the battery polarity has been corrected and wiring of cable tray is indicated (per discussions with K.J. Staggs).

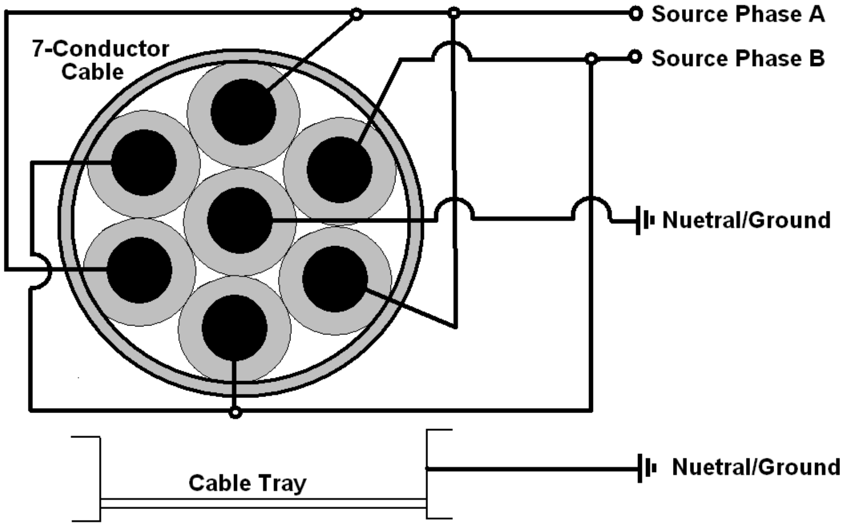


Figure A.10: Schematic of energizing circuit used in UL NC555 cable tray fire tests. Circuit voltage is not specified. Note that center conductor and tray are both grounded.

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.

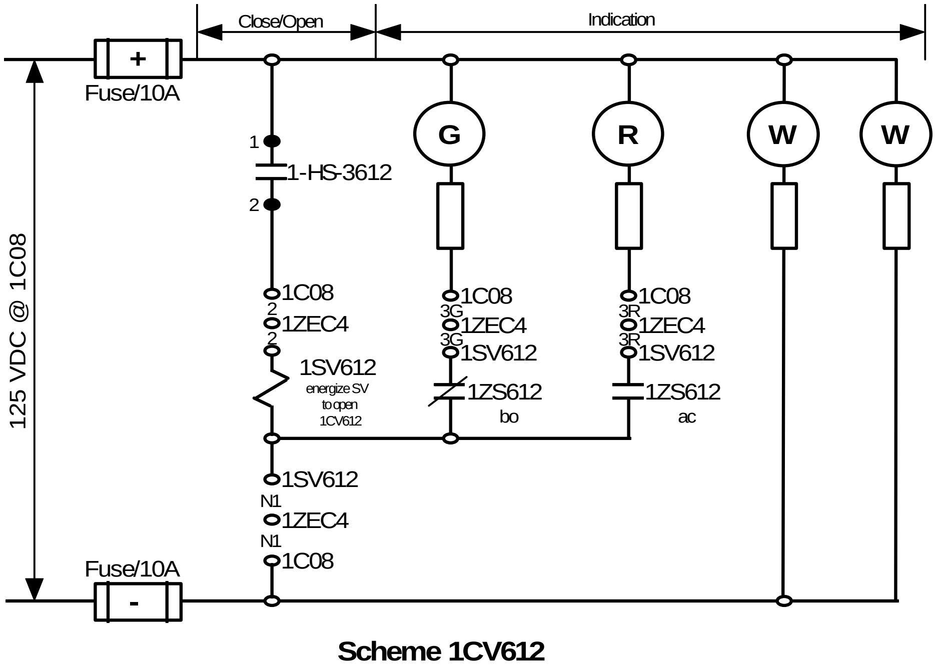


Figure B-1. Solenoid-operated valve control circuit.

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.

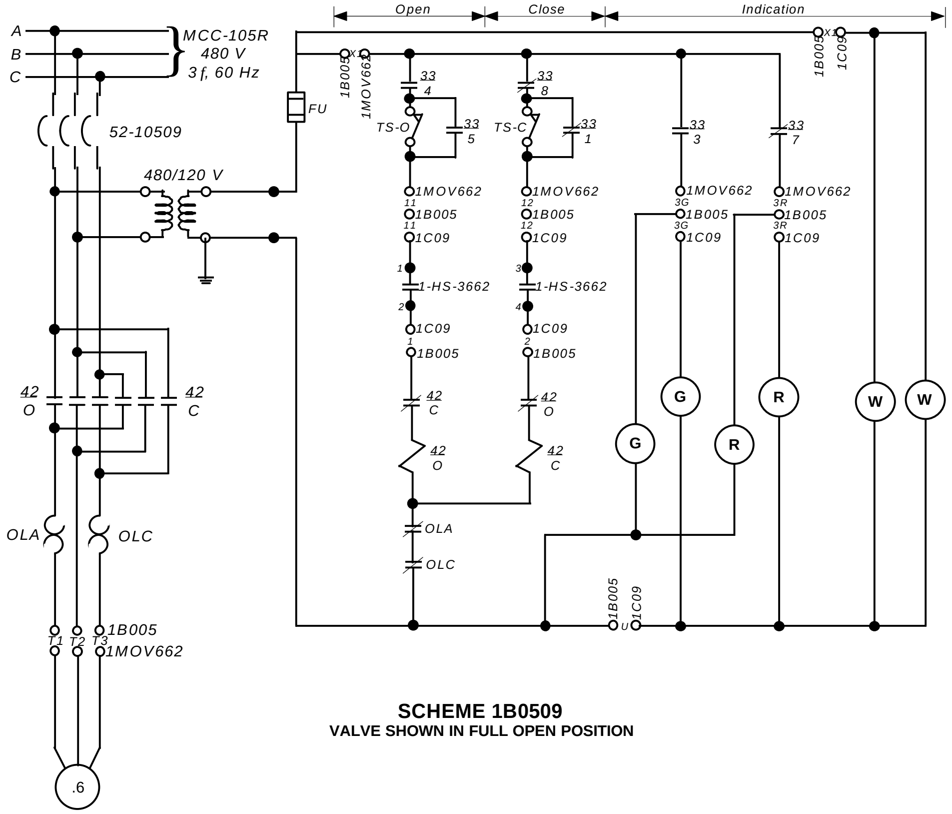


Figure B-2. Motor-operated valve control circuit.

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.

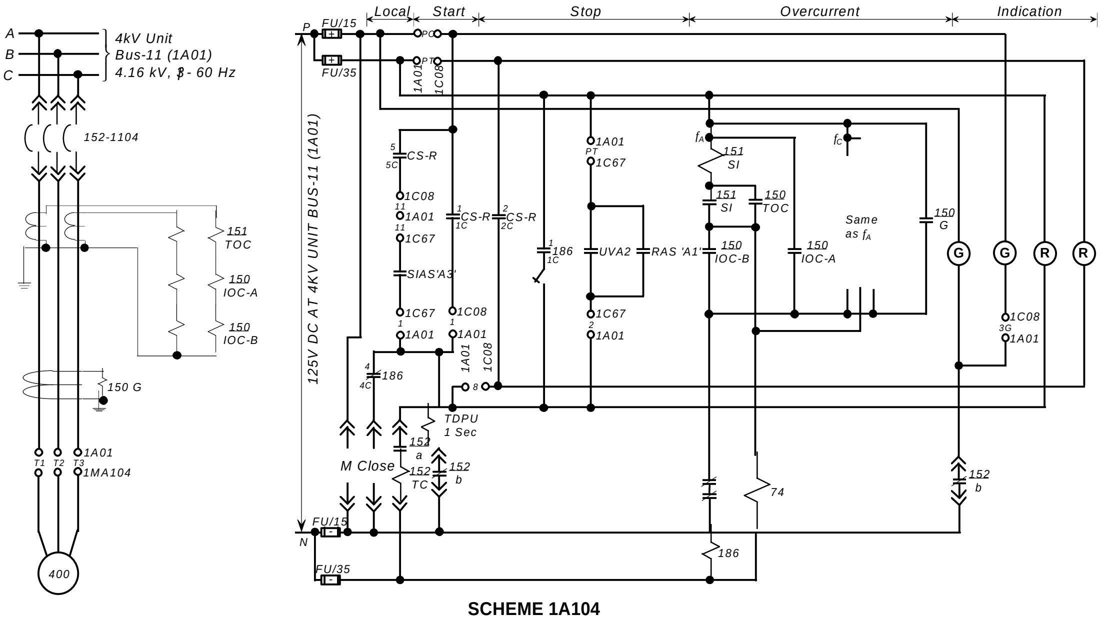


Figure B-3. Pump motor control circuit.

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 themocouple sensor circuit shown in Figure B-4. The results of the FMECA are provided in Table B-4.

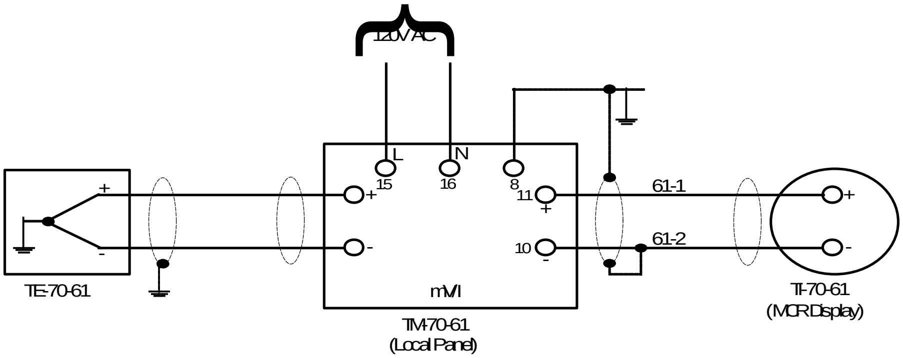


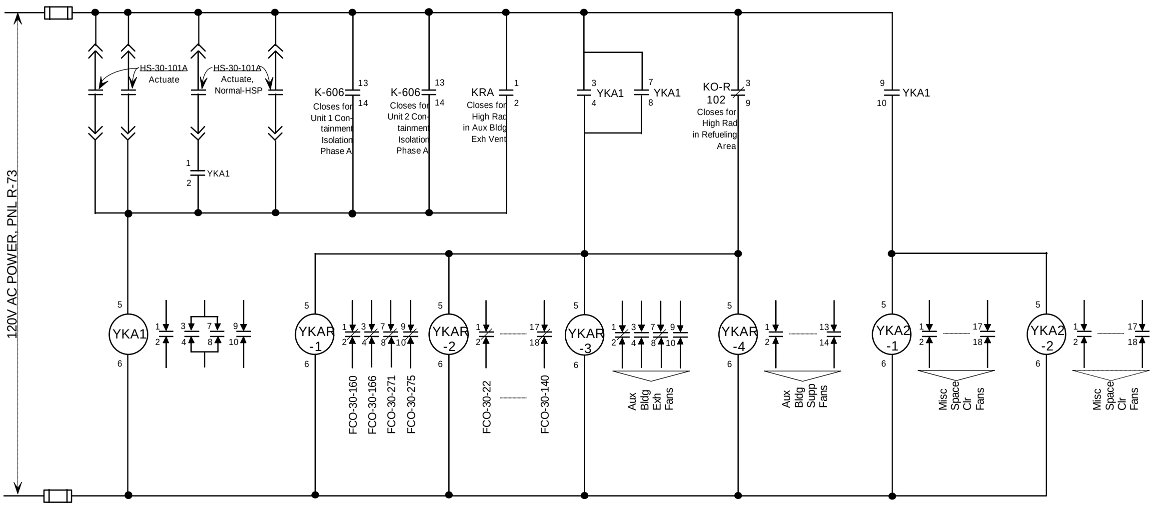
Figure B-4. Thermocouple sensor circuit.

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 1/2 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

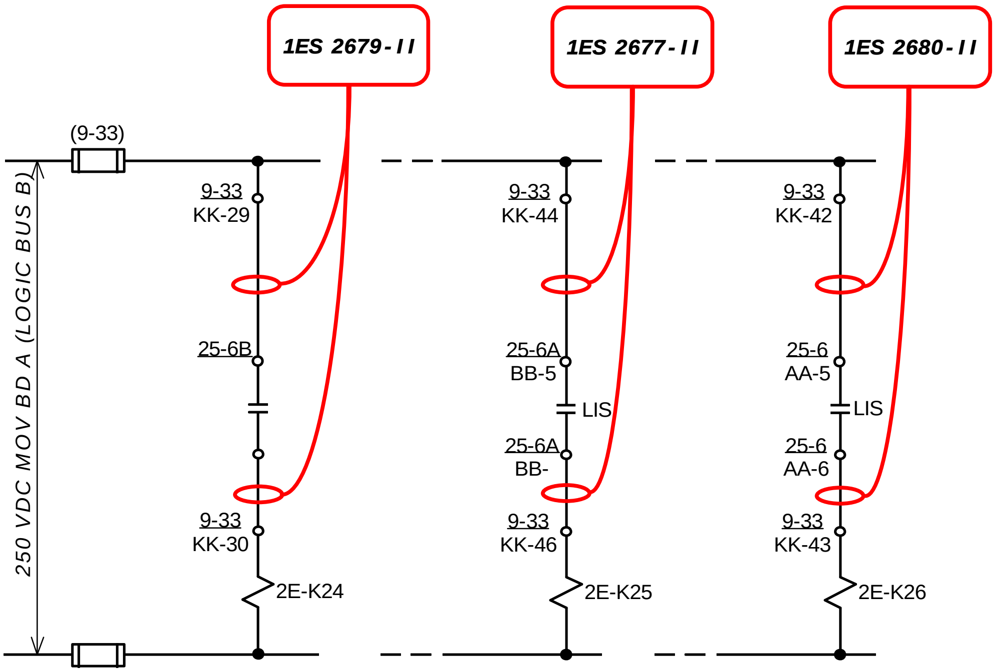
However, markups of the GE elementary drawing (730E929 SH 1) of the Automatic Blowdown System (ABS) indicate the cables listed in Table C-3, affecting circuit annunciator relays, as being damaged in the fire.

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.

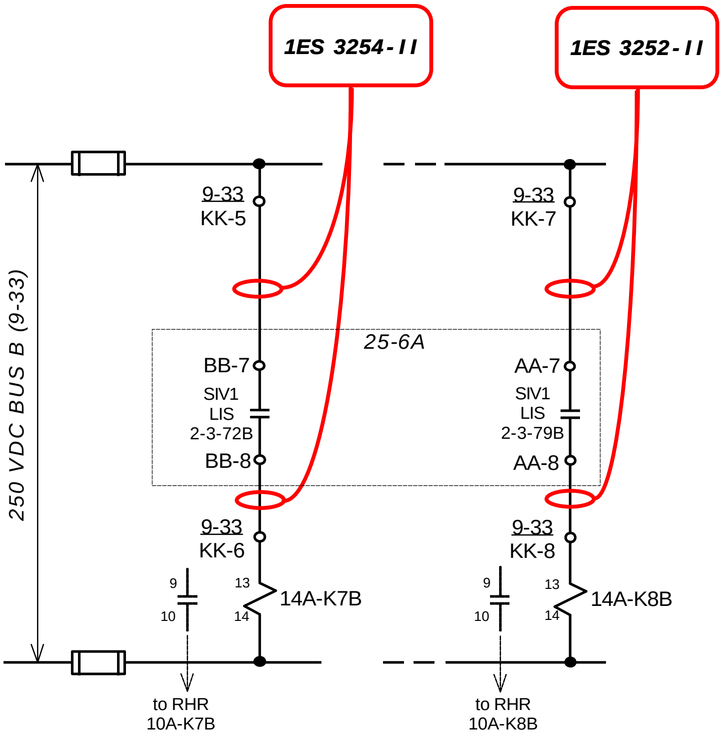
C.2.3 Core Cooling System/Diesels Initiate (12:40)

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

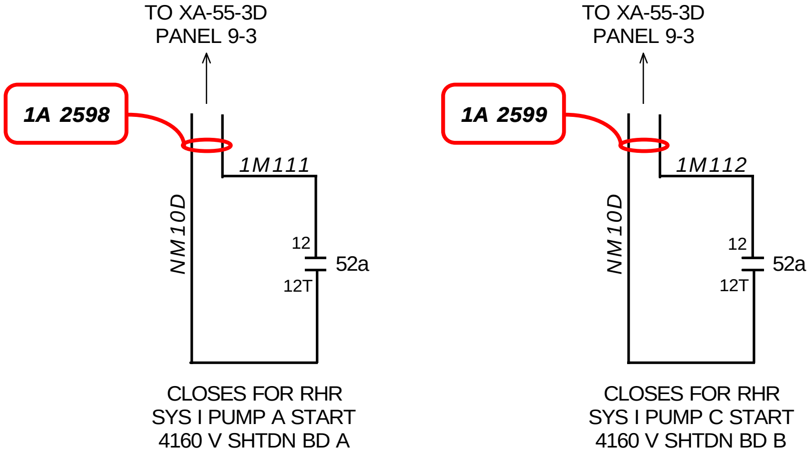
C.2.4 RHR Pump Start (12:42)

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.

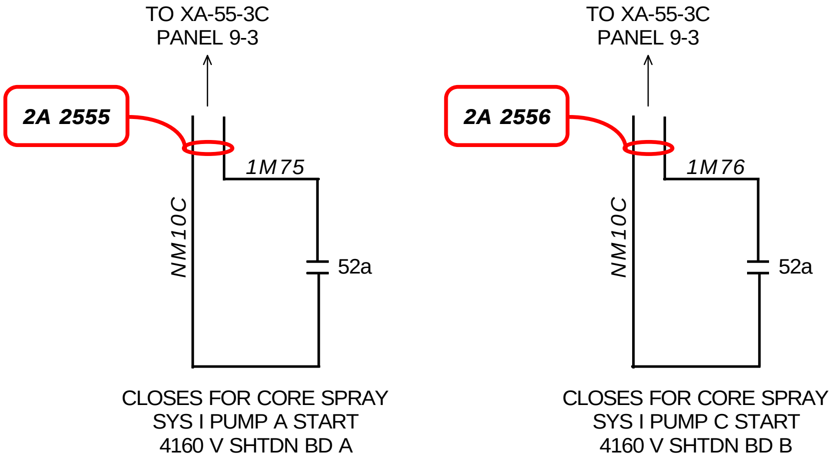
C.2.5 CS Pump Start(12:42)

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.

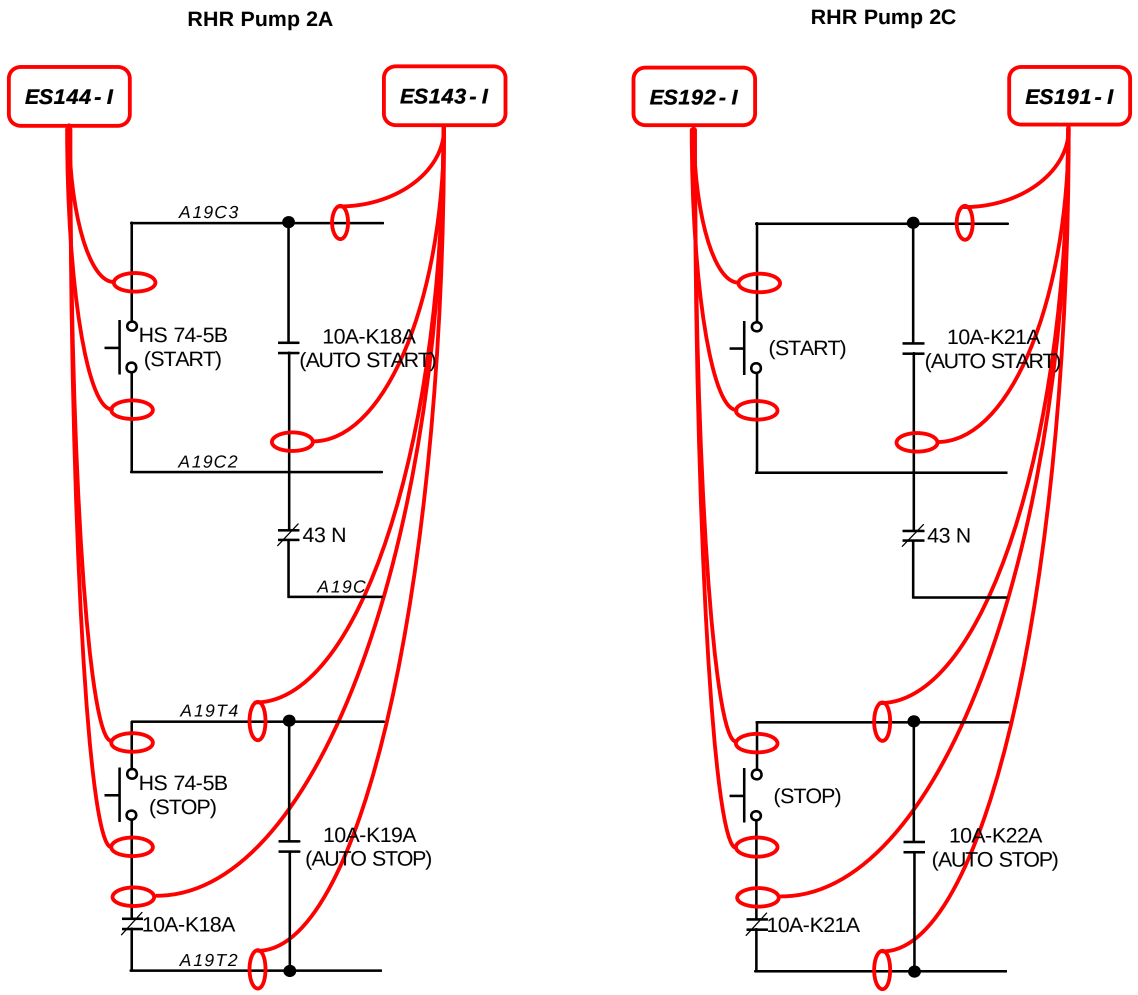
RHR Pump	Cable ID	Handswitch ID	Auto Start Relay	Auto Stop Relay
2A	ES144-I	HS 74-5B	--	--
2A	ES143-I	--	10A-K18A	10A-K19A
2C	ES192-I	HS 74-5B		
2C	ES191-I	--	10A-K21A	10A-K22A

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) <u>or</u> 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 <u>or</u> 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.

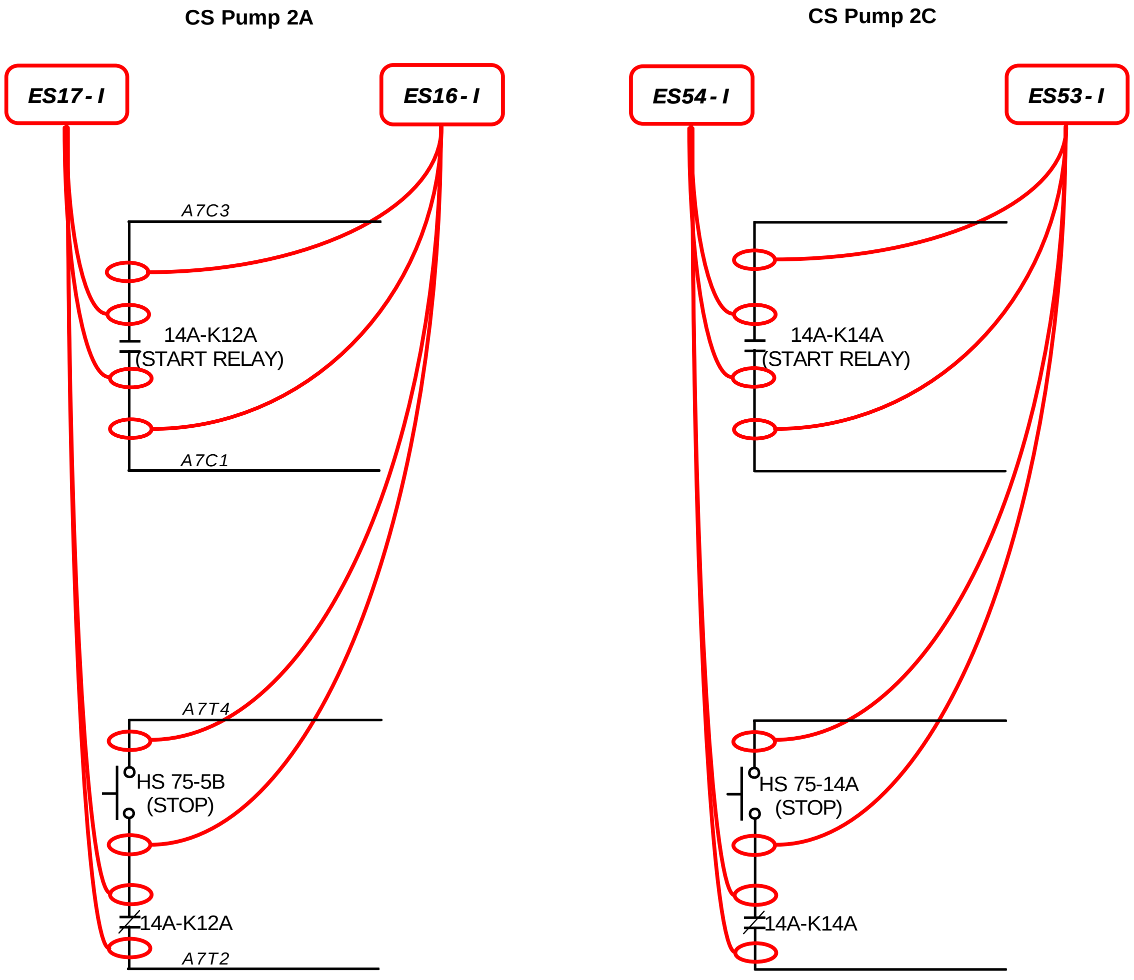
CS Pump	Cable ID	Handswitch ID	Start Relay
2A	ES17-I	--	14A-K12A
2A	ES16-I	HS 75-5B	14A-K12A
2C	ES54-I	--	14A-K14A
2C	ES53-I	HS 75-14A	14A-K14A

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

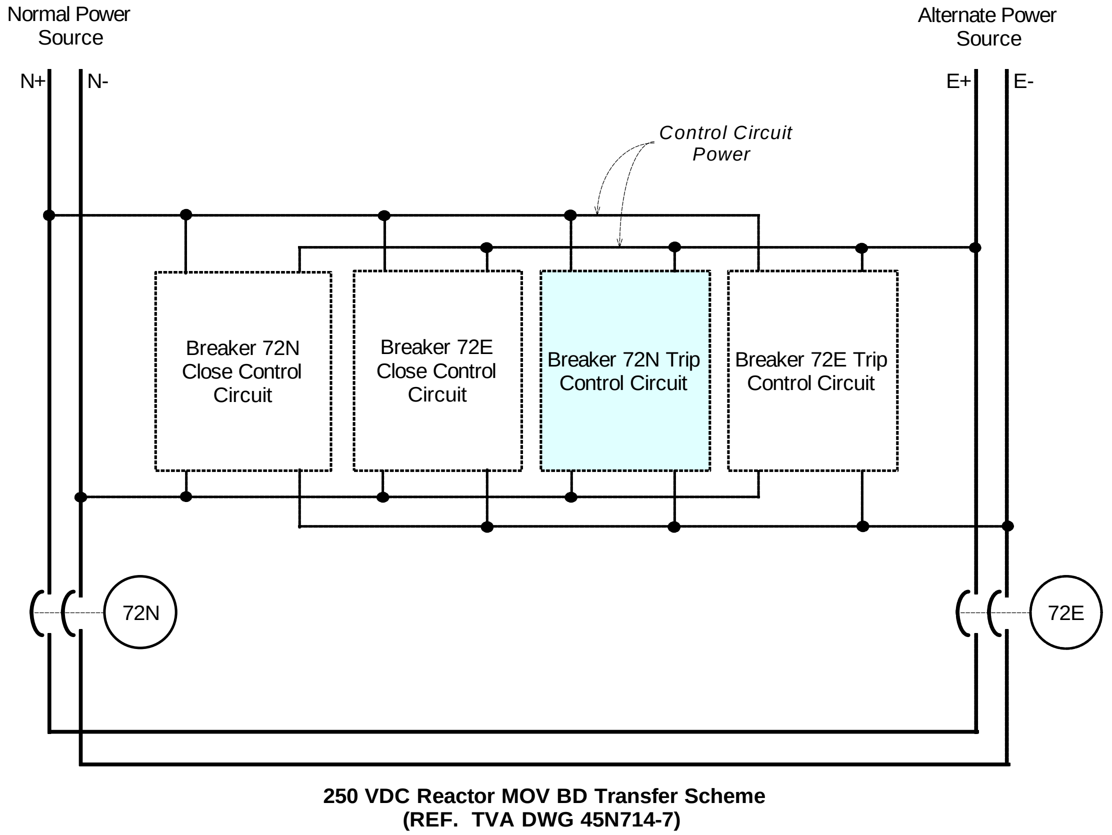
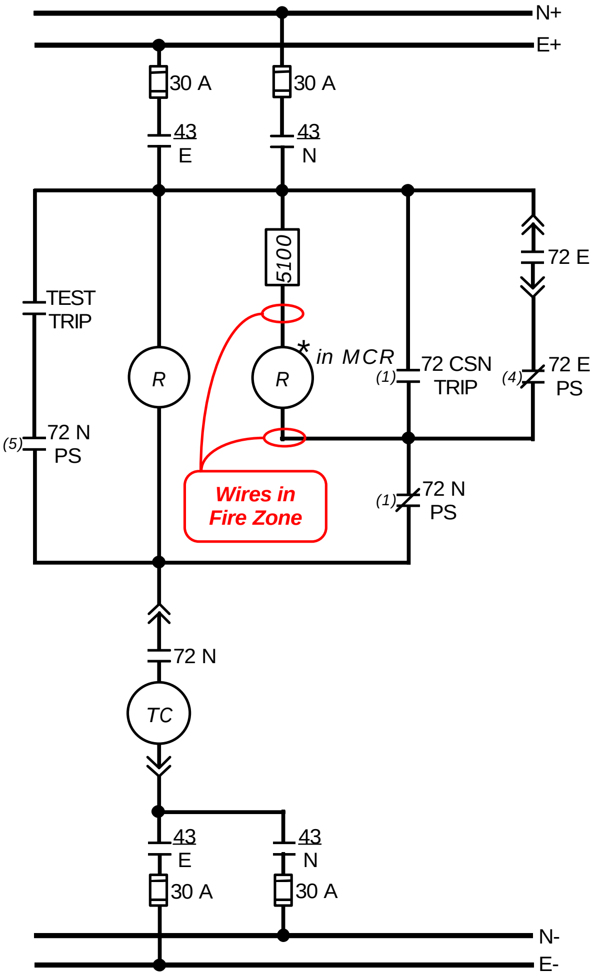


Figure C-7. Breaker control circuit block diagram. Note control power is tapped off both sources. (Detail of the 72N Trip Control Circuit is provided in Fig. 8.)

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.



BREAKER 72N TRIP CONTROL CIRCUIT

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

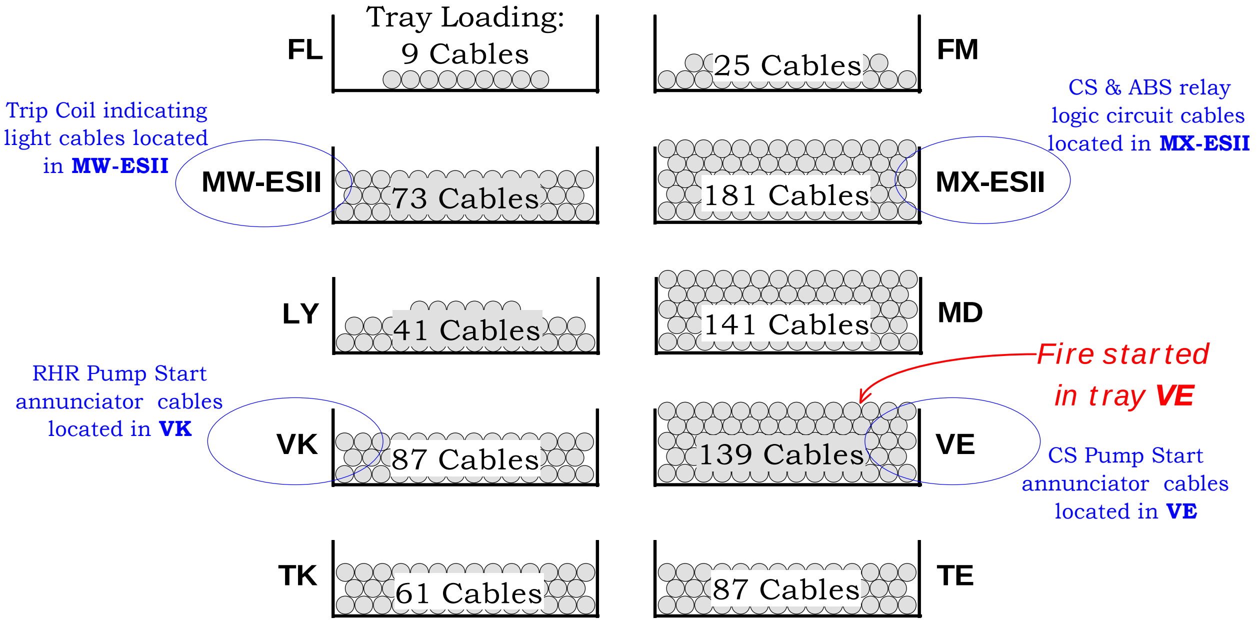


Figure C-9. Cable tray locations and contents. (Ref: Exhibit C1, pp. 30-32 of 69, *Physical Damage to Electric Cables and Raceways Involved in the Browns Ferry Nuclear Plant Fire on March 22, 1975*, contained in Regulatory Investigation Report Office of Inspection and Enforcement Region II.)

C.5 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.