Spurious Actuation of Electrical Circuits Due to Cable Fires

Results of an Expert Elicitation

Technical Report

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Final Report, May 2002

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REPORT SUMMARY

This report documents the third phase in a comprehensive program undertaken by EPRI in support of the nuclear industry's Fire-Induced Circuit Failures initiative. Specifically, it provides probabilities of these failures based on the results of fire tests—performed during the program's second phase—on cabling and circuits with actuation devices.

Background

This report details results of an expert elicitation process to develop conditional probabilities for spurious actuation of devices in electrical circuits due to fire-induced damage to electrical cables. These results will be used in guidelines being developed by the Nuclear Energy Institute (NEI) on evaluating fire-induced circuit failures (NEI 00-01).

Objective

To develop probabilities that fire will damage electrical cables in nuclear power plant electrical circuits and that devices in the circuits will spuriously actuate as a result of the damage.

Approach

The project team assembled a panel of experts in the areas of nuclear plant safe shutdown analysis, fire protection, electrical engineering, and probabilistic risk assessment (PRA). These experts represented industry, regulatory, and independent interests. The team and a technical integrator (TI) developed questions for panel members to answer and provided relevant data to evaluate. The members responded as individuals, and their responses were integrated by the TI using established procedures for eliciting expert opinion. An independent team of peer reviewers insured that the process was properly executed.

Results

Panel members developed responses to the following two key questions:

1. What is the probability of cable damage to electrical cables (of different types and configurations) given a specified set of time-temperature and fire-severity conditions? This was defined as $\mathbf{P_{CD}}$.
2. What is the conditional probability of spurious actuation of electrical devices in the associated circuits given cable damage? This was defined as $\mathbf{P_{SACD}}$.

Responses were based largely on a recent set of cable fire tests performed by EPRI to support this effort. The TI used these responses to develop the following combined set of probabilities for a variety of cable types and configurations:

$P_{SA} = P_{CD} \text{ X } P_{SACD}$

where $\mathbf{P}_{SA}$ = the probability of spurious actuations of one or more circuit components for a specific combination of fire temperature and fire duration.

Project results will be used in equations developed for NEI 00-01 (*Guidelines for Evaluation of Fire Induced Circuit Failures*) to be published by NEI.

EPRI Perspective

This project is part of a comprehensive EPRI program that supports the nuclear industry's Fire-Induced Circuit Failures initiative and its objective of quantifying the risk of cable fires causing undesirable consequences in nuclear plant electrical circuits. The first step in EPRI's program was to characterize fire-induced circuit failure modes. The second was a series of corroborating fire tests on actual cabling and assorted circuits with actuation devices. This report gives the process and results of the program's third step, which interpreted EPRI's fire tests and other available data. The fourth step will be a comprehensive report on the entire program to be published later in 2002. Information from this program will be used by the industry in NEI 00-01 after approval by the U.S. Nuclear Regulatory Commission (USNRC).

Keywords

Cable fires
Electrical circuits
Circuit failures
Spurious actuation
Damage probabilities

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1 INTRODUCTION

1.1 Objective

For many years the nuclear-power-reactor-safety community has wrestled with the following two-part technical question:

> Under what conditions could a serious fire affecting cabling in a nuclear power plant cause the spurious actuation* of electrical/electronic circuits that could affect the plant's safety? and What is the probability of such actuation conditional on those conditions?

The project reported here has as its objective to address this two-part technical question.

As will emerge below, only some aspects of this question are addressed, in the context of certain cables, certain circuits, and certain specified conditions.

1.2 Approach

This project's approach has been to utilize a Panel of technical experts to evaluate technical information relevant to the technical question, and a Technical Integrator (TI) to assemble the panelists' individual evaluations into a coherent, integrated overall evaluation that provides an "answer" to that question. This is the TI's overall evaluation report.

The technical approach has also involved two peer reviewers drawn from the nuclear-safety community, who monitored the project from start to finish. They participated in the conference calls, studied the intermediate project documentation such as the charge-to-the-panel, reviewed the draft final report, and had an opportunity to offer mid-course-correction advice if needed -- although no crucial mid-course advice came forth from them.

1.3 Roles and Responsibilities of the TI and of the Experts

The Technical Integrator is solely responsible for the overall evaluations herein, which are his intellectual work. Each expert panelist is responsible only for his own evaluation --- these are attached as Appendix material (Appendix B) and represent very valuable source material that

* Please note that the phrases "spurious actuation" and "inadvertent actuation" are used interchangeably throughout this report.

should be consulted by anyone using this report. While the TI's overall evaluation has used and built on the experts' evaluations, the overall evaluation has made no attempt to attribute explicit ideas or issues to one or more of the individual experts except in a few cases, first because to do so in every case would have been too complicated, and second because the overall evaluation inevitably would not be able to capture accurately all of each individual expert's contributions. Thus the TI's overall evaluation is some mix of the experts' individual inputs and the TI's own evaluation of both their input and the primary evidence itself.

1.4 Management

The project has been managed by Robert P. Kassawara of the Electric Power Research Institute, in coordination with Fred A. Emerson of the Nuclear Energy Institute. Kassawara and Emerson worked together to develop the project objective and approach. They also put the project together: they identified the TI, secured the financial support necessary for those participants whose time was not donated by their host institutions, and worked with the TI to monitor the project's progress and assure its successful outcome. The EPRI and NEI sponsors have coordinated this project with the U.S. Nuclear Regulatory Commission through Nathan O. Siu, a technical expert in NRC's Office of Nuclear Regulatory Research. However, NRC is in no way responsible for this project except insofar as two NRC staff members and one NRC contractor served as expert panelists, who are of course responsible for their individual evaluations.

Appendix A identifies the panel members, the peer reviewers, and the project management.

Appendix B contains the evaluations by each individual expert panel member.

Appendix C contains the peer reviewers' reports.

2 THE PROJECT'S METHODOLOGY FOR THE USE OF EXPERTS

The methodology for the use of experts employed in this project is modeled after the so-called "SSHAC methodology" described in NUREG/CR-6372 (Ref. 1) and the associated journal article (Ref. 2). The details of the SSHAC methodology will not be described here --- the interested reader can refer to the SSHAC reports for details. Suffice it to point out that the SSHAC methodology identifies four "levels" of effort/scope when a technical project uses experts to develop technical information, and that this project is modeled after SSHAC's Level 2, but includes some elements of Level 3. The key elements of the methodology used in this project will be described next.

2.1 Step 1, Identifying the Participants

The initial project step was that the TI, in consultation with the EPRI and NEI project sponsors, identified the experts who would serve as panelists and peer reviewers. There were three fundamental criteria for panel membership: First, each panelist must be an acknowledged expert on one or another of the technical subjects involved in the project's technical question. Second, the expert must agree to participate -- to follow the project's modus operandi and to do the evaluation work on the necessary schedule. And third, a balance was sought among the panel's membership between different "interest groups" who were known to have been involved in this issue over the past several years; these included the nuclear-power industry, the NRC and its contractors, the engineering-consulting community, and the academic community.

However, one crucial condition of service on the panel was that no member should consider himself as "representing" any interest or interest group -- the evaluations were to be those of the individual based on that individual's expertise alone. (The peer-review process was intended, in part, to evaluate whether this condition has been met.)

The criterion for the two peer reviewers was that each possess not only relevant technical knowledge and stature, but also sufficient independence to be free to express a peer-review opinion unencumbered by conflicts of interest. The two peer review reports are attached here in Appendix C.

As the panel was being assembled, EPRI identified the funding to support those panelists/peer reviewers who could not be supported by their home institution.

2.2 Step 2, Disseminating the Relevant Technical Information

The first step in the project per se was disseminating all the technical information that the project management believed to be relevant to the task. This included the statement of the problem, a proposal as to the form that the expert evaluations should take, and certain technical information about spurious actuation. The panelists were then asked to provide any other relevant information, to be circulated to all of the others. The most important information, the Omega Point test results and report (Ref. 3, see a longer discussion below), were not yet available when the project began, because the tests were still under way -- they were circulated later when they were finalized.

2.3 Step 3, Agreeing on the Formulation of the "Technical Question"

The opening sentence of this report (above) describes the project's two-part technical question. However, as posed, this question requires clarification. Specifically, in order that the panelists' evaluations would be amenable to "integration" into a useful final "answer" to the technical question, it was necessary to formulate one or more subsidiary questions in detailed form, so that each panelist would be attempting to answer the same questions. This required substantial time and effort in the form of several draft proposals and several conference calls, before the final formulation was agreed to. This was important: the SSHAC use-of-experts methodology insists that experts should not be asked to answer a question that they feel they cannot answer, and therefore that the experts must be able to reformulate a question as posed into one or more that they believe can be answered based on their expertise. (Section 4.1 below discusses this problem-formulation aspect in detail.)

2.4 Step 4, Panelists' Review and Evaluation of the Technical Information

The next step was the central one in the project, and consisted of the evaluation by each panelist of the relevant technical information. Although panelists were free to interact with each other, the expectation (which was realized) was that a separate evaluation would be provided by each participating expert in the form of a report. These reports can be found in Appendix B. It is important to note that the experts' own written evaluations were not distributed to each other until after all of them had been submitted to the Technical Integrator. At that point, they were distributed around along with an initial draft of this report (the TI's overall evaluation report).

2.5 Step 5, Technical Integrator's Evaluation and Integration of the Panelists' Input

In this step, the Technical Integrator reviewed the experts' evaluations, and integrated them into his overall evaluation. In the integration work, the TI utilized the integration guidance in the SSHAC methodology. The outcome was a report (this report) which has as input both the several expert evaluations and the TI's own evaluation of the primary evidence. The TI relied heavily on the experts' input (they are more expert than he about some of the detailed issues), but also brought his own evaluation into play, both to resolve issues where the evaluations of the experts did not agree from one to the next, and to expand on and interpret their input so as to present a broader picture of the current state-of-knowledge.

In the TI's work, there was almost no "integration" of the kind in which Expert A finds that a number is 10, expert B finds that it is 14, and the TI concludes in his overall evaluation that it is 12 (+ about 2). The character of the integration work turned out to be much more complex than simply manipulating numbers provided by the various experts. This was mainly because, despite efforts to get the experts to answer the same questions (Step 3 above and Section 4.1 below), the individual experts' evaluations were generally provided in different forms --- with a few exceptions, they generally answered different (sometimes very different) aspects of the overall question. This provided a richness of detail that makes the individual expert evaluations a valuable source of information themselves (see Appendix B), but it also made the TI's overall evaluation work very complex.

2.6 Step 6, Technical Integrator's Circulation of Draft TI Evaluation for Feedback

In this step, the Technical Integrator's draft report was circulated to the experts for feedback. The fundamental question asked of each expert was whether the TI had misunderstood or misrepresented the input from the given expert -- if this was so, it would be crucial to correct the problem before proceeding. Also of great importance was a second question asked of each expert, namely whether the draft report made sense in terms of providing a reasonable evaluation and integration of the information provided by the experts as a group.

The SSHAC methodology provides that the TI, after receiving feedback from the experts, can and indeed should modify the evaluation/integration to account for the feedback received. However, this is a matter for the TI to judge --- modifying the draft evaluation/integration merely to satisfy an individual expert's complaint in terms of the weighting given to that expert's view is not appropriate, whereas modifying it to account better for an enhanced understanding of an expert's individual evaluation is fully appropriate. The TI must adhere to a fine line here. In the end the overall evaluation is the TI's work, not that of the experts as individuals or as a group.

2.7 Step 7, Technical Integrator's Final Report

After the feedback cycle, the TI developed the final report in this step.

2.8 Step 8, Peer Review Report

At the end of the process, each peer reviewer provided a report summarizing his evaluation. The two peer reviewers were charged with evaluating both the <u>process</u> followed and the <u>technical product</u>. These two reports can be found in Appendix C.

3
SOURCES OF TECHNICAL INFORMATION FOR THE EXPERT EVALUATIONS

With the discussion above as background, it is useful to list the principal sources of technical information that the expert panel used to support its evaluations:

1) The EPRI-sponsored Omega Point test report, "Cable Tray Testing Within a Steel Enclosure" (Ref. 3). This report is accompanied by an extensive data set available only in CD format, and used by the panel.

2) The Sandia National Laboratories report of their own NRC-sponsored measurements made during the Omega Point tests, "Cable Insulation Resistance Measurements Made During the EPRI-NEI Cable Fire Tests" (Ref. 4).

3) The Sandia report on circuit analysis related in part to spurious actuation, "Circuit Analysis - Failure Mode and Likelihood Analysis" (Ref. 5).

4) The EPRI/NEI test plan that provided the framework for the Omega Point tests, "EPRI/NEI Test Plan for Evaluation of Fire-Induced Circuit Failures, Revision K", by Fred A. Emerson (NEI) and R. Kassawara (EPRI) (Ref. 6).

5) A monograph, "Cable Materials Used in EPRI/NEI Tests", by Fred A. Emerson of NEI (Ref. 7).

4
REFINING THE "TECHNICAL QUESTION"

The two-part "technical question" will be repeated here as an introduction to this discussion:

> Under what conditions could a serious fire affecting cabling in a nuclear power plant cause the spurious actuation of electrical/electronic circuits that could affect the plant's safety? and What is the probability of such actuation conditional on those conditions?

As formulated, this two-part technical question is too broad to answer in detail. For example, only certain types of cables and certain configurations have been studied experimentally, thereby allowing an "answer" to be formulated based directly on experimental information. (See sections 4.2 and 5.1 below.) Beyond those cable types and configurations, extrapolation is needed, which of course is one of the reasons why the use of expert judgment is necessary. Also, some related questions can be formulated, such as whether thresholds exist below which certain types of cable damage or circuit actuation are very unlikely.

4.1 Explicit Formulation of the Quantities to be Evaluated

Furthermore, and crucially, it was deemed necessary to formulate the question(s) posed to the experts in a form that would enable the evaluations to be used in a probabilistic risk assessment (PRA). In what follows, we will discuss this issue. Specifically, we will describe the PRA formulation in some detail, in order to provide the background necessary to understand just what the expert evaluations aimed to accomplish, and what the limitations were.

A level-1 PRA is itself aimed at calculating a core-damage frequency (CDF) that would arise from each of a large number of accident sequences. Each such sequence starts with an initiating event (in our case a damaging fire), which leads to core damage only if certain combinations of subsequent equipment failures and human errors occur. Using standard PRA notation, the way that a spurious actuation of an electrical or electronic circuit would enter the PRA is through calculating a change (ΔCDF) in the CDF arising because of that actuation. The generalized formulation for the ΔCDF is as follows, taken from report NEI 00-01 Section 4.2 (Ref. 8). This formulation was developed by the project's management team, and was presented to the expert panel at the start of the panel's deliberations:

$$\mathbf{\Delta CDF} = \mathbf{F_f} * \mathbf{P_E} * \mathbf{P_{AS}} * \mathbf{P_{DM}} * \mathbf{P_{SA}} * \mathbf{P_{CCD}} \text{ (per reactor-year)}$$

The terms in the equation are defined as follows:

F_f = frequency (per year) of fires of any size anywhere within the fire area of interest
P_E = fire size parameter; fraction of fires in the area capable of reaching damaging combinations of fire temperature and fire duration

P_{AS} = probability that automatic suppression will fail to control the fire

P_{DM} = probability that detection and manual suppression will fail to control the fire

P_{SA} = probability of spurious actuations of one or more circuit components for a specific combination of fire temperature and fire duration

P_{CCD} = conditional probability of core damage given fire-induced failures including spurious actuations of one or more components/combinations.

The term **$P_{SA,}$** the probability of spurious actuations, will be the focus of our attention. Of course, notice that this term is conditional on a specific combination of fire temperature and duration. Also notice that P_{SA} has elements within it involving fire phenomena issues, cable-damage issues, and circuit-fault issues.

During extensive discussions among the expert panelists as this project was in its early stages, several things became clear. One was that some of the experts felt more comfortable evaluating the fire-phenomena aspects of this broader problem, and less comfortable (or less experienced) with evaluating the cable-damage or the circuit-fault aspects. Others of the experts felt just the opposite -- they believed that their particular expertise lay in the cable-damage or the circuit-fault aspects rather than in the fire-phenomena aspects. Still other experts felt adequately comfortable with evaluating both of these broad aspects.

A different issue is that some experts recommended that the evaluation process should concentrate on the cable-damage and circuit-fault aspects, citing the existence of analytical methods that are available for calculating, for any given fire "size" external to the cables, what the heat release rate and the time-temperature profile at the target cables would be. The notion is that, given a fire "size" specified appropriately, the time-temperature environment at any given cable being analyzed could be worked out through appropriate analysis, and that lumping together this fire-phenomena aspect with the spurious-circuit-actuation aspect would unnecessarily complicate the experts' assignment.

On this subject, other experts felt just the opposite, namely that because the crucial experiments under evaluation (the Omega Point tests sponsored by EPRI, Ref. 3) were integral experiments that combined these aspects, the experts' evaluation of the combined issue, as expressed by the term P_{SA} as defined above, was essential.

The panelists struggled with this dilemma extensively. A proposal emerged to separate the two "parts" of the term P_{SA} as follows:

$$\Delta CDF = F_f * P_E * P_{AS} * P_{DM} * [P_{CD}][P_{SACD}] * P_{CCD}$$

Here the original P_{SA} has been replaced by the two-term product $[P_{CD}][P_{SACD}]$. The original definition of P_{SA}, from above, is:

P_{SA} = the probability of spurious actuations of one or more circuit components for a specific combination of fire temperature and fire duration

The two newly introduced entities are defined as:

P_{CD} = the probability of cable damage given a specified set of time-temperature and fire-severity conditions.

P_{SACD} = the probability of spurious actuation given cable damage.

One attractive feature of this formulation is that it offers the possibility that some experts on the panel, more comfortable with the fire-phenomena issues, could concentrate on evaluating the term P_{CD}, while others, more comfortable with the circuit-fault issues, could concentrate on evaluating P_{SACD}. Still others could evaluate the combination, namely the product $[P_{CD}][P_{SACD}] = P_{SA}$. This is a vital point -- the literature on expert evaluations and expert judgments (Ref. 1, 2) emphasizes that experts should never to asked to provide evaluations or judgments on questions about which they feel they are not well qualified, and further that each expert must be given the opportunity to formulate or re-formulate the question(s) being asked so that he/she is comfortable with them.

This final formulation is how the project proceeded. The experts were instructed to provide any of the three evaluations just cited: P_{CD}, P_{SACD}, or P_{SA}. They were free to choose which evaluation(s) to provide.

4.2 Limitations to the Evaluation: Concentration on One Specific Test Set, Specific Circuit, and Specific Cable Types

It is clear that the general formulation presented above cannot be the basis for a detailed expert evaluation until the specific cable types and circuit types are specified --- there are too many different cable types and too many different circuit types in use today in nuclear power plants. Thus no general values exist for the probability P_{SA}. The values must be tailored to a given combination of cable and circuit type. To overcome this limitation, the project reported here has concentrated exclusively on evaluating specific types of cables linked to specific circuits whose spurious actuation is being studied.

To be explicit, the whole project revolved around, and in fact was planned and executed to revolve around, a set of recent experimental tests sponsored by the nuclear industry through EPRI and intended to cast light specifically on these issues. These tests, the Omega Point tests (Ref. 3), were undertaken with broad industry support (and also with NRC participation in their planning) in order to address our technical question. It is not possible to describe here the detailed matrix of the 18 tests that were performed --- an introduction to them is in the next paragraph, but for the details it is necessary to refer to the descriptions in the Omega Point test report (Ref. 3). However, some of the expert reports in Appendix B, in particular those of Mowrer and Nowlen, contain excellent summaries of certain aspects of the tests.

Briefly, the test series, carried out in 2001, covered three different types of cables: a specific type of armored cable, several types of thermoplastic cable, and several types of thermoset control cable. Within these three broad types, different cables consisting of different numbers of conductors were tested, ranging from single-conductor to eight-conductor cables. With the exception of a few instrument cables tested by Sandia National Laboratories, all cables tested were control cables, not instrumentation or power cables. Eighteen different tests comprised the test matrix. The test fire, using a diffusion flame burner, was itself always external to the cables being tested, but sometimes the cables were in the direct fire plume and sometimes they were in the hot gas layer. The tests concentrated on cables in cable trays of differing loadings, but a few tests studied cables in conduit. Two tests used cables in a vertical configuration. The tests were all conducted in a steel room enclosure, 8 feet high by 10 feet square, with a simple opening for external ventilation in one wall, whose vertical location varied from test to test. During discussions among the expert Panelists, it was observed that some of the tests appeared to be characterized by limited ventilation. However, it is not known whether this had an important influence on the results, expressed in terms of temperature measured at the cable or of "cable damage" (however defined). The remainder of this report is written assuming that this influence is negligible.

Omega Point made extensive measurements during the tests, to characterize the thermal environment and the circuit responses well enough to support the evaluations reported here. The thermal measurements were made using arrays of thermocouples, and the electrical measurements were made at the relevant circuits. In addition, Sandia National Laboratories made measurements of the insulation resistance in certain cables during each of the tests (Ref. 4).

The cables being studied were linked to one specific control circuit whose spurious actuation was the object of study. This single circuit cannot, of course, represent all circuits that might actuate spuriously, but it was selected because it is a very common circuit type in nuclear power plants, and is considered highly typical. The circuit was a specific motor starter (a NEMA-1 starter) for a motor-operated valve, and is described fully in the Omega Point report (Ref. 3).

This brief introductory description cannot do justice to the detail in the Omega Point test report, nor to the discussion of certain measurements made by a Sandia National Laboratory team during the tests. The Sandia measurements (Ref. 4) had the specific objective of measuring insulation resistance in specific cables, typically one or two cables introduced into the test rig during the Omega Point test series.

4.3 Definitions of Certain Terms

The terminology in use in this field is complex, and made more so by the use of the same term in different ways by different authorities. This caused some confusion at the beginning of this project, as the experts discussed the issues together in several conference calls. S. Nowlen eventually clarified matters with a memorandum that was very useful. His definitions are essentially captured in the appendix to D. Funk's expert report (see Appendix B herein), so will not be repeated in the main report text here. Those using this report should refer to Funk's appendix for details.

The term "high confidence": In the evaluations in Section 7, the term "high confidence" is used several times. It is intended to mean the 95% confidence level. Thus if a number is said to lie with high confidence between 0.2 and 0.5, the plain meaning is that the author has 95% confidence that the number's actual value lies in this interval.

5
THE FIRE TESTS, CABLE "DAMAGE", AND FIRE MODELING

5.1 Phenomena Observed During the Omega Point Test Series

This section will provide further summary information about the Omega Point tests (Ref. 3) and the types of information measured during them. Again, this brief summary cannot do justice to the rich and detailed information in the test reports themselves.

The 18 tests all followed a common pattern. A test rig was constructed, with the subject cables located several feet above the floor in either cable trays or conduit. The specific physical configuration, which differed somewhat from test to test, was defined and reported. Different types of cables were used in different tests; some of the cables were single-conductor cables while others were multiple-conductor cables. Some of the test cables were energized (with 120 volts ac, 100 volts dc, or 24 volts dc), while others were not. Some of the energized cables were connected to the spurious-actuation test circuitry, which was located far enough away from the fire zone to be completely unaffected by the fire. Typically, four different device-actuation circuits and one insulation-resistance circuit were monitored in a given test. Numerous thermocouples were arrayed adjacent to the cables, in the cable trays, and elsewhere in the test room, so as to provide a thermal characterization of the test. Also, measurements were made of the voltage, current, and electrical impedance of selected cables, of assorted cable-to-cable or conductor-to-conductor impedances, and of the insulation resistance.

The test set-up had the capability to ascertain whether, for certain of the subject cables, the fire had induced either a short-to-ground, a short-to-another-cable, a short-to-another-conductor within the same cable, or an open circuit. For cables with multiple conductors, this shorting phenomenon could be measured, for some of the conductors, on a conductor-by-conductor basis. Also, circuit measurements were made to ascertain whether and when a spurious actuation of the circuit occurred, and/or whether and when protective fuses in the test control circuits blew.

For the fire itself, the heat release rate (which varied from 70 to 450 kilowatts) was determined through knowledge of the fuel consumption. After the test began (that is, after the fire was lit), essentially all of the thermal and electrical measurements were made as a function of elapsed time thereafter. Each test ran for a predetermined time, although for some tests that time was extended during the test itself, especially if no cable damage had been observed at the nominal termination time. At the end, a water spray was usually used to determine whether water would influence the likelihood of spurious actuations due to badly damaged cables, and the thermal and electrical measurements continued until extinguishment and cooldown.

5.2 Cable "Damage" and Cable Performance of its Function

Definition of cable "damage": If a cable connected to a circuit is exposed to a fire that can "damage" it, the definition of "damage" is ambiguous. If the cable burns up to a crisp, everyone would agree that damage has occurred, but for intermediate states in which the cable is still functional there is not general agreement. Recalling that for our purposes here we are dealing exclusively with control cables (rather than instrumentation cables or power cables), does "damage" occur when the cable's electrical impedance has been reduced below a certain threshold, or by a certain percentage? Is the correct figure-of-merit whether that cable can continue to perform its design function, which presumably involves carrying current or voltage from point A to point B? Quite generally, should "damage" be defined in terms of the degraded physical properties of the cable itself (such as burned insulation and jacket material), or in terms of the electrical phenomena (such as specific types of circuit faults) seen in the cables? These questions have no single answer, so in the context of this expert-evaluation exercise it was necessary to require that each expert panelist who used the "damage" concept must define what he/she meant by "damage", so that the evaluation can be more generally useful.

Cable function: Further, let us suppose that a given fire ultimately "burns the test cable up to a crisp." Well before that end-state has been reached, the cable will presumably reach an intermediate state which is defined as cable "damage", whichever definition of damage is used.

Suppose that our cable-of-interest is an energized cable, which would generally be the case (often, our "cable-of-interest" is a particular energized conductor within a multi-conductor cable). In actual fact, whether that cable or conductor first shorts to ground, or first shorts to another cable, or to another conductor within the same cable, is an important distinction in the context of answering our spurious-actuation question. If the circuit being evaluated has protective features (a fuse, say, that trips the circuit when the incoming cable manifests a short-to-ground), then a short-to-ground can lead to a safe state by design if that short-to-ground occurs first, before a short-to-another-conductor. Sometimes the subject cable carries a ground within it as the armored sheath or as one of the several conductors. Sometimes "ground" means the cable tray's electrical potential, or the potential of some other external ground. Again, each expert panelist was expected to define just what he meant when dealing with these concepts and using certain terms.

Relevant measurements: Measurements that can illuminate this issue include among others (a) measurements of the temperature-time profile at the cable; (b) measurements of the cable's or conductor's electrical voltage and current, from which is inferred the linear impedance (ohms/1000 feet); (c) measurements that determine that the cable (or conductor) has shorted to ground or to another cable or conductor, or has gone open-circuit; (d) measurements of insulation resistance; and (e) measurements of whether an actuation has occurred in the test circuit of interest.

5.3 Fire Phenomena Modeling: Capabilities and Limitations in our Context

Given a fire characterized by a specific heat release rate vs. time, in a specific location in a given room configuration, the fire-research community has developed a number of analytical models that can predict, what the temperature will be as a function of time elsewhere in that room.

Depending on the sophistication of the model, and of the level of detail in the specified configuration, these predictions can be quite good. Some models can do well in predicting other features too: the presence and extent of hot gases, the extent and character of convective heat transfer, the radiative transfer to the walls or to other objects. Of course, most of these are needed in order to predict the temperature as a function of location and time.

Unfortunately, no models exist -- and no models are likely to be developed, at least not soon -- with the ability to predict the extent of "cable damage" (however defined) or to predict "whether spurious actuation will occur", given the thermal environment established by the fire and geometrical-configuration parameters just discussed. This fact is precisely why actual fire tests, supplemented by the judgment of experts as they evaluate these tests, are needed to answer our spurious-actuation question.

6
THE TYPES OF EVALUATIONS THAT THE EXPERT PANELISTS COULD PROVIDE OR WERE ASKED TO PROVIDE

Given the above, there is a variety of different types of information that the expert panelists could provide, or were asked to provide. These types or categories of information, in the form of expert evaluations of the available evidence, will be listed and discussed here.

The "EPRI/NEI Test Plan" (Ref. 6) contains the following expectation, reproduced here in *italic* lettering:

"The test results are expected to provide information in the following areas:

- Likelihood of spurious actuations from hot shorts in multiconductor control cable
- Likelihood of spurious actuations from cable-to-cable hot shorts
- Likelihood of multiple spurious actuations
- Differences in effects between horizontal and vertical trays and air drops
- Plume effects vs. hot gas layer effects
- Likelihood of shorts-to-ground vs. hot shorts
- Likelihood of open circuits
- Insulation resistance in damaged cable
- Voltage and current values in damaged cable
- Differences in effects among cables with thermoset and thermoplastic insulation types
- Effects on armored cable
- Impact of water spray
- Effects of cable tray fill."

In addition to these, the following areas and issues were addressed by one or more of the experts:

- Overall likelihood of spurious actuation
- Cable-damage aspects
- Differences between cables in cable trays and in conduit

- Characteristics of a "hot short"
- Cable-to-cable vs. conductor-to-conductor phenomena
- Influence of location within the cable tray
- Cable electrical configuration
- Circuit and electrical-configuration issues (CPTs, circuit wiring, fuses).

The issues above comprise the list of issues to be addressed in the overall evaluation in the next section. However, the order of the issues will be rearranged to allow for a more logical progression of the discussion.

7
THE TI'S OVERALL EVALUATION OF THE ISSUES

7.1 Description of the "Base Case" used in the Evaluation

To discuss the various technical issues in a more orderly way, the Technical Integrator's overall evaluation will take the form of evaluating a "base case" (Section 7.2), followed by evaluations of situations that are departures or variants from that base case (Section 7.3).

The base-case has the following properties:

- Thermoset control cables, either 1-conductor or 7-conductor, or a mix
- Un-armored cables
- Cables in a horizontal cable tray
- Single layer of cables in the cable tray
- Target cables in the fire's hot-gas layer, not the fire plume
- Electrical circuit connection through a CPT (control power transformer).
- A time-temperature profile that is "stretched out", characterized by a gradual heat-up of the cables over many minutes, as was the case for all of the Omega Point tests that form the principal basis of the evaluations herein.

7.2 Evaluation of the "Base Case"

This section will provide an overall evaluation of the above "base case". The evaluation will take the form of a discussion of each of several "issues" as outlined above (Section 6). The "technical question" presented in the opening paragraph of this report will be addressed through the discussion of these issues.

Next, we will discuss each of the relevant issues in turn.

7.2.1 Cable damage aspects

This section will discuss estimates of the term $\mathbf{P_{CD}}$ as defined and discussed in Section 4.1:

$\mathbf{P_{CD}}$ = the probability of cable damage given a specified set of time-temperature and fire-severity conditions.

7.2.1.1 General cable-damage scenario

In the Omega Point tests, the way cable damage occurs with time as the cable heats up seems to be similar for the "base case" and for all of the variant cases. The insulation-resistance measurements and the electrical measurements (voltage, current, impedance) reveal the same approximate pattern with time, which for convenience can be thought of in three stages. In the first stage, insulation resistance and electrical properties slowly degrade, but overall cable function remains effective. In the next stage, a rapid degradation of insulation resistance and electrical properties occurs, which causes the cable to fail over a short period (here "fail" means "fail to maintain its electrical function".) In the third and final stage, the insulation resistance and the electrical resistance drop to very low values. The rates of failure differ from test to test but all tests followed this broad pattern.

A general observation is that the time period during which the cable passes from the first to the second stage is usually relatively rapid (minutes to tens of minutes).

If the cable damage takes the form of a "hot short" between an energized conductor and another conductor, rather than a short to ground or an open circuit, the tests reveal that generally this is a transient phenomenon rather than a long-lasting state --- sooner or later (and usually sooner), either a high electrical current will cause a fuse or other protective device to "blow", or there will be high-current burn-out causing a short to ground.

A figure-of-merit for failure based on ohmic resistance? Some analysts have proposed a figure-of-merit, in terms of electrical resistance, that could be used to distinguish a cable that would be termed "failed" from a functional cable. Sometimes, 1000 ohms is suggested, but other values have also been suggested. Based on the observations in the Omega Point tests, the choice of this parameter does not matter --- once the third and final phase of damage is reached, the electrical resistance quickly falls to very low values, and choosing 1000 ohms rather than some other number is not relevant to deciding whether the cable has or has not failed. To quote one of the expert reports, "Any value between about 10,000 ohms and 100 ohms yields the same answers."

In any event, no explicit use has been made of ohmic resistance as a figure-of-merit in the evaluations herein, nor is it thought to be of much use to a fire-PRA analyst.

7.2.1.2 "Failure" temperature -- a threshold for P_{CD}?

While it is possible to identify the approximate temperature at which "failure occurs" in any given test, it is difficult to generalize in a precise manner, in part because the cables under study in the Omega Point tests were being heated up in a transient way rather than a quasi-static way as they passed through the region of a possible threshold. Furthermore, the tests reveal that small cables are more likely to fail at slightly lower temperatures than larger cables; cables in loaded trays fail at slightly different temperatures depending on their location (see a separate discussion below on this aspect, Section 7.3.5); and seemingly similar tests show variable results, although within a reasonable temperature range. Cables also seem to fail more quickly in lightly-loaded trays than in more heavily-loaded trays; in horizontal rather than vertical trays; and if they are made of thermoplastic cable rather than thermoset cable.

However, as a matter of common experience there must be a threshold, below which no cable damage would occur. How to characterize it is not an easy matter.

Given the nature of the Omega Point tests, with their gradual heat-up of the cables, the best judgment is that for gradual heat-up conditions the threshold can be usefully characterized by a temperature, but not by a useful time-at-temperature. That is, while it is recognized that a fire characterized by very rapid heat-up of the target cable would likely produce a different failure behavior vs. temperature, the specific heat-up conditions are judged not to be a strong influence factor for fires characterized by a gradual heat-up, unless a cable "cooks" at a high temperature for a very long time, which is not likely in the fires of most interest in nuclear-power-plants.

The threshold temperature below which no cable damage will occur is estimated to be as follows:

Thermoset cable, "base case" configuration: P_{CD} threshold = 550 F

NOTE: The corresponding value for thermoplastic cable based on the Omega Point tests is 400 F (see Section 7.3.1 below.)

This threshold temperature for P_{CD} is to be interpreted as a high-confidence value --- there is believed to be high confidence that no cable damage will occur below the threshold.

The threshold temperature is also to be interpreted as the maximum temperature experienced by the target cable itself (as measured by the thermocouples in the cable trays, in our "base case" configuration).

7.2.1.3 A "Fragility Curve" for P_{CD} vs. Temperature

The probability of cable damage P_{CD} is obviously dependent on the temperature experienced by the cable as it is exposed to the fire's conditions. In principle, if one could specify all of the conditions influencing damage, including the thermal conditions, the thermal history, and all other important conditions, then one should be able to specify P_{CD}, the probability of cable damage, quite well. In practice, however, not enough is known either experimentally or in terms of models of damage to allow a highly accurate understanding of P_{CD}.

The Omega Point data provide useful information on this issue. Studying the different tests, it is feasible to extract information to support describing P_{CD} approximately in terms of temperature. If P_{CD} were a function solely of the peak temperature reached by the cable (which it surely is not!), then a functional relationship of P_{CD} vs. temperature would be all that is needed as a complete description of P_{CD}.

One expert provided the following judgment concerning the temperature at which there exists "the potential for cable damage leading to electrical activity". Notice that this end-point, which is a specific and narrow definition of "cable damage", is not the same end-point as "spurious actuation", since it relates to cable electrical activity (leakage current, insulation-resistance changes) rather than the effect on a given circuit.

The judgment is expressed in terms of three temperatures. For thermoset cable, these three temperatures are:

Temperature below which essentially no electrical activity occurs	680 F
Median or best estimate point	800 F
Temperature at which activity will almost surely occur	1200 F

NOTE: For thermoplastic cable, the corresponding values are judged by this expert as being 400, 450, and 800 F. (See Section 7.3.1 below.) For armored thermoset cable, the three temperatures are given as 570, 750, and 830 F. (See Section 7.3.2 below.)

With certain caveats to be explained below, these temperatures make sense and can be used in cable-damage analysis.

But first, one needs to assign some specific probabilities to these estimates. Let us interpret these temperatures as the temperatures where P_{CD} is 5%, 50%, and 95%. This assignment of an exact probability to P_{CD} is surely a little too precise, but can serve as a useful way to understand the information being presented. If the numerical probabilities are not taken too seriously in detail, the three temperatures are a way to capture the overall behavior of P_{CD} vs. temperature.

One of the major things to notice is the wide range, representing uncertainty. At first glance, one might say to oneself, "Surely the range is narrower than that." But there are good reasons for this range, in part because this approach tries to capture in one single parameterization a wide variety of issues that affect cable damage and its probability.

Much of the range (much of our "uncertainty") is due to differences in test conditions for the various tests evaluated, different impacts of different fires characterized by the same time-temperature profile, and/or cable-to-cable differences that are not knowable. But the wide range is also due to uncertainties in the judgments involved in arriving at the estimates. The best judgment seems to be that no matter how long-and-hard one examines and evaluates the underlying data, they simply cannot support a narrow range for P_{CD}. Indeed, this range is the uncertainty. Furthermore, in using the P_{CD} estimates in a fire PRA, it is probably most appropriate to consider all of the uncertainty range as representing aleatory uncertainty, given that so much of the uncertainty arises from differences in test conditions and cable-to-cable differences. (Aleatory uncertainty in this context is uncertainty introduced by the failure to account in the analytical model for the variability in conditions such as from test to test and from cable to cable.) Assuming that the uncertainty is entirely aleatory means that the P_{CD} can be used directly in the equation for ΔCDF in Section 4.1.

On balance, these three temperatures are judged to be a reasonable description of P_{CD}, provided that the cable at issue is subjected to gradual heat-up by the fire.

Based on these three points as cited and discussed a few paragraphs above, one can develop a piece-wise-linear "fragility curve" for (P_{CD}) vs. (temperature). In Figure 1, three such fragility curves are plotted for thermoset, thermoplastic, and armored cable. They can be used to determine P_{CD} approximately for intermediate temperatures. While the three points plotted at 5%, 50%, and 95% are less firmly supported than the high-confidence threshold at 0%, they still provide a useful guide to the behavior of P_{CD}.

Please note that it is also feasible to structure a broader probabilistic risk analysis (PRA) in a way to utilize such information. That is, given an analytical model or supporting data to help determine the peak cable temperature, and given that the conditions (similar cables in similar cable trays or conduit, slow heat-up, etc.) are not too different from those in the underlying Omega Point tests, these piece-wise-linear curves can be used in a PRA. (Of course, to work out the probability of spurious actuation, P_{SA}, one will still need to multiply P_{CD} by the probability P_{SACD}, as explained in Sections 4.1 and 7.2.4.)

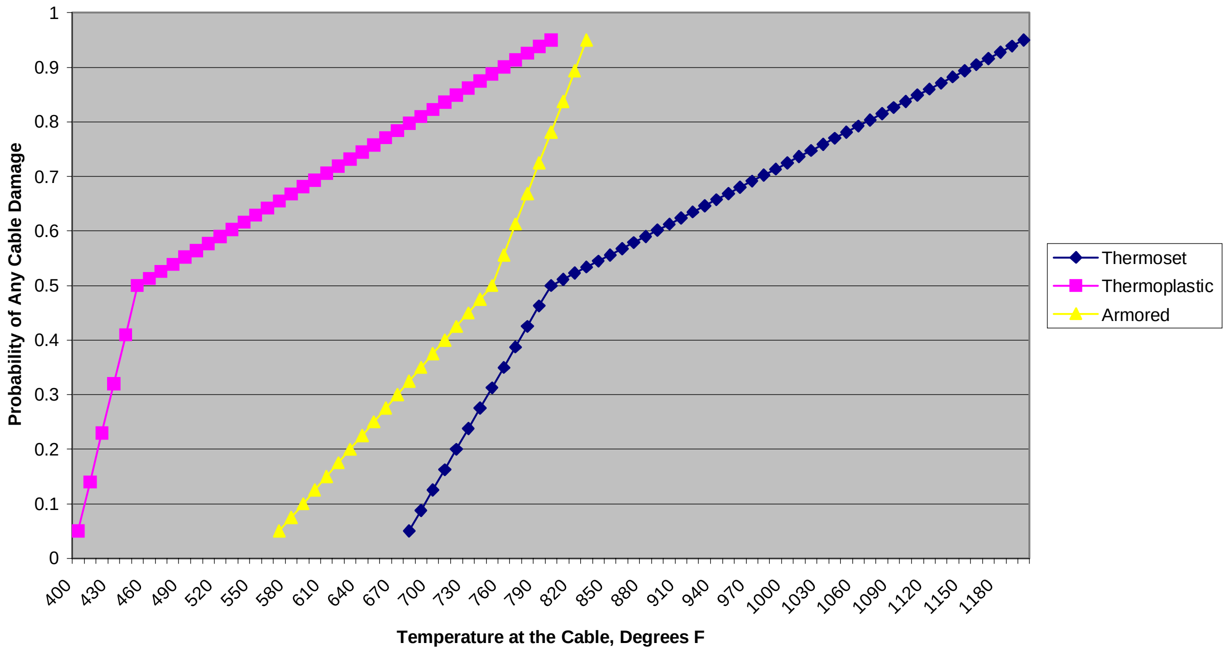

Figure 7-1
Fragility Curves for Thermoset, Thermoplastic, and Armored Cable Anchored to the 5%, 50%, and 95% Probability Values for P_{CD} (See text, Section 7.2.1.3)

7.2.2 Conductor-to-Conductor (and Cable-to-Cable) Phenomena

The extensive discussion in this section 7.2.2 is all a lead-in to section 7.2.3 that will provide evaluations of $\mathbf{P}_{SACD}$, the probability of spurious actuation given cable damage.

Background: In general, when a fire damages a cable (or conductor-within-a-cable), the first change exhibited is degradation in the cable's/conductor's electrical integrity, manifested by a small leakage current, and/or a small change in its insulation resistance. As damage progresses, the cable or conductor ultimately "fails", manifested when the formerly functioning electrical conductor wire either shorts-to-ground, shorts-to-another-conductor, or becomes an open circuit by a break in the electrical conductive path.

Our interest is focused on inadvertent or spurious actuation, which roughly speaking means an undesired electric connection between one conductor that we will call the "source" conductor, and a second conductor that we will call the "target" conductor. The source conductor is generally energized and the target conductor is usually not, but may be. Typically, the circuitry is designed so that actuation occurs when desired by sending a signal through the relevant conductor. (Sometimes the desired actuation requires a voltage signal, and sometimes it requires a certain amount of current to pass.) However, spurious actuation can occur not only when the desired conductor is involved by itself, but also when certain other undesired conductors become involved through faults, the details of which are highly individualized to the circuit design at issue. For each conductor, be it the one that the circuit designer intended to use for the actuation or another unintended one, both the electrical properties and the spatial configuration aspects are important in determining whether spurious actuation will or will not occur.

Furthermore, most circuitry at issue here has designed-in fuses or similar protective devices that will "trip", protecting the circuitry from short-circuit high currents or high voltages, and also typically protecting the circuitry from spurious actuation, thereby ending the danger. Again, the details of these protective features are highly individualized.

Also, if the "source" conductor is energized and is short-circuited not to a "target" conductor but to a ground potential (either to an intentionally grounded conductor or to another nearby ground such as the cable tray, steel support, conduit, etc.), this grounding will usually cause an electrical-protection trip by design, ending the danger of spurious actuation.

What actually happens in practice when a given fire damages a given cable or group of cables is not only highly dependent on the detailed layout and cable configuration, but also somewhat stochastic, in the sense that what happens first --- which conductor shorts to which other conductor, or shorts to ground, or goes to an open-circuit state --- depends on too many variables to be understood or analyzed deterministically. Some of these variables concern the fire phenomena and others concern the layout and electrical properties of the cable(s). As we will deal with them here, these phenomena cannot be known in detail -- they can only be described and dealt with statistically and probabilistically.

7.2.2.1 The open circuit end-point

In the Omega Point test series, no open-circuit end-points were observed, which places an upper bound on such an end-point in the range of a 1% probability, given the number of possible open-circuits.

7.2.2.2 Phenomena in multi-conductor cables

Let us begin with multi-conductor cables, which in our "base case" means an unarmored seven-conductor thermoset cable in a horizontal cable tray, exposed to the fire's hot-gas layer but not to the direct fire plume. Let us assume that the configuration involves one or more nearby single-conductor cables and one or more similar seven-conductor cables.

The Omega Point tests reveal several interesting features, assuming that the 7-conductor cable has reached a "failed" state:

- For a given ("source") conductor in the 7-conductor cable, shorting to another ("target") conductor within the same cable ("intra-cable" shorting) is much more likely than shorting to a target conductor in another cable ("inter-cable" shorting). <u>This seems to be a general feature.</u>

- The probability in the Omega Point tests that a given conductor in a "failed" cable will make an intra-cable short is very high, in the range of 70% to 80% --- let us call this 75% as a point estimate. The uncertainty on this estimate is perhaps ± 10 to 15% to encompass a high-confidence range. Of course, not all of these shorts are even potentially able to produce a spurious actuation -- for example, many of them are shorts to ground, or will activate the protective device/fuse that is designed into the circuitry to avoid just such an undesired event.
- Whether the intra-cable target conductor is a ground conductor or an ungrounded target conductor is a configuration-dependent issue that for our purposes is stochastic. The probability can be estimated using certain analysis methods (see below, under "Probability of a conductor-to-conductor short", Section 7.2.2.4).
- The presence of one grounded conductor among the 7 conductors in a multi-conductor cable seems to have a major influence on whether a short-to-ground occurs first. If a grounded conductor is present among the several conductors, there is a high probability that the source conductor will find it and short to it. This seems to decrease the probability by about half that the source conductor will find a non-grounded conductor to which to short.
- The probability that a source conductor in a damaged multi-conductor cable will short to an adjacent one-conductor target cable is generally <u>lower</u> than the probability that an intra-cable short will occur. If an intra-cable short does occur, it is generally observed to occur earlier than an inter-cable short. If there is no intra-cable short, the inter-cable probability is in the range of 20% from the Omega point tests. (The remaining probability comprises shorting-to-external-ground.) However, it is worth noting that the way the Omega Point test configuration bundled the single-conductor cables directly adjacent to the multi-conductor cables may have produced closer proximity than would be the general case for adjacent cables lying in trays in typical nuclear power plants. Thus the 20% probability just cited may be on the high side, although by an unknown amount. The uncertainty in this 20% estimate is in any event significant, perhaps ± 5 to 15% to encompass a high-confidence range. For thermoplastic cables, this probability is somewhat higher, perhaps 1.5 to 2 times higher.
- For a given damaged 7-conductor cable, there is no reason in practice why one of its conductors might or might not exhibit an intra-cable short to another conductor, while a different conductor might exhibit another intra-cable short or an inter-cable short to an adjacent conductor cable. All of these outcomes are feasible, are generally independent of each other (see the discussion in section 7.2.3.5), and depend on configuration and electrical details that can be described probabilistically.
- From the Omega Point tests, given cable damage, if a short to another non-grounded conductor occurs first, the time interval before an eventual short-to-ground is typically quite short, seldom more than a few minutes for thermoset cable. (For thermoplastic cable the time interval is much shorter still, sometimes only seconds or tens of seconds. See Section 7.3.1 below.)
- The Omega Point test program had only two tests in which multi-conductor cables were adjacent and tested to ascertain the likelihood of inter-cable effects. The evidence is therefore weak, but the test results do show that intra-cable conductor-to-conductor interactions occur before cable-to-cable interactions. In any event, the cable-to-cable

interactions took place a very long time into the test, more than two hours, so the primary insight is that these interactions are unlikely, since actual nuclear-plant cable fires are not likely to burn that long.

The data are unfortunately too sparse to support the quantification of the effect. Nevertheless, this probability is not likely to be higher than the probability that a conductor in a multi-conductor cable will short to an adjacent single-conductor cable, which is cited as about 20% (see the discussion three "bullets" above.)

7.2.2.3 Phenomena in single-conductor cables

Consider a single-conductor thermoset cable adjacent to another cable, either another single-conductor cable or a multi-conductor cable, in the base-case configuration, with one a "source" and the other a "target". The data indicate that these single-conductor cables, once damaged, will usually short to ground before shorting to another cable. The probability is about 85% to 90% with ample data to support this estimate. (For thermoplastic cables, this probability is still high but smaller, only about 70% to 75%, but has larger uncertainties because it is based on far fewer data.)

7.2.2.4 Probability of a conductor-to-conductor short

Here we will restrict ourselves to multi-conductor cables, and to intra-cable shorts.] This probability, predicated on cable damage, comes down to a "competition" between shorting to another conductor vs. shorting to ground, and is amenable to approximate determination by analysis. The analysis needs to account for geometrical/configuration-adjacency factors for the individual conductor at issue and its near neighbors. One would use the ratio of grounded to ungrounded neighbor conductors as a starting point.

One of the expert panelists, Dan Funk, has developed an elaborate analysis approach to estimate this probability, which is presented in his expert report (see Appendix B). He presents tabular results for the above probability as a function of different configuration parameters. Funk also presents an algorithm for determining what he calls the "cable configuration factor", intended to be applied to the probability of a conductor-to-conductor short, to account for the number of source conductors and the number of target conductors in a given multi-conductor cable. The determination of this numerical factor also relies on counting conductor types, including accounting for conductors within the cable that are neither source nor target conductors and are thus neutral vis-à-vis the spurious actuation issue covered here.

The approach would be quite complex and uncertain were there a large number of both source and target conductors in a given cable under review. The approach is liable to be more useful and accurate in the simpler cases. On this subject, it is illuminating to quote from Funk's report: "From my experience in fire-related circuit analysis, the number of target conductors in a single cable is most always one. The number of source conductors varies, but it too is generally a low fraction of the overall number of conductors."

Funk's basic approach makes sense, and can be used in a real case to develop numerical factors useful in tying down the overall spurious-actuation probabilities more closely. But of course the approach cannot be more than an approximation to reality (nor is it advertised otherwise), given that several factors that are not explicitly treated can affect this probability.

Overall, Funk's approach seems like a useful addition to the analyst's tool-box. His report should be referred to for details (Appendix B).

7.2.3 Probability of spurious actuation given cable damage (P_{SACD})

This section will deal with the probability $\mathbf{P_{SACD}}$ (the probability of spurious actuation given cable damage) that was defined in Section 4.1.

All of the discussion in the previous section 7.2.2, related to phenomena after the postulated fire has caused cable damage, is a lead-in to support the evaluation here of P_{SACD}.

As above, we will restrict the discussion here to the "base case" configuration (see Section 7.1 above), and then deal with variants in Section 7.3 below. Note that the base case explicitly involves circuits in which the electrical connection uses a control-power transformer (CPT). Also, note that the 7-conductor cables used in the tests always had one grounded conductor.

Again, based on the Omega Point test series, we will deal separately with multi-conductor cables (in our case 7-conductor cables) and single-conductor cables.

7.2.3.1 P_{SACD} for multi-conductor cables, intra-cable shorts leading to spurious actuation

The data recorded a significant number of spurious actuations, given cable damage. Different experts offered different numerical values for P_{SACD} and this is in part because it is not sufficient simply to count up the number of events with and without actuation -- one needs to apply judgments to the conditions.

The estimate presented next covers only the outcome in which at least one spurious actuation occurs, in a configuration in which one source conductor exists together with one or two target conductors within the same cable, and one of the conductors within the cable is grounded. Based on an evaluation of both the experts' input and the primary test evidence, P_{SACD} for this case is estimated with high confidence to lie between 0.10 and 0.50, with a best-estimate point value near 0.30.

This estimate is based on the Technical Integrator's own evaluation of the primary data, supported by input from the expert reports. The wide range is an indication that there is considerable uncertainty in the numerical values of P_{SACD}.

7.2.3.2 P_{SACD} for single-conductor cables, inter-cable shorts with other single-conductor cables leading to spurious actuation

This case deals with one single-conductor energized source cable, interacting with an adjacent single-conductor target cable so that, given the interaction, the undesired actuation occurs. The Omega Point data contain such events, although as noted above it is most common for a single-conductor cable to short to ground. The difficulties in interpretation involve estimating the population of cable pairs from which the positive-event sample is drawn. On balance, the probability P_{SACD} for this case is estimated to fall with high confidence between 0.05 and 0.30, with a best-estimate point value near 0.20.

7.2.3.3 P_{SACD} for a multi-conductor cable, in which one of its conductors experiences an inter-cable short with an adjacent single-conductor cable

This case deals with one energized source conductor within a multi-conductor cable, interacting with an adjacent single-conductor target cable so that, given the interaction, the undesired actuation occurs, and the multi-conductor cable contains one grounded conductor. The Omega Point data contain such events, but as discussed above the likelihood that a source conductor in a multi-conductor cable will find an intra-cable short is far higher than that it will find an inter-cable short. The value of P_{SACD} for this case is lower, and is estimated to fall with high confidence between 0.05 and 0.20, with a best-estimate point value near 0.10.

7.2.3.4 P_{SACD} for a multi-conductor cable, in which one conductor experiences an inter-cable short with a conductor in an adjacent multi-conductor cable

As discussed above (Section 7.2.2.2, last bullet), the test data for these effects are sparse, but inter-cable effects between multi-conductor cables did occur very late into the tests (more than two hours). Thus the probability of spurious actuation in a real nuclear-plant fire due to such interactions seems to be quite small. The value of the probability is difficult to estimate --- perhaps it is in the range of 0.01 to 0.05. This applies when each of the multi-conductor cables has one grounded conductor among its several conductors.

7.2.3.5 Likelihood of correlated multiple spurious actuations

The Omega Point test data reveal several instances of multiple spurious actuations in the same test, sometimes involving different conductors in the same multi-conductor cable. Given the complexity of the configuration and of the phenomena, this is not surprising. One expert noted that in some cases the multiple-short outcome was more probable than the single-short outcome. However, to develop a correlation coefficient that would support a probability for such a multiple-short scenario would require that the coefficient be tailored to some quite specific conditions, since any correlation coefficient or probability would need to be conditioned on a specific configuration.

The arguments supporting the opposite conclusions (as to whether the correlation coefficient is large or small) are easier to present than to differentiate among. Suppose that two to four actuations occur together (close in time) during a given test. We consider the issue of whether there is a strong correlation coefficient. On the one hand, the same fire has caused all of the damage, and certainly that is one source of positive correlation. Furthermore, some tests showed several (two or three or even more) conductors in the same or adjacent cables that exhibited damage phenomena (low insulation resistance, for example) that are precursors to spurious actuation --- this would tend to support an important correlation effect. On the other hand, if the only determinant of whether conductor/cable damage and then spurious actuation occurs is the temperature reached by the conductor/cable, then except for the fact that adjacent conductors/cables will tend to experience the same temperature, there would not be a particular reason for much correlation. Furthermore, sometimes if two or three conductors exhibited the phenomena, they were among a group of say 8 or 10 or more conductors --- and the others did not exhibit the same phenomena. This would support an interpretation that the correlation coefficient is small.

On balance, after attempting to extract a meaningful understanding of the test data to support developing meaningful correlation insights, it was concluded that this issue is too complex and the test data too difficult to work with. An experimental program specifically designed to test this aspect would be needed, but without careful reflection it is not at all obvious how to design and execute such an experimental program.

Some guidance can nevertheless be given, based on insights from the tests. Let us suppose that a fire-PRA analyst is attempting to use P_{SACD} values, and the issue of dependence has arisen. Specifically, suppose that the fire PRA is analyzing a circuit configuration in which spurious actuation will occur only if two different cable failures occur, each cable failure associated with a different conductor --- that is, there are two different hot-short events, occurring in the same fire.

Based on an evaluation of the evidence, the two P_{SACD} values used in the fire PRA should be taken as independent events, provided that the phenomena really do occur in different conductors --- thus the P_{SACD} probabilities should be multiplied together. This is the proper interpretation of the P_{SACD} probabilities presented here.

It is of course incumbent upon the analyst to demonstrate that the two hot-short events are clearly independent in the sense above. This would certainly be the case if the cables are in different cable trays, but it should hold also for different cables in the same cable tray. Whether it holds for different conductors within the same multi-conductor cable is more problematical, and the analyst should take great care in this case. The bounding assumption, of course, would be that the second actuation is assigned a P_{SACD} probability of 1.0 conditional on the first one.

As one expert, G. Parry, points out in his report (see Appendix B), the use and interpretation of a multiple-actuation probability would require structuring the underlying PRA in a way that could account for the phenomena accurately. Doing so would be very difficult except in specific simple cases.

7.2.4 Overall likelihood of spurious actuation (P_{SA})

This section will discuss $\mathbf{P_{SA}}$, defined in Section 4.1:

$\mathbf{P_{SA}}$ = probability of spurious actuations of one or more circuit components for a specific combination of fire temperature and fire duration.

Note that P_{SA} in our formulation can be expressed as the product of two terms, P_{CD} (discussed in Section 7.2.1 above) and P_{SACD} (discussed in Section 7.2.3 above):

$$P_{SA} = [P_{CD}][P_{SACD}]$$

The probability P_{SA} obviously differs among the several different cases covered in section 7.2.3. Also, recall that for P_{CD} the discussion in Section 7.2.1 centered around describing a temperature threshold below which cable damage would not occur.

Thus, one productive way to develop P_{SA} from the P_{SACD} information is to use the probabilities for P_{SACD} from Section 7.2.3, conditional on the cable having reached at least the threshold temperature for "damage" cited in Section 7.2.1. If a probability distribution for "cable damage" vs. temperature for P_{CD} is needed, then either a "fragility curve" of the kind discussed in 7.2.1 can be developed, or some other analysis used to work out the likelihood that the damage temperature is reached.

Direct Evaluation of P_{SA}: Only one of the experts offered a direct evaluation of P_{SA} for use in this integration. This evaluation, which attempts to cut across the whole swath of detail, finds as follows:

For thermoset cable exposed to a well-developed hot-gas layer, meaning conditions that are interpreted here as "above the P_{CD} threshold" for cable damage, the overall probability of a spurious actuation is distributed as follows:

- It is very unlikely that P_{SA} is smaller than about 10^{-5}.
- The best-estimate or most-probable value for P_{SA} is in the range of 0.001.
- It is very unlikely that P_{SA} is larger than about 0.01.

NOTE: For thermoplastic cable, the three probabilities are presented by this expert as being (0.001, 0.1, and 0.5) See Section 7.3.1.

These P_{SA} estimates are significantly lower than those developed above using the more detailed approach involving P_{SACD}. On balance, these estimates seem too small, and are in conflict with the detailed Omega Point data.

7.3 Evaluation of Variants on the "Base Case"

Section 7.1 described the "base case" configuration that has been the object of all of the evaluations in Section 7.2. In this section, evaluations will be presented for a variety of cable-spurious-actuation issues representing departures from or variants on the base case.

7.3.1 Differences between thermoset and thermoplastic cables

P_{SACD}, the probability of spurious actuation given cable damage: It is important

to point out that, once cable damage has occurred, be it manifested as a hot short or as another phenomenon, the probability of spurious actuation given cable damage (P_{SACD}) does not display significant differences between thermoset and thermoplastic cables. What we will discuss below are differences in the phenomena associated with cable damage and P_{CD}.

Cable damage: As a general observation, the Omega Point tests reveal that thermoplastic cables perform significantly less well than thermoset cables vis-à-vis cable damage and shorting. All of the evidence points this way, and there is no contrary evidence. That is, there seems to be no parameter or condition related to cable damage after a fire for which thermoplastic cable seems to perform better.

Some of the evidence has been touched on in Section 7.2, as the performance of thermoset cable was being evaluated. It is summarized here:

Threshold for cable "failure" (section 7.2.1):
The thermoplastic cable threshold is 400 F, compared to 550 F for thermoset cable.

"Fragility curve" for cable failure vs. temperature (section 7.2.1):
The thermoplastic cable's fragility curve is represented by the three temperatures of 400, 450, and 800 F compared to thermoset cable's 680, 800, and 1200 F.

Time interval between a hot-short and a short to ground (section 7.2.2.2)
For thermoplastic cable this time interval is typically only seconds to tens of seconds, compared to several minutes for thermoset cable.

Probability of shorting to ground rather than to a non-grounded conductor, for a fire-damaged single-conductor cable (section 7.2.2.3)
This probability is slightly less (70% to 75%) for thermoplastic cable than the 85% to 90% probability for thermoset cable.

Probability of an inter-cable short between a conductor in a fire-damaged multi-conductor cable and an adjacent single-conductor cable (section 7.2.2.2)
This probability is somewhat greater for thermoplastic cable than for thermoset cable, perhaps 1.5 to 2 times greater.

Insulation-resistance changes

Thermoplastic cable exhibits insulation-resistance changes at lower temperatures than thermoset cable.

7.3.2 Effects in armored cable

The Omega Point test program included two tests using armored multi-conductor thermoset cable in cable trays. These cables (8-conductor-type but similar otherwise to the 7-conductor cables used in the majority of the unarmored-cable tests), were exposed to the fire's hot gas layer but not to the fire plume. Thus the conditions do not differ much from the "base case" conditions set out above in Section 7.1. The armor shield was maintained at ground potential. Because the number of tests was few, the data are sparse, but nevertheless some clear trends and differences emerge.

The general observations about the differences in performance compared to unarmored thermoset cable follow:

- The threshold below which cable damage is not expected to occur is similar to that for unarmored thermoset cable, perhaps slightly lower but the evidence for the difference is not strong. (Section 7.2.1.2 presents the discussion of the threshold phenomenon.)
- The "fragility curve" for cable damage vs. temperature (see Section 7.2.1.2) falls at lower temperatures than for unarmored thermoset cable, according to the one expert who developed this type of information. The fragility curve is characterized by the temperatures of 570, 750, and 830 F, whereas for unarmored thermoset cable these temperatures are 680, 800, and 1200 F.
- The presence of the electrical ground in the armor shield means that, once fire-caused cable damage has set in, the probability that an individual conductor will short-to-ground is significantly higher than for unarmored cable. Instead of the 70% to 80% fraction of conductors that are observed to have shorted to another conductor (intra-cable shorting), for armored cable this fraction is in the 20% to 30% range. (Section 7.2.2.2 presents the discussion of this issue for unarmored cable.)
- Because the armor is an effective electrical ground, the opportunity for inter-cable shorting to another cable is nil. This probability should be zero.
- Overall, the value for P_{SACD}, the probability of spurious actuation given cable damage, is smaller for armored cable because the shorting-to-ground probability is higher. The decrease in P_{SACD} is perhaps a factor of about three to five reduction. Given the estimate (Section 7.2.3.1 above) that for the base case (unarmored thermoset cable) the probability P_{SACD} lies between 0.10 and 0.50 with a best estimate point value near 0.30, the corresponding probabilities for armored cable are evaluated to be P_{SACD} between 0.02 and 0.15, with a best estimate point value near 0.075. (The user should recognize that a good deal of judgment has gone into the specific numbers here.)

Also, some nuclear-power-plant electrical configurations are arranged so that whenever one conductor in a multiconductor armored cable shorts to ground (most likely to the armor), a fuse will force all other conductors within that cable to become de-energized. For such configurations, the value of P_{SACD} is probably smaller by about an order to magnitude. This decrease (of a factor of ten) is reflected in Table 7-2.

7.3.3 Cable Trays vs. Conduit

The Omega Point test program included four tests (three using thermoset cables and one test using thermoplastic cable) in which the cables were located in conduit, enabling a study of the difference in performance compared to cable trays. The conditions did not differ much otherwise from the "base case" conditions set out above in Section 7.1. The conduit was maintained at ground potential. Although the number of tests was few and the data are not numerous, several clear differences emerged from the tests.

The general observations about the differences in performance compared to cable trays follow:

- For conduit, the threshold below which cable damage is not expected to occur is likely to be somewhat lower than for similar unarmored thermoset cables in cable trays, especially for cable trays with multiple layers of fill. This is due to the lower thermal capacity of the cables in the conduit. However, this effect needs more experimental investigation before it can be quantified usefully.
- For the same reason, the "fragility curve" for cable damage vs. temperature (see Section 7.2.1.2) would likely fall at lower temperatures than for cables in cable trays. However, this is also an unquantified effect until more information is available.
- The presence of the electrical ground in the conduit means that, once fire-caused cable damage has set in, the probability that an individual conductor will short-to-ground is observed to be significantly higher than for cables in cable trays. This is an effect similar to that observed for armored cable. Whereas in cable trays the fraction of conductors that were found to have shorted to another conductor (intra-cable shorting) is 70% to 80%, in conduit the fraction was found to be in the 20% to 30% range. (Section 7.2.2.2 presents the discussion of this issue for the cable tray case.)
- Because the conduit is an effective electrical ground, the potential for inter-cable shorting to another cable rather than to ground is undoubtedly reduced. However, the numerical value of the reduction in this probability cannot be developed from the sparse data.
- Overall, the value for P_{SACD} , the probability for spurious actuation given cable damage, is significantly smaller for cable in conduit because the shorting-to-ground probability is higher. The decrease in P_{SACD} is perhaps a factor of 3 to 5 reduction.

7.3.4 Plume effects vs. hot gas layer effects --- exposure issues

The Omega Point test series included a number of different fire exposure conditions. For over half of the 18 tests, the cables were exposed directly to the fire plume; however, for a half-dozen of them the cables were located in the hot gas layer but out of the plume. The fire size (heat release rate) varied considerably also, from 70 to 450 kilowatts.

Also, although the test conditions were controlled and stylized, the test fires cannot be "typical" of all the fires of concern in nuclear plants. The fire experiments also were carried out in a steel room whose ventilation conditions were not always the same from one test to the next. How much difference these aspects make to the usefulness of the results herein is uncertain.

The experts who evaluated this issue concluded that while the exposure conditions varied, the only important parameter useful for our purposes was the actual temperature reached by the target cables. The fact that the temperature rise was gradual, as revealed by the thermocouples, means that transient aspects were less important than for a fast-burning fire of brief duration but high intensity.

One expert observed that for a multi-layer cable tray, the cables at the top would experience harsher conditions in a hot-gas-layer-exposure scenario, whereas the cables at the bottom would experience harsher conditions in a plume-exposure scenario. The cables in the middle of a densely packed tray would then be the least likely to suffer damage in either scenario. This observation makes sense, and reinforces the conclusion that for slowly-developing fires the local temperature at the cable is the primary determinant of cable failure behavior. Another expert observed that the other exposure parameters are of secondary importance.

It is of course possible that some aspects of the exposure environment could affect heat transfer to cables in ways that are preferential among failure modes. This is undoubtedly true in principle, but the detailed differences seem to be beyond our ability to parse and analyze from the data available in these tests.

7.3.5 Effects of cable tray fill and location within the tray

For reasons very much related to those discussed just above concerning exposure conditions (Section 7.3.4), cable tray fill and cable location within the tray are believed to be of secondary importance compared to the dominant role played by the temperature profile at the target cable. Of course, the temperature experienced by an individual cable depends a lot on the degree of cable-tray fill and the cable's location therein.

The tests show that a cable tray with less fill is more susceptible to damage than a tray with more fill. One expert observed that for intra-cable conductor-to-conductor behavior in a multi-conductor cable, these issues make little difference, whereas for inter-cable shorting the effects of a heavily-loaded cable tray are to increase the probability of a spurious actuation. Another expert didn't see much correlation with these issues.

On balance, the effects of these issues are probably second-order in importance compared to the dominant effect of the local temperature profile vs. time at the target cable.

7.3.6 Horizontal and vertical cable trays and air drops

The Omega Point test series included two tests in which vertical cable trays were used instead of the horizontal configuration for the other tests. One test exposed thermoset cable and the other exposed thermoplastic cable. One actuating-device cable bundle was placed adjacent to the tray to simulate an air-drop configuration. The cables were exposed to the fire's radiant energy and also to its hot gas layer, but not to the fire plume itself.

The test using thermoset multi-conductor cable showed a gradual decrease in insulation resistance but not to the point where cable failure was indicated, although important leakage current was measured between two of the conductors. The test using thermoplastic cable, on the other hand, showed cable failure at temperatures in the same range as for thermoplastic-cable failures in horizontal-cable-tray tests.

Taken together, these tests are suggestive of an effect -- that exposure mainly to radiant heat is less damaging -- but are not conclusive in demonstrating important differences in cable behavior for the vertical compared to the horizontal cable-tray configuration. Whether more extensive exploration of this issue would reveal systematic differences is unknown.

7.3.7 Impact of water spray

During many of the Omega Point test runs, the test was terminated by using a water spray to cool down the test rig. The monitoring of the electrical circuitry continued during the application of this spray, and for one of the tests this spray caused a spurious circuit actuation that had not occurred previously.

Thus the fact that such a spray can cause the undesired actuation has been established, and the probability is not miniscule. However, a generally useful or applicable interpretation of this observation is very difficult to find. Such sprays, in a real fire in a real power plant, are liable to be highly variable in their effects, more variable than the sprays in these tests which were similar from one test to the next. Quantifying this effect would be speculative at best, beyond the observation that, since the actuation occurred, the probability is unlikely to be smaller than, say, in the range of a few percent, perhaps greater.

7.4 Electrical Configuration Issues

7.4.1 Influence of the Control Power Transformer (CPT)

In the Omega Point test series, one particular circuit was used, a specific motor starter (a so-called NEMA-1 starter) for a motor-operated valve. In an actual nuclear power plant, the control cabling would essentially always be connected through a Control Power Transformer (a CPT), whose function is to maintain proper electrical function, filter out certain transients, and isolate the circuit from certain outside influences. In this test series, CPTs were not used in the early tests because of experimental problems, but after the difficulty was solved they were used in the later runs.

Note, however, that all of the evaluations presented above (Sections 7.2 and 7.3) are for what we have called the "base case" configuration, described in Section 7.1, which includes a CPT in the circuit. Here we will explore the influence of the presence of a CPT.

Only one expert provided an evaluation of the CPT issue. Based on his evaluation and an independent review of the test data, it appears that the absence of a CPT in the circuit increases the probability P_{SACD} (the probability of spurious actuation given cable damage and intra-cable shorting in a multi-conductor cable) by about a factor of two, perhaps less. The data are difficult to parse beyond a finding approximately along these lines, because the number of test results is sparse. Whether these conclusions also apply to inter-cable shorting is not clear --- they should apply, but the data to support such a finding are insufficient.

Note that in developing the P_{SACD} estimates throughout sections 7.2 and 7.3, the above factor of 2 has been taken into account and included. Specifically, all of the P_{SACD} values in sections 7.2 and 7.3 apply to the "base case" configuration set down in Section 7.1, which configuration includes a CPT in the circuit. When evaluating those Omega Point tests in which there was no CPT in the circuit, the P_{SACD} probabilities derived from these tests have all been doubled so as to be applicable instead to either the "base case" or specific variants of it that include a CPT. This doubling thus applies to all of the P_{SACD} numbers in cases B-1 to B-13 in Table 7-2.

7.4.2 Cable/circuit electrical-configuration influence factors

Given fire-caused cable damage, it is clear that whether a spurious actuation occurs or not depends in detail on the design of the actuation circuitry and indeed on the cable configuration. A number of electrical-configuration influence factors exist that can affect the overall P_{SACD} (the probability of spurious actuation given cable damage). Among them are the following, many of which have been touched upon above in earlier sections of this report:

- Cable-proximity issues -- the presence or absence of a source conductor and a target conductor is central.
- Relative location --- the proximity or absence of a ground conductor or other ground plane is a major factor. This is an influence factor especially if an unarmored multi-conductor cable has no grounded conductor within it.
- Latching circuitry and fuses -- the presence or absence of latching circuitry and/or protection devices such as fuses has an impact on whether actuation will occur before a circuit can be protected from it by these devices. Among the issues is the circuit-design-specific question of how long a hot-short contact must be in place before protection can come into play. The presence of double-breaker configurations would be another consideration --- it is easy to speculate that these would decrease P_{SACD} substantially if present.
- Circuit wiring -- the detailed wiring configuration, as the actuation conductor enters the circuit, should have some influence. For example, while the circuit is designed for a specific input signal (a voltage change, an electrical current pulse of a certain size, etc.), the very essence of a spurious-actuation "signal" is that it is spurious and hence has a different electrical character. Issues such as the stray capacitance or input impedance at the input side of the circuit could be determinants of the ultimate behavior, but are obviously not an explicit part of this evaluation.
- Circuit failures causing spurious actuation -- It is possible that in some cases the spurious actuation was not caused directly by the incoming signal, but by a circuit failure of another kind, related for example to a false permissive signal. This issue has not been evaluated here.

As this discussion reveals, there are a large number of factors related to the electrical circuit design and configuration that, in detail, can influence or even determine whether P_{SACD} is large or small --- whether spurious actuation occurs or not. None of them have entered explicitly into the evaluations presented above, which is part of why the uncertainties in the numerical values for the probabilities (P_{CD}, P_{SACD}, P_{SA}) are as large as they are. Indeed, given the variability implied by these several factors, and the sensitivity of the outcome to them, the ability to estimate these probabilities at all could be called into question.

7.5 Summary of the Evaluation

7.5.1 Evaluation of the Expert-Panel Process

The expert-panel process that was used in this project is described in Section 2. It consisted of 8 steps. The 8-step approach was intended to provide both a structured process and an orderly sequence of events, that the experts could understand beforehand.

While the process worked reasonably well in terms of its structure and orderliness, one aspect left something to be desired. This aspect, touched upon briefly in Section 2.5 where "Step 5" is discussed, concerns how the various experts dealt with the technical subject matter. In Section 4.1, an extended discussion provides insight into how the Panel arrived at the final formulation of the questions to be answered. This was accomplished through a series of conference calls and written proposals. After much back-and-forth discussion, it was agreed that the various experts could pick-and-choose which among the various technical issues they would address in their evaluations. This approach was intended to allow each expert to concentrate on those aspects of the broader spurious-actuation issue where he believed that his expertise would be most applicable and helpful.

So far, so good --- but when the various expert evaluations were completed, it turned out that some of the important technical issues presented above in sections 7.2 through 7.4 were addressed by only one or two of the experts. One good example is the issue of the influence of CPTs (control power transformers) in the circuitry --- their presence influences the probability of spurious actuation by about a factor of two, but the issue was addressed by only one of the experts. A few other important issues suffered from the same problem. This made the task of the Technical Integrator significantly more difficult.

In the end, the TI (the author of these lines) made his own evaluation of each key technical issue, based wherever he could on the inputs from the various experts but supplemented by his own personal evaluation of the primary evidence. For many of the issues, where expert input was sparse, his own evaluation is the primary determinant of the "results" herein, or at least it needs to be understood as having sometimes received perhaps 50-50 weight along with the evaluation of the one or two experts who provided relevant expert input. (The issue of the influence of the CPTs is a good example. The one expert who provided input had a major influence, but the TI modified that expert's input slightly in arriving at the final evaluation in Section 7.4.1.)

The fact that the TI's influence dominates some of the important evaluations is well within the bounds of the process used here. However, the author (the TI) feels compelled to call this possible limitation to the attention of the reader in the interest of avoiding future misunderstanding.

7.5.2 Technical Summary

The probabilities in Sections 7.2, 7.3, and 7.4 are summarized in Table 7-1 and Table 7-2, supplemented of course by the more detailed discussions in the referenced sections. The analyst must use the table entries cautiously. As discussed above, the overall probability of spurious actuation, P_{SA}, is given by the product:

$$P_{SA} = P_{CD} \times P_{SACD}$$

As an example of how to work out P_{SA}, consider a fire affecting a single multi-conductor thermoset cable in an ordinary cable tray, for which the systems/circuit analysis reveals that the only potential spurious-actuation concern would involve an intra-cable hot short between two specific conductors in the same cable. We assume that there is a CPT in the circuit. Consider the case in which fire modeling shows that the temperature at the cable itself gradually reaches a maximum temperature of 800 F. To work out P_{SA}, we first go to the "fragility curve" in Figure 1, and determine that the probability P_{CD} of cable damage at 800 F is 0.50 for this cable. We then use Case B-1 (in Table 7-2) and determine that P_{SACD} has a best estimate value of 0.30. Then the best estimate value for $\mathbf{P_{SA}}$ is the product of P_{CD} and P_{SACD} , or 0.50 x 0.30 = **0.15**. The **high-confidence range**, from Table 7-2, is 0.50 x (0.10 to 0.50) = **0.05 to 0.25**.

If there is no CPT is the circuit, the P_{SA} value should be doubled (Case B-14).

If the same cable were armored, then the calculation of P_{SA} is different. At a temperature of 800 F, the P_{CD} value from Figure 1 is 0.80, not 0.50. From Table 7-2, we should use Case B-9, which has a best estimate value for P_{SACD} of 0.075. The best-estimate for P_{SA} is now different: $\mathbf{P_{SA}}$ = 0.80 x 0.075 = **0.06** with a CPT in the circuit, or double that value without a CPT in the circuit. The **high-confidence range** with a CPT in the circuit is 0.80 times (0.02 to 0.15) or about **(0.016 to 0.12)**.

It is important to point out here that the P_{SACD} values presented in Table 7-2 are derived from a narrow set of test conditions (a specific and small group of cable types and configurations, certain fire sizes and growth-rates, a specific circuit subject to spurious actuation, and so on.) When applying these probability values to another configuration, the analyst must assess carefully how similar the configuration being analyzed is to the Omega Point test conditions upon which the P_{CD} and P_{SACD} values are based, including for example an assessment as to whether the time-temperature profile of the fire being analyzed has the stretched-out, gradual-heat-up character of the fires in the Omega Point tests.

Also, the most obvious conclusion of the whole exercise, as represented by the P_{SACD} values in Table 7-2, is that <u>hot shorts leading to spurious actuations cannot be regarded as of negligible importance</u>, if the fire under consideration produces cable temperatures above the thresholds identified herein.

Finally, the amount of detail in Tables 7-1 and 7-2, with different probability values and ranges associated with various configurations, provides a rich source of numerical information useful for fire PRAs. However, its use must always account <u>in detail</u> for the actual configuration being analyzed (see the discussion of various influence factors in Sections 7.3 and 7.4, and in

LaChance et al. (Ref. 5)). The analyst who simply "grabs a number" from the Tables for use in a PRA, without careful consideration of these issues, does so at the peril of making a major error ---- *caveat emptor*, "buyer beware."

Table 7-1
Summary of the Probabilaities Cited in Section 7

Case #	Short Description of Case (see text for details)	Best Estimate	High-Confidence Range (see Section 4.3 for a definition)	Discussion Reference
G-1	Open circuit		< 0.01	7.2.2.1
Thermoset				
G-2	M/C, Tset, any intra-cable short given cable damage	0.75	0.60 - 0.90	7.2.2.2, bullet 2
G-3	Same as #G-2, except hot short to a non-grounded conductor given presence of a grounded conductor	0.40	0.25 - 0.55	7.2.2.2, bullet 4
G-4	M/C to 1/C, Tset, given no intra-cable short	0.20	0.05 - 0.35	7.2.2.2, bullet 5
G-5	1/C to 1/C or M/C, Tset, hot short before short-to-ground	0.10 - 0.15		7.2.2.3
G-6	M/C to M/C, Tset, given no intra-cable short	< 0.20		7.2.2.2, bullet 8
Thermoplastic Variants				
G-7	Same as #G-4 except Thermoplastic	0.40	0.25 - 0.55	7.2.2.2, bullet 5
G-8	Same as #G-5, except Thermoplastic	0.25 - 0.30		7.2.2.3
Armored Variants				
G-9	Same as #G-2 except armored	0.25	0.10 - 0.40	7.3.2, bullet 3
G-10	Same as #G-4 and #G-5, except armored	0	0	7.3.2, bullet 4
Conduit Variants				
G-11	Same as #G-2, except in conduit	0.25	0.20 – 0.30	7.3.3. bullet 3
G-12	Same as #G-4, except in conduit	< 0.2		7.3.3, bullet 4
G-13	Same as #G-5, except in conduit	< 0.1		7.3.3, bullet 4

Abbreviations in Tables 7-1 and 7-2:
1/C - One-conductor cable   Tset - Thermoset cable   M/C - Multi-conductor cable

Table 7-2
Summary of the Probabilities (P_{SACD}) Cited in Section 7

Case #	Case	Short Description	Best Estimate For P_{SACD}	High Confidence Range (see Section 4.3 for a definition)	Discussion Reference
P_{SACD} BASE CASE					
B-1	P_{SACD} base case	M/C Tset cable Intra-cable	0.30	0.10 – 0.50	7.2.3.1
B-2	P_{SACD} base case	1/C cable, Tset, inter-cable	0.20	0.05 – 0.30	7.2.3.2
B-3	P_{SACD} base case	M/C with 1/C, Tset, Inter-cable	0.10	0.05 – 0.20	7.2.3.3
B-4	P_{SACD} base case	M/C with M/C, Tset Inter-cable	0.01 - 0.05		7.2.3.4
P_{SACD} VARIANTS					
Thermoplastic Variants					
B-5	P_{SACD} variant	Same as #B-1 except Thermoplastic	0.30	0.10 – 0.50	7.3.1, last paragraph
B-6	P_{SACD} variant	Same as #B-2 except Thermoplastic	0.20	0.05 – 0.30	7.3.1, last paragraph
B-7	P_{SACD} variant	Same as #B-3 except Thermoplastic	0.10	0.05 – 0.20	7.3.1, last paragraph
B-8	P_{SACD} variant	Same as #B-4 except Thermoplastic	0.01 - 0.05		7.3.1, last paragraph
Armored Variant					
B-9	P_{SACD} variant	Same as #B-1 except armored	0.075	0.02 - 0.15	7.3.2 bullet 5
B-10	P_{SACD} variant	Same as #B-1 except armored cable with fuses (see 7.3.2)	0.0075	0.002 - 0.015	7.3.2 bullet 6
Conduit Variants					
B-11	P_{SACD} variant	Same as #B-1 except In conduit	0.075	0.025 – 0.125	7.3.3 last bullet
B-12	P_{SACD} variant	Same as #B-2 except In conduit	0.05	0.0125 – 0.075	7.3.3 last bullet
B-13	P_{SACD} variant	Same as #B-3 except In conduit	0.025	0.0125 – 0.05	7.3.3 last bullet
B-14	P_{SACD} variant	Same as #B-4 except In conduit	0.005 - 0.01		7.3.3 last bullet
Control Power Transformer (CPT) Variant					
B-15	P_{SACD} variant	Same as #B-1 except without CPT	0.60	0.20 – 1.0	7.4.1

8
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A
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B
INDIVIDUAL EXPERT PANELISTS' REPORTS

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Appendix B-1 Report of Daniel Funk

Spurious Actuations Resulting from
Fire-Inducted Circuit Failures
Daniel Funk – Expert Panel Input

Introduction

Contained in this paper is my formal input to the Expert Panel Technical Integrator (TI). This information is not intended for circulation beyond expert panel members. I am assuming all panel members are familiar with the issues at hand and the expert panel charter. Accordingly, I have intentionally omitted background information, general discussions, and lengthy explanations.

In formulating my input, I have relied on the following sources of information:

- NEI/EPRI test results from the Omega Point fire tests
- Sandia test results from the Omega Point fire tests
- Selected historic information; including past cable fire test data; cable environmental test reports; general industry documents; and industry/regulatory codes, standards, and guidelines

The Omega Point fire test results are by far the most influential data used in formulating my input. These tests were conducted specifically to collect information about fire-induced cable damage behavior and failure modes. It is therefore no surprise that the Omega Point test results are the most relevant information pertaining to the questions that the Expert Panel is attempting answer.

Definitions

The expert panel – and the industry as a whole – has struggled with standardized definitions and terminology for this unique area of study. Having seen first hand the confusion and misconceptions caused by different terminology and meanings, I urge the TI to not underestimate the importance of this aspect of the Expert Panel's cumulative output.

Steve Nowlen provided to the panel a short paper containing suggestions for standard terminology for fire-related circuit analysis. The paper captures well the progression of events for circuit analysis as it relates to fire-induced electrical failures: First, the fire causes cable damage, which ultimately leads to cable failure via a definable failure mode. Based on the circuit design and characteristics, the cable failure mode can be analyzed for its effect on the circuit to determine the related circuit fault modes. Finally, the functional impact of the circuit faults can be assessed, assuming required boundary conditions are known or presumed.

I agree in general with most of the definitions proposed by Steve – we have discussed before. I am, however, still concerned about the term "hot short". This term is non-standard across **ALL** traditional electrical engineering sub-disciplines, and continues to cause consternation within nuclear fire-related circuit analysis.

Appendix A contains my suggested definitions for fire-related circuit analysis. My perspective and opinions relating to terminology has continued to evolve throughout my work in this area and most recently the expert panel process. Thus, I must apologize in advance for proposing these terms so late in the game. In arriving at these definitions I have followed the following principles:

- To the maximum extent possible, we should use standardized electrical and fire protection terminology, as sanctioned by national standards, industry consensus standards and codes, governing regulatory documents, and long-standing accepted trade terms. We should not invent new terms or mutate the meaning of established terms.
- IEEE 100 (ANSI C42), *Standard Dictionary of Electrical & Electronic Terms,* is the definitive reference for electrical terminology in the US. IEEE 383 (the governing standard for cables used at US nuclear plants) references IEEE 100 as the source for related definitions.
- The proposed terminology should not conflict with important NRC requirement and guidance documents.
- Many of the traditional terms used to define electrical faults are based on power cable faults. These terms are not always a good fit to describe the characteristics and behavior of the control circuit failures/faults of interest to us. Thus, some unique terminology for fire-induced circuit analysis is inevitable.

In deriving the suggested definitions contained in Appendix A, I went through the exercise of comparing many source documents. I was amazed at how consistent the definitions were between the various industry, regulatory, and standards documents.

General Observations

This section contains general, or overall, observations that are apparent from the work and testing conducted to date.

1. There exists a threshold of thermal insult below which cable failure (either partial or complete) does not occur, or is extremely unlikely. This observation excludes long-term degradation or a reduction in cable life. Reasonably conservative temperature values appear to be:

    Thermoset cable: 550ºF

    Thermoplastic cable: 400ºF

    Note that these are actual temperature values based on the thermocouple readings of the cables themselves. The Sandia test data showed similar results, except the thermocouple readings associated with the Sandia data were the air temperature in the vicinity of the cables. Using surrounding air temperature, the threshold values are estimated as:

Thermoset cable: 700ºF

Thermoplastic cable: 600ºF

Temperature alone may not be the best way to capture this “Damage Threshold”; heat release rate (HRR) may be more appropriate. The point I make here is that a lower threshold of thermal insult (fire intensity) exists below which cable damage (as defined for our purposes) is not expected to occur for a REALISTIC INSTALLATION. See discussion below regarding cable damage probability factor (P_{DF}) for additional input.

2. A conductor-to-conductor hot short is an unstable and transient electrical state. Ultimately, the electrical energy (current flow) from the *source conductor* will seek the path of least resistance to the voltage source reference ground. This path may be via ground conductors (conduit, cable tray, wireway, enclosure, etc.) or a common cable conductor associated with the voltage source (i.e., neutral wire). In either case, a *dead short* (no inherent circuit impedance) is created, which will result in a high fault current that actuates an overcurrent protective device (assuming a properly designed circuit). Once the overcurrent protective device operates, power is removed from the source conductor, the hot short terminates, and the circuit assumes a stable state (deenergized). Both the NEI/EPRI and Sandia test data confirm this observation. In no case did a spurious operation (NEI/EPI data) or conductor-to-conductor fault (Sandia IR data) continue indefinitely. Sufficient data was available to statistically quantify the duration of a hot short – see the Duration of Spurious Actuation section below.

3. Cable failure behavior for all types of cables tested was similar. During the first stage of measurable damage, insulation resistance decreased slowly and somewhat predictably, but not to a level that resulted in cable failure or circuit faults. During the next phase, the rate of insulation resistance degradation increases sharply, causing the cable to fail in a short period of time. During this final failure phase, the insulation typically dropped for several thousand kilo-ohms to a few ohms. The rates of failure differed between thermoset and theroplastic insulated cables. Thermoplastic cables generally went through this transition in a matter of seconds. The transition for thermoset cables was much slower, and sometimes took a few minutes. The most important aspect of this observation is that the resistance value used to define “cable failure” has very little overall impact on the probability of a spurious actuation. The data showed that once a cable was driven to the failure point, it ultimately failed with very low impedance. There is apparently no middle ground – the cable is either functional or it is not.

   Note: Fred proposed using 1,000 ohms as the threshold for failure. I agree with this value. However, to be conservative I considered 2,000 ohms as the failure threshold in reviewing the test data. Any value between about 10,000 ohms and 100 ohms yields the same answers.

4. Regardless of the insulation types, fire-induced cable failures have the propensity to develop very low resistance faults. The data did not reveal the existence of a fault resistance threshold attributable to the failure mechanism of the insulating materials.

Probability of Spurious Actuation

In reviewing the test data and reflecting on the inputs and recommendations of the expert panel, I have settled on the following probability factors for inclusion in the overall ΔCDF formula:

P_{SA} = CCF x P_{CC}

P_{DF}

Where:

P_{SA} (Probability of spurious actuation) is the probability of a spurious actuation for a specific circuit given a fire of sufficient intensity to cause cable damage.

P_{CC} (Probability of conductor-to-conductor short) is the probability that a conductor-to-conductor short will occur PRIOR to a short-to-ground or short to a grounded conductor.

CCF (Cable configuration factor) is a factor applied to P_{CC} that accounts for the relative number of source conductors and target conductors. Target conductors are those conductors of a circuit that, if energized by an electrical source of proper magnitude and voltage, will result in spurious actuation of the circuit, component, or device of concern. Source conductors represent energized conductors that are a potential source of electrical energy

P_{DF} (Probability of damage factor) = The probability that a fire of a given intensity (HRR and temperature) will result in cable failure.

Note: It may be more useful to define this factor as the probability that a fire of a given intensity for a given period of time will result in cable failure – discussed in more detail below.

Note: P_{DF} is the "M" term used in previous discussions and documents. I renamed it be more descriptive.

<u>Calculating</u> P_{CC}

P_{CC} is a probability factor that accounts for the likelihood of conductor-to-conductor faults occurring before a conductor-to-ground fault. A conductor-to-ground fault could be a short directly to a grounded surface (e.g., conduit, tray, steel member, etc.) or it could be a short to an intentionally "grounded" conductor (i.e., the neutral or common conductor of a circuit). The predicted outcome is the same in either case. For an energized conductor, fault current will flow, causing a circuit overcurrent protective device (circuit breaker or fuse) to actuate. For a non-energized conductor, the ground fault places the grounded conductor in a benign state since any subsequent fault to an energized conductor will behave as a short-to-ground as described above[1].

[1] This argument is not strictly true for ungrounded systems because earth ground does not provide a free return path for fault current to the reference ground. A dead short (what we are calling a short-to-ground) only happens when an energized conductor of the ungrounded system touches a reference ground conductor for the system.

P_{CC} is calculated as follows:

Cable Tray: $P_{CC} = (TC – GC) / [(TC – CC) + (2 x GC) + 1]$

Conduit[2]: $P_{CC} = (TC – GC) / [(TC – CC) + (2 x GC) + 3]$

Where:

TC = Total number of conductors in the cable of interest

GC = Number of grounded (or common) conductors in the cable of interest

The bases for the P_{CC} formulas are as follows:

1. The probability factor is based on a ratio of grounded and ungrounded conductors. Intuitively, the likelihood of a conductor-to-conductor fault increases as the number of grounded conductors decreases. Conversely, the likelihood of a short-to-ground increases as the proportion of grounded conductors in a cable increases. In electrical terms, the effective ground plane is increased as the proportion of grounded conductors increases.

2. The formulas are based on the number of conductors in an individual cable. In other words, the formulas do not consider inter-cable shorts. My rationale for considering only intra-cable faults in this factor is:

   - The NEI/EPRI and Sandia test data clearly indicate that, for multiconductor cables, intra-cable faults occur before inter-cable faults. This is not to say that inter-cable faults (i.e., cable-to-cable faults) will not occur, only that they will occur after intra-cable faults.
   - The test data also indicates that inter-cable faults are at least an order of magnitude less likely than intra-cable faults. Thus, they have a secondary or tertiary effect at best.
   - Since P_{CC} is a ratio of conductors. It is reasonable to assume that external cables surrounding the cable of interest will have conductor ratios similar to the cable of interest. Hence, even if these cables were specifically accounted for, it is unlikely that the overall ratio would be significantly altered.
   - In practicality, it is not possible to characterize which cables are next to each other throughout a raceway.

3. Grounded conductors are given a weighting factor of two (2). This factor is intended to account for the observed bias that exists for grounded conductors. Energized conductors have a stronger affinity to the grounded conductors because they represent the path of least resistance for the electrical energy as it strives to achieve its most stable state. The factor is not imperially derived; it was chosen based on judgment and because it appears to work with the available data.

[2] Armored and shielded cable should use the equation for conduit. The armor certainly increases the effective ground plane; however, the effect does not appear to be as significant as one might presume. The mylar banding beneath the armor wrap appears to act as an additional barrier against internal conductors touching the shield.

4. Cable trays and conduit represent a ground return path for circuits in which reference ground is tied to earth ground. The formulas treat these short circuit paths as simply additional grounded conductors. The NEI/EPRI data shows that the external ground plane becomes an increasingly insignificant ground path as the number of conductors in a multiconductor cable increases. A conservative factor of one (1) is used for cable tray. The NEI/EPRI and Sandia test data showed a substantially stronger influence of the ground plane for cable in conduit. Thus, a factor of three (3) has been selected for cables in conduit. For ungrounded systems (e.g., typical Class 1E nuclear 125 V safety system) these factors should be omitted from the formulas since the ground plane does not provide a current return path.

5. The formulas are not dependent on the insulating material. The test data reveled distinctive differences in the behavior of the cables based on insulation type; however, none of the observable differences influence this factor.

6. Note that the formulas work for a single conductor, as well multiconductor cable.

Example: P_{CC} for a 7-conductor cable routed in tray with one (1) grounded conductor would be:

$P_{CC} = (7 - 1) / [(7 - 1) + (2 \times 1) + 1]$

$P_{CC} = 6 / 9$

$P_{CC} = 0.667 = 66.7\%$

Table 1 below gives P_{CC} for several different cable configurations and internal ground conductors. This table is intended to give a general "feel" for the values; it is not by any means all-inclusive. As expected, the calculated probability of the first failure being a conductor-to-conductor fault increases with the number of conductors in the cable and decreases as the number of grounded conductors increases.

Table 1
P_{cc} Probability Factors

Cable Parameters		P_{cc}	
Total Conductors (TC)	**Grounded Conductors (GC)**	**Tray**	**Conduit or Armored Cable**
1	0	50%	25%
2	1	25%	17%
3	1	40%	29%
5	1	57%	44%
	2	38%	30%
7	1	67%	55%
	2	50%	42%
8	1	70%	58%
	2	55%	46%
	3	42%	38%
9	1	73%	62%
	2	58%	50%
	3	46%	40%
15	2	72%	65%
	3	63%	57%
	5	48%	44%
21	3	72%	67%
	5	59%	55%
	7	48%	45%

<u>Calculating CCF</u>

Not all conductor-to-conductor faults result in a spurious operation. A conductor-to-conductor fault might cause an indicating light to falsely illuminate, the fault might be to a spare conductor and thus cause no effect, or it might cause the circuit to fail in the desired state. The point is that only a certain combination of conductors has the ability to initiate a spurious actuation. The Cable Configuration Factor (CCF) adjusts P_{CC} to account for the combinations of conductors that have the potential to initiate a spurious actuation.

The conductors of interest for this factor are the source conductors and the target conductors. Recall that source conductors are the conductors expected to be energized at the onset of the event. They possess the electrical energy that has the potential to cause a spurious actuation should one of these conductors make electrical contact with a target conductor. A target conductor is any conductor of the circuit that, if contacted by a source conductor, will transmit the electrical energy to the device or component of concern, causing the component or device to actuate.

CCF is calculated as follows:

Non-armored cable: CFF = {TGC x [SC + (.5 / TC)]} / TC

Armored cable: CFF = (TGC x SC) / TC

CCF ≤ 1.0 If the calculated value of CCF is greater than 1, set CCF = 1

Note: In real applications it is highly unlikely that the calculated value of CCF will ever exceed 1. For this to occur, virtually all conductors in the cable would need to be a source conductor or target conductor.

Where:

SC = Total number of source conductors in cable

TGC = Total number of target conductors in cable

TC = Total number of conductors in the cable

The bases for the CCF formula is as follows:

1. The formulas offer a simplistic means of accounting for differences in the proportion of conductors within a cable that pose a concern, either because they are a source conductor or a target conductor.

2. The term (.5 / TC) in the formula for non-armored cable accounts for external source cables that could initiate a spurious actuation due to inter-cable shorting. Although the NEI/EPRI test data shows that inter-cable shorts do occur, their statistical significance for a spurious actuation appears to decease rapidly as the number of conductors in a cable increases. Thus, this term has been defined such that it has a fairly significant impact for 1-conductor cable, and then deceases in significance as the total number of conductors increases. For armored or shielded cables, it is not considered credible that external source cables could reach a target cable without first grounding to the armor.

3. Several different formulas were tested for correlation with the test data. The formulas presented above appear to work well in the overall P_{SA} equation to predict the number of spurious actuations documented in the NEI/EPRI test data.

Example: CCF for a 7-conductor, non-armored cable with 2 source conductors and 2 target conductors would be:

CCF = {2 x [2 + (.5 / 7)]} / 7

CCF = 0.58 = 59%

Table 2 below gives CCF for several different cable configurations. As before, the table is intended to give a general "feel" for the values and is not all-inclusive. From my experience in fire-related circuit analyses, the number of target conductors in a single cable is most always one. The number of source conductors varies, but it too is generally a low fraction of the overall number of conductors.

Table 2
CCF Adjustment Factors

Cable Parameters			Cable Type	
Total Conductors (TC)	Source Conductors (SC)	Target Conductors (TGC)	Non-Armored	Armored
1	0	1	.50	0
2	1	1	.63	.50
3	1	1	.39	.33
5	1	1	.22	.20
	2	1	.42	.40
7	1	1	.15	.14
	2	1	.30	.29
	2	2	.59	.57
9	1	1	.12	.11
	2	1	.23	.22
	3	1	.34	.33
	2	2	.46	.44

<u>Calculating P_{SA}</u>

Recall the formula for calculating P_{SA}:

$$P_{SA} = CCF \times P_{CC}$$

With CCF and P_{CC} determined using the formulas discussed above, calculating P_{SA} is straightforward. The obvious question at this point is how well does the formula predict the test data.

For the 7-conductor cable there were 31 out of 80 possible spurious actuations for those tests in which cable damage occurred. This yields an experimental probability of spurious action of 38.8%, given cable damage. Using the equations derived above:

$$P_{SA} = CCF \times P_{CC} = .59 \times .67 = 39.5\ \%$$

The predicted value of P_{SA} appears to match well with the experimental results.

For the 1-conductor cable there were 11 out of 44 possible spurious actuations for those tests in which cable damage occurred. This yields an experimental probability of spurious action of 25%, given cable damage. Using the equations derived above:

$$P_{SA} = CCF \times P_{CC} = .5 \times .5 = 25\%$$

The predicted value of P_{SA} again matches well with the experimental results.

Now for a real world case…the 7-conductor test circuit is a good representation for an MOV circuit. However, in practice spurious actuation of the MOV in only one direction is of concern. Thus, only one target cable would exist. On this basis, the probability of a spurious actuation of an MOV given fire damage to the MOV's control cable is:

Tray: $P_{SA} = CCF \times P_{CC} = .3 \times .67 = 20\%$

Conduit: $P_{SA} = CCF \times P_{CC} = .3 \times .55 = 16.5\%$

In developing the equations, I have obviously been mindful to ensure they predict well the experimental values. Nonetheless; the equations appear to work within reason. The weakness with these equations, as well as any other approach used to predict P_{SA} is that the test data covers only a limited number of cases and configurations. Thus, we inevitably make assumptions in extrapolating the results to cases not tested.

It is important to note that the probability of spurious actuation calculated here does not consider any factors associated with timing or the likelihood of a fire causing cable damage (P_{DF})

Probability of Cable Damage (P_{DF})

Fire damage modeling is not an area in which I have much expertise. So I do not plan on providing detailed information for this factor. This said, I do believe this is one of the most important factors in the overall equation. The test data clearly shows that fire intensity and time are key factors in determining if and when cable damage will occur. The importance is obvious – no cable damage, no spurious actuation.

My vision of this factor is that a cumulative distribution function can be derived from the data such that P_{DF} is essentially zero at some finite temperature below which no damage is expected and is equal to one at some upper temperature, where damage is virtually assured.

The cable damage distribution function could then be matrixed with another distribution function that accounts for exposure duration. Exposure to a high intensity fire for a minute or two is certainly not the same as exposure for 10-20 minutes. Here again it seems that a cumulative distribution function could be developed for the test data.

Ultimately these distribution functions could be used to populate tables with axes of time and temperature. I would anticipate that different tables would be developed for the different insulation materials because of the differences in their resiliency to fire damage.

Duration of Spurious Actuation

As discussed in the General Observations section, conductor-to-conductor hot shorts are a transient phenomena. The NEI/EPRI and Sandia test results show that cable failures ultimately degrade to a ground fault, which in a real circuit will cause a protective device to actuate. An analysis of NEI/EPRI test data provides the following statistical distribution for the expected duration of a spurious actuation.

Median	0.7
Mean	1.59
Standard Deviation	2.255
2 sigma	4.51
3 sigma	6.77

This data is not normally distributed and almost takes on the appearance of a bi-model distribution. Given this, care should be exercised in applying the statistics.

Appendix A to Daniel Funk's Report

Definitions – Fire-Related Circuit Analysis

Failure (cable): A cable that is unable to perform its required function. *{Differs only from Steve's definition by the term required instead of design}*

For the purpose of fire-related circuit analysis, the following fault resistance values are proposed to establish a specification limit defining "compete cable failure":

Circuit Type	Failure Threshold (Ohms)	Basis
Power	2,000 Ohms (Complete Failure)	2,000 Ohms corresponds to a leakage current of 0.24 A at 480 V. This amount of leakage current into or out of a 480 V power circuit is not expected to cause failures.
Control	2,000 Ohms (Complete Failure)	2,000 Ohms corresponds to a leakage current of 60 mA at 120 V. 60 mA at 120 V is not sufficient to actuate 120 V control devices, based on a review of industry literature.
Instrument	25,000 Ohms (Partial Failure)	30,000 Ohms corresponds to a 5% signal error in a standard 4-20 mA instrument loop. Partial cable failure is considered for instrument circuits because the circuit may continue to function by provide erroneous readings.

It is emphasized in presenting these cable failure resistances that cable failure is high insensitive to the actual value used. The test data repeatedly demonstrated that once a cable has undergone sever degradation, its insulation resistance (IR) value changed from Mega-ohms or Kilo-ohms to 100 Ohms or less in a very short period of time. The IR values did not "hang" in the nebulous zone of failure-none failure.

Failure, complete: Failure resulting from deviations in characteristic beyond specified limits such as to cause complete lack of the required function.

Failure, partial: Failure resulting from deviations in characteristic beyond specified limits, but not such as to cause complete lack of the required function.

Degradation: Failure that is both gradual and partial. In time may result in complete failure.

Fault (wire and cable): A *partial* or *complete* local failure in the insulation or continuity of a conductor. A cable fault is a physical event that results in partial or complete cable failure. *{I realize this term is potentially confused with the term Circuit Fault, as defined by Nowlen's* *paper. However, this term is entrenched in the vocabulary of anyone working in the electrical analysis area and thus cannot be ignored.}*

Fault (circuit or component): A physical condition that causes a circuit, component, or device to fail to perform in a required manner. A faulted circuit will perform in an imperfect or impaired manner. For the purposes of fire-related circuit analysis, a circuit fault is presumed to be caused by a cable failure. Circuit fault modes include, but are not limited to total loss of function, partial loss of function, loss of indication, undesired actuation (i.e., spurious operation), and degraded indication.

Spurious actuation: A circuit fault mode in which a component or device of the affected circuit becomes energized as a result of a hot short.

Ground fault: see Short-to-ground

Line fault: see Conductor-to-conductor short

Cable Failure Modes (Primary): Open Circuit and Short Circuit

Open circuit (general): A loss of electrical continuity in a an electrical circuit, either intentional or unintentional.

Short circuit (general): An abnormal connection (including an arc) of relatively low impedance between two points of different potential.

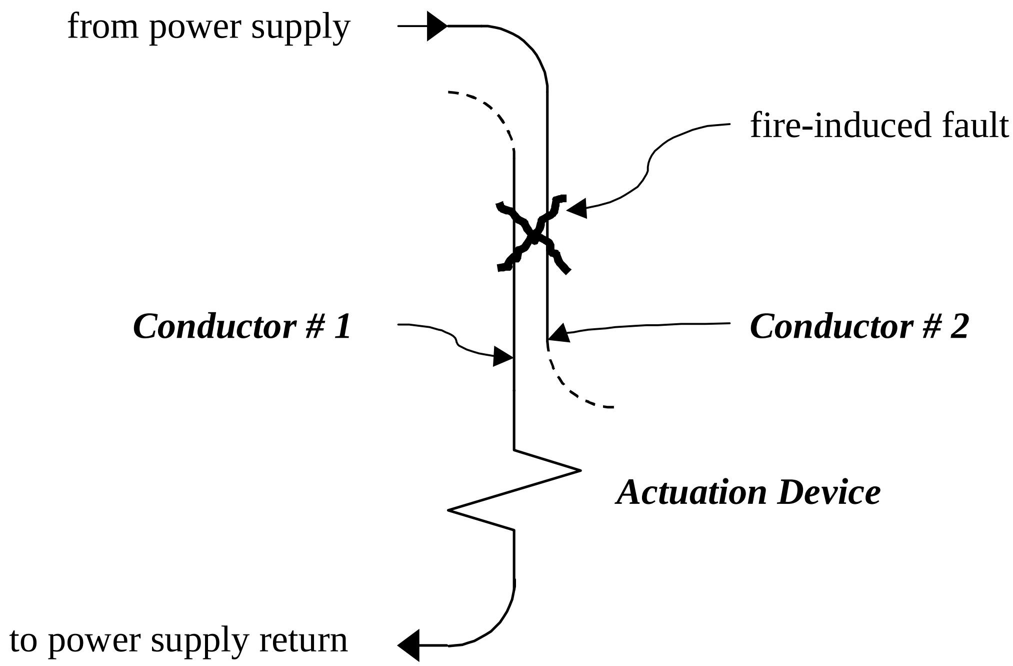
Short circuit (specific):

- Short-to-ground: An abnormal connection between a conductor and a grounded conducting medium. The grounding medium refers to any conduction path associated with the reference ground of circuit. This might include structural elements (tray, conduit, enclosures, metal beams, etc) or intentionally grounded conductors of the circuit (neutral conductor). Components connected to earth ground are only considered to be a grounded medium for systems with reference ground tied to earth ground. A short-to-ground (ground fault) is characterized by abnormal current flow (fault current) attributable to the lack of any significant circuit burden (i.e., load).
- Conductor-to-conductor short: An abnormal connection between conductors not involving a coincident short to ground (including grounded neutral conductors). Conductor-to-conductor shorts may or may not involve an energized conductor.
- Hot short: A conductor-to-conductor short in which one or more of the conductors is energized at the time of the short. A hot short has the ability to cause an undesired actuation of equipment.

Appendix B-2 Report of Harvey Leake

Evaluation of Fire-Induced Spurious Actuation Probability
Harvey Leake
Palo Verde Nuclear Generating Station
September 5, 2001

The fire-induced spurious actuation scenario is shown below. A fire damages the cable insulating materials associated with *Conductors #1* and *#2*, creating a circuit path (“hot short”) between them and inadvertent energization of the *Actuation Device*.



Spurious Actuation Scenario

<u>Probability Formula</u>

NEI 00-01 defines the change in core damage frequency per reactor-year as a result of spurious actuations as:

$$\Delta CDF = F_f \times P_E \times P_{SA} \times P_{AS} \times P_{DM} \times \Delta P_{CCD}$$

F_f = Fire frequency. Frequency of fires of any size anywhere within the fire area

P_E = Fire size parameter; fraction of fires in the area capable of reaching damaging combinations of time and temperature

P_{SA} = Probability of spurious actuations of a component/combination given cable damage

P_{AS} = Probability that automatic suppression will fail to control the fire

P_{DM} = Probability that detection and manual suppression will fail to control the fire

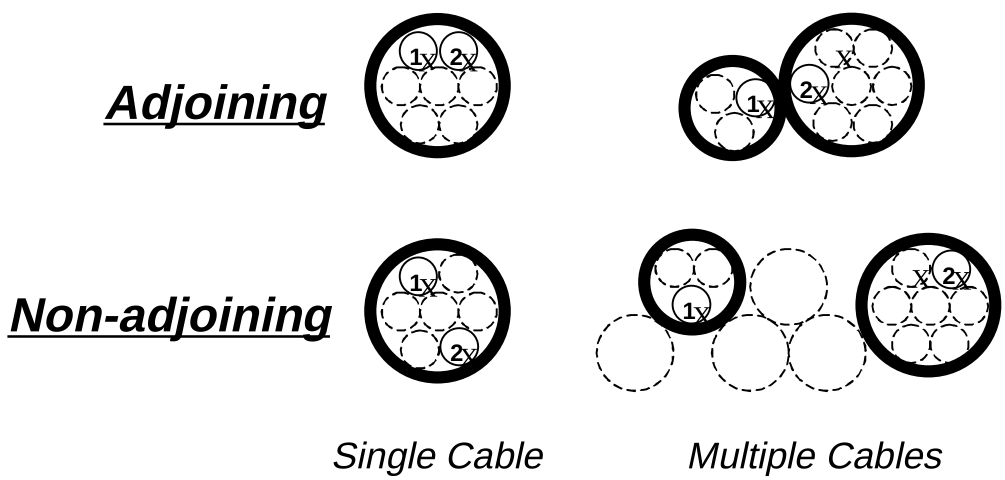
P_{CCD} = Conditional probability of core damage given fire-induced failures including spurious actuations of a component/combination

P_{SA} can be further broken down as follows:

$$P_{SA} = \sum_{Paths} P_{Adj} \times P_{Flt} \times P_{Energ}$$

Σ_{Paths} = Sum of probabilities for all possible circuit paths within the damaged cables (i.e., all *Conductor #1* and *Conductor #2* combinations) that could cause spurious actuation due to faulting. How many such paths are present is a plant-specific question that is determined through a circuit review.

P_{Adj} = Probability that *Conductor #1* and *Conductor #2* adjoin one other within the zone of cable damage. This is a a plant-specific question that is determined through a review of the particular routing conditions of the two conductors. If they are within the same cable, they could either be adjoining or separated by one or more other conductors, as shown below. If they are in different cables, they adjoin if: (1) their respective cables adjoin, and (2) they are positioned within their cables such that they could short together following deterioration of the intervening insulating material.



Since the exact routing of individual cables within a raceway is generally not known, statistical methods may be needed to determine P_{Adj}.

P_{Flt} = Probability that the fire will cause deterioration of the insulating material between *Conductor #1* and *Conductor #2* to the extent that significant fault current could flow. Results of fire testing can be used to establish this value. Modifiers are needed to address variables that affect the probability of such faulting. For example, P_{Flt} is higher for two adjoining conductors in the same cable than it is for two adjoining conductors in different cables due to the additional layers of intervening insulating materials in the latter case.

P_{Energ} = Probability that sufficient energy will be available to actuate the *Actuation Device* following faulting of *Conductor #1* and *Conductor #2*. Spurious actuation will not occur if the power supply is *off*, the upstream protective device has tripped due to a prior or simultaneous fault, or the available voltage is below the *Actuation Device* pickup requirement. The probability that the circuit would be *off*, the number of circuit paths whose faulting could lead to tripping, and voltage and impedance characteristics of the circuit are plant-specific values that are determined through circuit reviews.

<u>Assessment of Available Test Results</u>

Of the parameters discussed above, only P_{Flt} can be derived from the fire testing results. The others are functions of specific plant design characteristics.

Based on available test data, P_{Flt} is significantly less than 1, but significantly greater than 0—perhaps in the range of 1E-1 to 1E-2. Further quantification, with consideration for the effects of various influencing conditions, would require a detailed review of the physical effects of the fires on the test cables, and may require a larger test sample.

Even if a P_{Flt} is assumed to be 1, however, the Δ_{CDF} might still be below the established threshold of concern due to the low net probability of the other factors.

<u>**Note:**</u>

The credibility of a cable-to-cable hot short is not just a spurious actuation question. For example, if credible, a short between a larger supply conductor and a smaller return conductor could result in sustained fault current below the protective device setting of the large conductor but above the safe operating current of the small conductor. This could cause combustion of the latter within other fire zones—a secondary fire issue.

Appendix B-3 Report of Frederick W. Mowrer

NEI/EPRI Expert Elicitation Panel Report
prepared by:
Frederick W. Mowrer, Ph.D., P.E.

Introduction

NEI and EPRI sponsored a series of 18 cable fire tests that were conducted within a 10 ft. by 10 ft. by 8 ft. high steel enclosure with a single natural ventilation opening in one wall. The cable tests took place at Omega Point Laboratories, located in Elmendorf, Texas, during the weeks of January 8 – 12, January 22 – 25, April 2 – 6, with the final two tests conducted on May 31 and June 1, 2001. The purpose of the fire tests was to evaluate the effects of fire conditions on circuit integrity and the potential for fire-induced spurious or inadvertent activation of circuits.

A number of parameters were varied during the fire tests, including:

- The types of electrical cables, including armored, thermoset and thermoplastic;
- The number of conductors within a cable, including 7/c, 5/c, 3/c and 1/c;
- The functions of electrical cables, including instrumentation and control;
- The voltage applied to electrical cables, including 120 VAC, 100 VDC, 24 VDC;
- The placement of cables within a cable tray or conduit;
- The fill level of cables within a cable tray and the locations of cables within the fill;
- The orientation of cables, including vertical and horizontal;
- The intensity of the fire source, including 70, 145, 150, 200 and 350 kW fires;
- The location of the cables relative to the fire, including plume, hot gas layer and radiant exposures;
- The elevation of the horizontal cable tray, including 5 ft. 6 ft. and 7 ft. above floor level
- The height of the wall ventilation opening, including 2 ft., 3 ft. and 5 ft. high openings.

In view of the limited numbers of tests conducted and large number of parameters varied, few of the fire tests represented duplicates of each other.

Approximately 100 thermocouples were used to measure temperatures at a number of locations within the test enclosure. Most of the thermocouples measured temperatures within the cable bundles or along the cable tray. Two thermocouple trees, identified as the east tree and the west tree, were used to measure the vertical temperature distribution of the atmosphere within the enclosure.

In addition to the temperature measurements, a number of electrical circuits were monitored for circuit integrity for some of the cables within a cable tray. NEI/EPRI typically monitored up to four different device actuation (DA) circuits, while SNL typically monitored one or two cables for insulation resistance (IR).

The purpose of this report is to present the opinions I have developed based on a review of the fire test data. These opinions are offered as part of an expert elicitation panel being chaired by Robert Budnitz of Future Resources Associates, Inc., in Berkeley, California. In light of the number of fire tests conducted, the large number of parameters involved and the quantity of data generated, these opinions should be considered as preliminary. Further, more detailed analysis of the data would be likely to result in further insights.

Report organization

After extensive review of the available data and constant flipping back and forth between various reports and data files, I decided to present the results and data for each test sequentially according to test number. While this makes for a bulky report that duplicates information available in a variety of other sources, it permits more convenient consideration of the results of each test.

Summary of opinions

Detailed observations are provided in the following section, which contains discussion of each test individually. Here, a summary of the opinions I have developed based on my review are provided:

- Thermoplastic cable is more likely to degrade to the point of allowing leakage currents large enough to cause device actuations or blown fuses than either armored cable or thermoset cable for the same exposure conditions.
- Smaller cables are more likely to be damaged, and to be damaged earlier, than larger cables of similar construction for the same exposure conditions. This is due to lower thermal capacity of the smaller cable.
- Cable trays with less fill, i.e., fewer layers, are more likely to be damaged for a given exposure condition than cable trays with more fill. This is due to lower thermal capacity of the lesser fill.
- Cables located in conduit are more likely to be damaged for a given exposure condition than cables located in cable trays with multiple layers of fill. This is due to the lower thermal capacity of the cables in the conduit.
- The location of a cable within a cable bundle has a significant influence on the potential for damage as well as the time to damage. Cables located along the bottom layer of fill are more likely to be damaged in fire plume scenarios, while cables located in the top layer of fill are more likely to be damage in hot gas layer scenarios. Cables located in middle layers are least likely to be damaged for either scenario.
- It is very difficult to determine a specific “damage temperature” or even a fairly narrow range of damage temperatures for different types of cable based on these fire tests. This is because failures occurred at a range of temperatures and the cables were undergoing transient heating when they failed.

- Water spray on damaged cables can cause spurious activation of circuits to occur.
- For the range of exposure conditions considered in this test series, the influence of cable ignition on the potential for spurious activation was not evaluated.

Individual test reviews

The remainder of this report contains diagrams, descriptions, results and data for each of the 18 cable fire tests, in sequence. **[It consists of 114 pages and is not reproduced here.]**

(Supplement 1)
NEI/EPRI Expert Elicitation Panel Report

prepared by:
Frederick W. Mowrer, Ph.D., P.E.
25 October 2001

In the report submitted previously, much of the data from the 18 NEI/EPRI tests was consolidated to make analysis of the data easier. A number of data charts were inserted into the previous report to permit visual identification of the types and magnitudes of electrical activity induced by the fire conditions in the cable trays. While this report would permit readers to draw their own conclusions regarding the likelihood of circuit activity for a given test, estimates for spurious circuit activation frequencies were not provided. These estimates are needed by the expert elicitation panel coordinator to summarize the opinions of the experts. This supplemental report provides these estimates, based on my review of data and test reports provided to me.

To develop these estimates, I have attempted to identify the maximum cable temperatures at the times of significant electrical activity. I have used the maximum cable temperatures rather than the average temperatures because I believe these would be more representative of the temperatures at the locations of cable insulation failure. In some cases it is difficult to determine the exact measured temperature at the time of electrical activity, so I have rounded the temperatures to the nearest 10 °F.

In some cases, high voltages resulted from the breakdown in cable insulation. These cases were considered to be complete failures. In other cases, only small voltage changes occurred. I considered these to be "incipient failures" and indicative that a cable might have failed under slightly different conditions. Temperatures associated with "incipient failures" were documented. For cases where no electrical activity was observed, the maximum cable temperature was noted. A summary of these data interpretations is provided in Table 1 below.

Based on my analysis of this data, I offer the following supplemental opinions to those offered in the previous report:

- The most significant variables influencing the potential for damage appear to be the cable construction and the cable temperature. The thermoplastic cables used in this test series failed at a much lower temperature than either the thermoset or armored cables. Based on the data, the following estimates for the potential for cable damage leading to electrical activity are provided:

	Thermoplastic	Thermoset	Armored
Minimum failure temperature (°F)	400	680	570
Mean failure temperature (°F)	450	800	750
Maximum failure temperature (°F)	800	1200	830

- I am not able to provide an estimate of the likelihood of spurious activation, given electrical activity. This will depend on the nature of the circuit and on the likelihood of circuit breaker activation. I expect this likelihood to be some fraction of the likelihood of electrical activity, but I cannot provide an estimate of what this fraction might be.
- I am not able to provide quantitative estimates of the impact of other influence factors on these estimates. Wyant and Nowlen discuss a number of these factors in the Conclusions section of their draft report "Cable Insulation Resistance Measurements Made During the EPRI-NEI Cable Fire Tests." Based on my review of the data, these other influence factors are relatively weak in comparison with the influence of the cable construction and the exposure conditions.

In summary, it appears to me that these test results are consistent, to a large extent, with previous work on cable damageability, particularly the oven aging tests conducted at SNL years ago. By this, I mean that it appears that 400°F is the approximate degradation temperature of the thermoplastic cable used in these experiments and 700°F is the approximate degradation temperature of the thermoset cable used in these experiments. Beyond these degradation temperatures, the potential for the loss of insulation resistance and consequent electrical activity is likely to depend on a number of factors that are difficult to characterize based on the 18 tests conducted for this project.

Table 1
Summary of approximate failure temperatures discerned from test data and reports.

							Approx. max. temp. at failure (deg-F)				IR results
Test No.	**Cable type**	**Location**	**Fill layers**	**HRR (kW)**	**Tray hgt**	**Door hgt**	**DA1**	**DA2**	**DA3**	**DA4**	
1	AC	HGL	2	350	6	5	570	700	700	580	NF (680)
2	TS	Plume	2	70	5	2	680	NF (690)	NF (510)	NF (580)	NF (570)
3	TS	Plume	2	145	6	2	780	680	NF (870)*	NF (760)	700
4	TP	Plume	2	145	7	2	NF (750)	400	520	540	420
5	TS	HGL	2	200	7	2	NF (590)	NF (650)	NF (550)	NF (620)	NF (625)
6	TP	HGL	2	200	7	3	470	500	NF (718)	NA	450
7	TS	HGL	2	350	6	5	NF (890)	IF (790)	740	IF (800)	800
8	TS	Plume	3	145	6	2	770	NF (750)	IF (690)	NF (570)	790
9	TS	Plume	1	145	6	2	750	IF (950)	920	IF (1000)	1025
10	TS	Vertical	1	200	2	2-3	Bad data	NF (1180)	IF (970)	NF (950)	IF (1100)
11	TS	Plume	4	145	6	2	NF (570)	NF (660)	NF (630)	NF (740)	NF (750)
12	TS	Plume	1	145	6	2	NF (680)	IF (810)	IF (700)	NF (890)	800
13	AC	HGL	2	350	6	5	IF (730)	IF (760)	IF (830)	IF (710)	800
14	TS	Plume	3 pyramid	145/150	6	2	Current on unpowered conductor test				
15	TS	Plume	15	350/200/450	6	5	Bad data	990	IF (840)	IF (920)	800
16	TP	Plume	2	145	6	2	NF (1040)	NF (830)	460	NF (530)	400
17	TS / TP	Vertical	1	200	3	2	480	NF (770)	NF (640)	NF (770)	400
18	TS	HGL	3 pyramid	250	7	4	Current on unpowered conductor test				

NF(xxx) - no failure (maximum temperature)

IF (xxx) - incipient failure (temperature at incipient failure)

* failure during water spray

Appendix B-4 Report of Steven P. Nowlen

Fire-Induced Cable Failure Spurious
Actuation Likelihood Estimates
Input to the EPRI/NEI Expert Panel On Spurious Actuation

Steve Nowlen
Sandia National Laboratories
Revision 0

Problem Statement

The question originally posed to the expert panel was (paraphrased) "what is the likelihood of spurious circuit actuation given certain fire exposure environments characterized by time-at-temperature profiles for electrical control cables." I have argued that this question is virtually unanswerable as posed because it mixes in too many behaviors relating to the cable type and material properties as well as the fire environment itself (see Attachment 1). An answer would require consideration of each specific cable insulation material and it's specific thermal damage limits and all of the associated cable damage literature, an effort outside the stated scope of the panel. I have chosen to express my opinions using the alternate formulation; namely, "what is the likelihood of spurious circuit actuation given a fire-induced cable failure."

Given this alternate formulation, we have largely eliminated the fire exposure problem from the formulation. Features of the fire exposure may influence the failure mode, but my current opinion based on the available evidence is that fire exposure effects are, for the most part,[3] of second order. Nonetheless, the question still covers a wide range of phenomenological territory. In particular, the question still covers factors relating to cable construction, cable routing, and circuit configuration. These factors must also be considered in answering the question. Even under the alternate formulation, this is not a "one size fits all" issue. The likelihood of spurious operation given cable failure must be tailored to account for these critical factors.

Bounding the Problem

In formulating my response, I have limited my consideration to spurious actuations arising from fire-induced failures involving control cables. I am excluding consideration of instrument circuit failures that might cause a spurious actuation (e.g., through a false permissive signal). The potential for such events has not been investigated and no reasonable answer to this question is currently possible in my view. I am also excluding consideration of "smart shorts" between power cables leading to spurious actuation. This configuration has also not been explored and cannot be answered with any confidence.

[3] One exception may be highly intense exposures versus more moderate exposures. In particular, direct exposure to a high temperature flame may not yield the same behaviors as more moderate exposures such as plume and hot gas layer conditions.

Terminology

I want to define certain terms I will use in presenting my responses in order to avoid confusion:

Cable Failure: A breakdown in the electrical insulation of the conductor(s) in a cable such that the cable is no longer able to maintain the electrical integrity of the associated circuit sufficient to ensure proper operation of the circuit. The specific criterion for cable failure (e.g., minimum insulation resistance) is established in the context of the circuit under consideration.

Conductor-to-Conductor Short Circuit: A cable failure mode where two or more electrical conductors experience a low-impedance electrical contact that does not involve an external ground (e.g., the raceway). Note that a conductor-to-conductor failure is totally general regarding the nature of the conductors which short together. The conductors may be of the same multi-conductor cable (an Intra-Cable Conductor-to-Conductor Short Circuit) or of two or more separate cables (an Inter-Cable Conductor-to-Conductor Short Circuit).

Hot Short: A specific subset of conductor-to-conductor shorts where at least one conductor is energized and at least one conductor is neither energized nor grounded. That is, a hot short implies that one or more non-energized, non-grounded conductors becomes energized due to cable failure.

Primary Cable: The cable that is under analysis as a potential fire-induced failure target and as the target which might cause a spurious circuit actuation.

Secondary Cables: Other cables co-located with the primary cable in a common raceway. Secondary cables are of interest primarily because they might provide a source for intra-cable hot shorting behavior impacting the primary cable.

Source Cable or Source Conductor: A cable or conductor that is energized on an electrical bus and is therefore capable of powering a spurious actuation should it come into contact with the target conductor.

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

Target Cable or Target Conductor: A cable or conductor that is not energize, but that if energized by contact with an appropriate source cable or source conductor, would lead to a spurious actuation of the circuit.

Problem Structure

In my efforts, I chose to divide the problem (as posed in the "alternate formulation" discussed above) into three major parts. First is the physical or root behavior of the cable upon failure. Second is the electrical configuration of the cables, both the primary cable and those secondary cables surrounding the primary cable in the same raceway. Third is the behavior of the circuit given the behavior of the cable. These three parts of the problem are discussed separately below.

Root Cable Failure Behavior

With regard to the root behavior of the cable on failure, the sub-question I posed to myself is: given that the cable fails, what is the likelihood that the failure mode will be one that might lead to a spurious actuation? This part of the problem deals only with the physical behavior of conductor's on failure, that is, conductors coming into contact with each other and/or an external ground. There is no consideration at this stage of any aspect of the associated circuit or electrical configuration. In many regards, I consider this part of the problem to be the most certain and well characterized. It is in this area that we have the greatest store of data.

Nonetheless, many short circuit configurations are possible and uncertainty remains. Only a subset of the possible cable failure mode configurations have the potential to cause spurious operations even putting electrical/circuit issues aside for the moment. In particular, I will assume that only conductor-to-conductor shorts might lead to spurious operation.[4] Spurious actuations may result from either intra- or inter-cable conductor-to-conductor shorts. I will treat these cases independently as the likelihood appears substantially different.

Note here that I am specifically excluding consideration of multiple shorts to ground for an ungrounded circuit causing spurious operation. This mode may be of interest, in particular, for ungrounded DC control circuits. We have no direct evidence to characterize this problem. I have not considered this scenario explicitly, and my input is not intended to cover this particular case.

In general, the evidence regarding intra-cable conductor-to-conductor shorting is strong. The data review documented in our circuit analysis report of June 2000 (provided to all panel participants) and the EPRI/NEI tests (including the SNL/NRC IR measurements) support my conclusions in this regard. I conclude that the likelihood of conductor-to-conductor shorts given failure of a multi-conductor cable is high. For cables in trays, the likelihood is on the order of 70-80%. The likelihood may approach unity for some configurations (e.g., a air drop cable where the fire is well below the upper physical support point). For cables in conduits, the probability appears lower, although evidence remains weak. I will assume a conductor-to-conductor short probability of on the order of 20-30% for this configuration based on the limited evidence available. Armored cables appear to have similar features to conduits.

The likelihood of inter-cable conductor-to-conductor shorts appears to be substantially lower for all configurations, although the evidence for these cases is not nearly as strong. Our earlier review (see the circuit analysis report) revealed little data on inter-cable shorting. While the NEI/EPRI tests provided some new data, the cable bundling used - three single-conductor cables bundled using tape to one multi-conductor cable - put the cables into far more intimate contact than would be expected in a normal installation (Test 14 being the single exception). This configuration would over-estimate the inter-cable interaction potential, but by how much is

[4] I will later refine this to an assumption that a hot short is required to cause the spurious operation. However, hot short implies that particular conductor-to-conductor shorts occur, and this takes us to the second aspect of the problem, cable electrical configuration, which I discuss separately below.

unclear. Hence, I put relatively little stock in the inter-cable behaviors observed in the NEI tests beyond demonstrating that under some circumstance at least, inter-cable shorts can lead to spurious operation.

I will assume that the likelihood of inter-cable conductor-to-conductor shorts for general cables is on the order of 20% or less. Indeed, for some configurations I consider the likelihood to be far less than 0.2. For example, for cables in cable trays, those cables located on the bottom of the tray likely have a much higher likelihood of shorts to ground. However, since we will rarely know exactly where a cable might be located, and because the current evidence for this remains weak, I cannot separate this effect out based on our existing data. Rather, I will include this in my uncertainty. For cables in conduits, the evidence is again weak. I will assume a somewhat lower value for conduits versus trays, namely, 10% or less.[5] I consider inter-cable conductor-to-conductor shorts to be virtually impossible for armored cables, for cables in separate cable trays, and cables in separate conduits. This assumes that the armor or raceway will be grounded so that conductors would have to first short to ground before cables could short to each other for these configurations. (Recall that I am not explicitly considering multiple shorts to ground.)

My conclusions on cable failure mode likelihood for this part of the problem are summarized in Table 1. The values represent the likelihood of conductor-to-conductor short circuits for three configurations (trays, conduits, and armored cables) and considering intra- and inter-cable short circuits separately. I have includes a qualitative indication of my confidence in these values (High, Medium, or Low).

Table 1
Likelihood of conductor-to-conductor shorts in cables based on routing, intra- versus inter-cable, and armored versus non-armored

Case	Confidence Level	Likelihood
Intra-cable shorting for non-armored cables in trays	High	0.7-0.8
Inter-cable shorting for non-armored cables in trays	Medium	≤0.2
Intra-cable shorting for non-armored cables in conduit	Medium	0.2-0.3
Inter-cable shorting for non-armored cables in conduit	Low	≤0.1
Intra-cable shorting for armored cables (not dependant on routing)	Medium	0.2-0.3
Inter-cable shorting for armored cables or cables in separate raceways	High	0.0

[5] I presume that the cables are co-located in the same conduit.

Cable Electrical Configuration

The second aspect of cable behavior to be considered is the fact that only certain conductor-to-conductor shorts will lead to a spurious operation. In particular, I am assuming that a hot short configuration is needed, and the hot short must impact a conductor or conductors that can cause operation of the circuit. This aspect substantially complicates the problem. The likelihood of getting an actuating hot short depends on several factors. In my view, this aspect of the question is one of two major sources of uncertainty in the overall problem (the second is discussed below and relates to the circuit itself). Furthermore, it is my view that the uncertainty associated with this aspect of the question is quite high.

The expert panel was formulated without specific cable configurations being posed. Unanswered questions include: how many conductors are present in the primary cable; how are those conductors at least nominally connected to the circuit (e.g., is there a grounded conductor present?); how many secondary cables are present and what is their configuration; and what types of interactions are required to cause spurious actuation? The answers one assumes for these questions are critical to the overall answer of spurious actuation likelihood. This is by no means a "one size fits all" question as I noted above. I will parse my opinions along certain lines in an attempt to address such questions. However, even so, my final answers will reflect this view and will be cited as containing considerable uncertainty, much deriving from this aspect of the problem.

As noted above, intra-cable conductor-to-conductor shorts appear more likely than inter-cable conductor-to-conductor shorts. For the intra-cable case, spurious actuation requires a hot short involving the proper energizing source and proper target (or actuating) conductors. Other conductors in the cable may or may not mitigate the actuation if they also become involved in the short circuit. For example, the presence of a grounded conductor might cause the control power to open circuit should it be involved in a short to the energizing source. A cable which lacks an explicit ground conductor should be far more susceptible to spurious actuation as this will remove a significant potential mitigating behavior.

For the inter-cable case, similar requirements regarding the nature of the shorts needed to cause a spurious actuation come into play. However, an additional constraint is that a nearby or adjacent cable must include a conductor energized by an appropriate electrical source, and this conductor must short to the target actuation conductor before shorting to a ground point.

The relative role of intra- versus inter-cable shorting in spurious actuation behavior seems virtually impossible to quantify given current knowledge. Nominally, one can assume that the intra-cable shorts will dominate the overall likelihood if such shorts can lead to spurious actuation. However, the likelihood of inter-cable shorts causing actuation may also be non-trivial particularly for configurations where intra-cable shorts cannot lead to spurious actuation (i.e., the correct combination of conductors is not present in a single cable). I have formulated my response based on the following assumptions regarding intra- versus inter-cable shorting:

- If the proper combination of conductors is present in a single cable such that spurious actuation is possible, then intra-cable hot shorts will dominate the overall likelihood of spurious actuation. For this case, I consider the intra-cable shorting behavior only and assume the additional contribution from inter-cable shorts will be a second order effect at most.
- If the proper combination of conductors is not present in a single cable (i.e., all intra-cable shorting combinations are shown not to cause spurious operation), then only inter-cable interactions might cause spurious actuation.. If the required sources are or may be present in the same raceway as the primary target cable, then consideration is given to inter-cable shorts. This is quantified as a separate case.
- If an inter-cable short is required for actuation, and if the lack of appropriate energizing sources in the same raceway can be demonstrated, then spurious actuation is not possible. For this case, I perform no analysis - this is the equivalent of a case screened from my response.

Hence, my final estimates of the spurious actuation likelihood values will distinguish between two cases: cases where intra-cable shorts might cause actuation; and cases where intra-cable shorts cannot cause actuation but inter-cable shorts may. Due to the high uncertainty associated with this aspect of the question, I will not estimate the individual likelihood values for these cases, but rather, will fold these considerations into my final spurious actuation likelihood estimates.

Circuit Configuration

The third part of the problem is consideration of the circuit itself. The expert panel was formulated without any specific circuit configurations being put forward beyond the surrogate MOV circuits tested by NEI/EPRI. Many factors relating to the circuit under analysis may impact the likelihood of spurious actuation. This is the second area that I feel contributes to substantial uncertainty. Unfortunately, while I understand basic electrical control circuits, I cannot claim extensive expertise in these systems. I cannot, for example, clearly characterize what is truly representative and what is the range of control configurations out there. This has made this particular aspect of the problem very difficult for me to address.

We have tested very few circuit configurations in actual practice. We are primarily dependant on the NEI/EPRI tests here. NEI/EPRI focussed on a surrogate MOV circuit that was tested in at least three configurations (without CPTs, with CPTs, and without CPTs or fuses). However, it is not clear to me how far we should take any one of the NEI/EPRI circuit configurations as being representative of NPP control circuits in general. Circuit design factors of importance include:

- Use (or lack) of control power transformers (CPTs): The NEI/EPRI tests demonstrated a clear impact due to the addition of control power transformers during the last phases of testing.
- Latching circuits: It is not clear how common these are, but a latching circuit would require only a momentary hot short to lock in an actuation.
- Ungrounded DC circuits versus grounded AC circuits: We know little about DC circuit response having tested only an AC circuit in the NEI/EPRI tests.

- System response time: Relates to how long a short must be maintained to cause a circuit actuation.
- Pick-up and drop-out current and voltage levels: These factors will influence the "quality" of the shorts required to actuate a circuit.
- Fuse ratings (e.g., relative to pick-up currents): The margin between current required to actuate the circuit and that required to blow the fuse may be very important.
- Non-MOV control circuits versus the tested MOV circuit: For example, do general motor/pump, breaker, and switchgear control circuits look anything like the tested MOV circuit?
- Double-break versus single-break control configurations: Double break configurations should substantially reduce spurious actuation likelihood.

I am at rather a loss as to how to characterize these factors in terms of the overall likelihood of spurious operation. We have been given virtually no information regarding these factors (beyond a description of the NEI circuits) upon which to base our assessments. I am forced to parse the problem based on the above factors, and yet I still consider the level of uncertainty to be very high. Again, I will not attempt to break out likelihoods for this aspect of the problem, but rather, will fold this into my overall estimates of spurious actuation likelihood.

Analysis of the NEI Circuit Actuation Test Data

Overall, the NEI/EPRI tests were a key factor in the formulation of my current opinions regarding spurious actuation likelihood. That is, while I have considered all of the available data, I have relied heavily upon our analysis of the NEI/EPRI tests in formulating my overall response. Hence, I feel it appropriate to spend some time on our efforts to analyze those tests.

As is well known, SNL is also working on the USNRC Fire Risk Research Program. Tasks 1 and 11 of that program are addressing issues of fire PRA circuit analysis. Under Task 1, a NUREG/CR report on circuit analysis tools, methods, and data is being prepared. This NUREG/CR will expand on the SNL circuit analysis letter report that was provided to all members of the expert panel at the outset of the panel efforts. An analysis of the NEI/EPRI test data has been undertaken by SNL as a part of this NUREG/CR preparation effort. This work was a joint effort of Frank Wyant, also of the SNL staff, and myself. My analysis of the NEI test data for the purposes of the expert panel is based in part on these results and findings.

In addition, I have assembled my understanding of the industry fire test results in the form of five tables. These tables are presented in Attachment 2. I have identified the presumed response of each cable bundle in each test. The tests have been parsed by the type of cable (thermo-set, thermo-plastic, or armored), and by raceway location (tray or conduit). These summary tables are based directly on the information provided to the panel by NEI ("Conduct and Results of EPRI Fire-Induced Circuit Failure Testing," April 20, 2001) and represent a relatively simple reformatting and sorting of the NEI information.

The NEI/EPRI data is rich in information. My analysis of the data was necessarily limited by the time available. We did have time to dig into the data in a number of different ways, and debated our overall approach to presentation of the results. Two specific features of our data interpretation should be clearly recognized:

- In examining the NEI test data, SNL distinguished between intra-cable shorting behaviors and inter-cable shorting behaviors.
- For the intra-cable shorting behavior, we generally looked at each MOV circuit as presenting one opportunity for spurious operation. That is, there are actually two target conductors in each multi-conductor cable tested, but we only counted one opportunity for spurious operation. If either or both target conductors became energized during the test one device actuation would be counted.
- For inter-cable spurious operation, the data have been parsed to consider three inter-cable hot short possibilities: either of the two 1/C source cables hot-shorting to the 1/C target (1/C source on a 1/C target); a 1/C source hot-shorting to either of the multi-conductor target conductors (1/C source on a 7/C target); and either of the multi-conductor source conductors hot-shorting to the 1/C target cable (7/C source on a 1/C target). Hot shorts of all three types were indeed observed.

SNL parsed the test results in various ways specifically to assess the role of various "influence factors" in the spurious actuation behavior. SNL has looked at the following influence factors and reached the following general conclusions:

- Cable insulation/jacket material (thermo-plastic versus thermo-set): The data indicate that there may be a moderate dependence of the spurious actuation likelihood for thermo-plastic versus thermo-set cables relating to intra-cable shorting behaviors. Nominally, it appears that thermo-plastic cables are more prone to inter-cable hot shorts than are thermo-set cables. However, the evidence is relatively weak given relatively few tests involving the thermo-plastic cables.
- Number of conductors: We found that for 7/C and 9/C cables, the likelihood of spurious actuation versus fuse blows was nominally similar. Hence, we conclude that the conductor count, at least over this limited range, was at most a weak influence factor. We caution that this result is not easily extrapolated to a wider range of conductor counts.
- Armored versus non-armored: This factor was found to be a strong influence factor. Armored cables showed a much greater tendency to blow fuses and a reduced tendency to cause spurious operations than did the non-armored cables. As was noted above, I have concluded that armored cables illustrate similar behavior as multi-conductor cables in conduits.
- Routing in trays versus conduit: The NEI/EPRI results for trays versus conduits do not appear to be as clear cut as the corresponding SNL/NRC insulation resistance tests. This is likely due to the small number of conduit failure cases observed. The NEI/EPRI data, in particular for the cases with CPTs, tend to show a reduced likelihood of spurious actuations for cables in conduits as compared to cables in trays. This is consistent with the SNL results, although the SNL results are more pronounced - shorts to ground appeared far more likely than conductor-to-conductor shorts. In general, I consider the raceway type to be an important influence factor with hot shorts less likely for cables in conduits.

- Cable tray loading: The data on cable tray loading is also somewhat weak. However, the evidence tends to indicate that intra-cable shorting behavior is not impacted significantly by tray loading. However, the likelihood of inter-cable hot shorts may increase with increasing tray loading.
- Cable tray orientation: The data set contains only limited results for vertical trays. The test data appear to indicate that raceway orientation is a weak influence factor with regard to intra-cable shorting. However, vertical trays appeared to experience a higher rate of actuations attributed to inter-cable hot shorts than did cables in horizontal trays.
- Exposure mode and intensity: In the NEI/EPRI test, the mode of exposure (i.e., plume versus hot layer) and the fire intensity tend to be inextricably linked. That is, smaller fires were used only for plume exposures and larger fires were used only for hot layer exposures. The exposure mode/intensity was found to be a weak influence factor.
- Cable-to-circuit wiring configuration: This factor relates to the manner in which the individual cable conductors were connected to the MOV circuit as compared to the conductors relative position in the multi-conductor cables. This factor was found to have a strong influence on the likelihood of spurious actuation as the mode of failure. In particular, the relative location of the grounded and powered conductors was critical.

Note that given my choice of the panel problem statement - what is the likelihood of spurious actuation given cable failure - those cables tested by NEI that did not fail provide no information relevant to the formulation of my responses. Only those cases where cables did fail are relevant.

Overall, the NEI/EPRI tests demonstrated a spurious actuation likelihood that was relatively high for some configurations. Excluding Tests 14 and 18, at least one cable failure was observed in each of 14 (out of the 16) tests. Furthermore, at least one spurious device operation was observed in 12 of these 14 tests. Indeed, for the majority of the tests there was at least one device actuation observed, and for several tests multiple actuations were observed. For example, for multi-conductor thermo-set cables in cable trays with no CPTs in the circuit, about 1/2 of the observed cable failures resulted in a spurious actuation due to intra-cable hot shorts. For other configurations, the fraction of failures leading to spurious actuation was lower, in some cases considerably lower. However, there was at least one spurious operation observed for almost every configuration tested with the exception of certain configurations that were tested only once.

Spurious actuations due to inter-cable hot shorts were also observed with fair frequency. For some configurations, as many as one in three failed cable bundles experienced at least one spurious actuation attributed to inter-cable hot shorts. In two cases, a single cable bundle actually experience two device actuations each attributed to separate inter-cable hot shorts. I believe the industry test configuration overstates this effect, as noted above, but even so I found this result to be surprising.

Overall, the likelihood of spurious actuation given failure was found to be somewhat higher than I might have assumed prior to conduct of the tests.

It should also be observed that in estimating the likelihood of spurious operation, I have not explicitly considered issues of timing and duration. For example, if the industry tests report relay "chatter" I counted this as a spurious actuation. Also, given a circuit lock-in, I also counted this as an actuation regardless of how long the actuation held. In practice, some consideration will need to be given to the timing and duration of the hot shorts in order to get an accurate estimate of risk implications.

Overall Assessment

I have parsed my overall assessment of spurious actuation likelihood given cable failure along several lines. Below are several subsections that provide my estimates of the spurious actuation likelihood for various primary cases. Within each subsection, or primary case, secondary cases may also be called out.

Overall, the available test data as a whole demonstrate that at least four factors are critical to the assessment of spurious actuation likelihood: armored versus non-armored cables; cables in trays versus cables in conduits; cable-to-circuit wiring configuration; and circuits without CPTs versus circuits with CPTs. In addition, the thermo-plastic and thermo-set cables appeared to show substantial differences with regard to inter-cable shorting. For cable trays, raceway loading may also be a significant factor, although the results appear inconclusive based on the analyses performed to date. Some additional analysis may elucidate further insights. Those other factors that were varied during testing appear to have only a weak influence on the results.

It appears that the fact that all the NEI/EPRI tests involved one explicitly grounded conductor was also significant. That is, the SNL/NRC IR results illustrate that conductor-to-conductor interactions are far more likely than conductor-to-raceway interactions, at the least for cables in trays. For the multi-conductor cables, the fact that one conductor in the MOV circuit was always grounded likely had a strong influence on the number of fuse blows versus actuations seen. While it is anticipated that this will, indeed, be the predominant configuration for actual circuits, it would appear inappropriate to apply these same results directly to cases where there is no ground conductor present in the cable.

I also conclude that two factors will contribute to large uncertainty in the likelihood results: uncertainty regarding how the cable is wired to the circuit (e.g., number of conductors, how each conductor is connected to the circuit, and presence or lack of a ground conductor); and uncertainty associated with the design features of the circuit (e.g., latching circuits, double breaks, fusing levels, CPTs or the equivalent, actuation timing, etc).

<u>Non-Armored Cables in Trays:</u>

This subsection deals with non-armored cables located in a cable tray. Two subsets of this case are considered; namely, cases where intra-cable shorts can lead to actuation, and cases where inter-cable shorts are required to cause an actuation.

The first case assumes that internal shorting among the conductors of a multi-conductor cable (i.e., intra-cable conductor-to-conductor shorts) could lead to spurious actuations (i.e., an appropriate source conductor and a vulnerable target conductor are present in the same cable). This possibility can be easily established for a given circuit through deterministic analysis. In this case no external source conductor is required for actuation. For this case I assume the intra-cable hot shorts will dominate the spurious actuation behavior and my estimates reflect these assumptions. Two sub-cases are called out: the case where a ground conductor is present in the cable (i.e., an intra-cable short may be a short to ground rather than a hot short) versus those where no ground conductor is present (i.e., an external short to ground would be required to prevent the actuation). The same values apply to both thermo-plastic and thermo-set cables given the focus on intra-cable interactions.

The IR results showed 70-80% of the initial cable failures on the multi-conductor cables involved intra-cable conductor-to-conductor shorting. Relevant statistics from the industry MOV tests include the following:

- For thermo-set cables in trays without CPTs in the circuit, about 50% of the spurious actuation opportunities were realized due to intra-cable hot shorts given cable failure (8 actuations versus 9 fuse failures).
- For thermo-plastic cables in trays without CPTs, the figure is about 25% (2 actuations versus 6 fuse failures).
- Overall, for all cables in trays without CPTs, the figure is about 40% (10 actuations versus 15 fuse failures).
- With CPTs in the circuit, all spurious operations for all cables in trays were reduced to about 25% (3 actuations versus 9 fuse failures).

Consider inter-cable hot shorts leading to spurious actuation. The IR tests showed less likelihood of a cable-to-cable hot short interaction. This appears to be borne out in the industry tests to some extent:

- For cables in trays, overall 33% of the cable bundles that failed experienced at least one actuation attributed to an inter-cable hot short (12 actuation cases versus 24 non-actuation cases).
- In two cases, the failure of a cable bundle was accompanied by two separate actuations, each attributed to a separate inter-cable hot short.
- Inter-cable hot shorts were dominated by shorts between single-conductor cables, but actuations due to shorts between the single-conductor and multi-conductor cables also were observed.

Overall, the nominal likelihood of spurious actuation for these cases appears relatively high. One can certainly conclude that the likelihood of spurious actuations due to intra-cable hot shorts is on the order of 0.25 or greater, depending on the nature of the cables and other factors. If one were to take away the explicitly grounded conductor from the MOV circuit, the likelihood of spurious actuation would certainly increase. Also, with a CPT in the circuit, the likelihood of spurious actuation was sharply reduced. The IR results by their very nature did not explore this behavior. Table 2 summarizes my estimates for the intra-cable shorting cases.

Table 2
Spurious actuation likelihood estimates for multi-conductor cables in cable trays where intra-cable shorts may cause a spurious actuation.

Case/Configuration	Cases without CPTs		Cases with CPTs	
	Best Estimate	**Range***	**Best Estimate**	**Range***
Cases with a grounded conductor present	0.5	0.25 - 0.6	0.25	0.1 - 0.5
Cases without a grounded conductor present	0.6	0.4 - 0.8	0.4	0.1 - 0.7
* Range is influenced primarily by the cable-to-circuit wiring configuration but also considers the influence of other test insights and, for some cases, the scarcity of relevant results for the NEI/EPRI tests.				

The second subset for this general case is for those cases where an analysis has shown that intra-cable shorts cannot cause a spurious actuation, but that an inter-cable short may. As stated above, the industry tests probably overstate the likelihood of inter-cable hot shorts due to the bundling of cables using tape (as discussed above). However, the likelihood of spurious actuations due to inter-cable hot shorts cannot be dismissed. My estimates are shown in Table 3 and assume that a cable with the appropriate energizing source is present in the same raceway as the target cable (either by demonstration or assumption). In this case, I have distinguished between thermo-set and thermo-plastic, as the industry tests seem to show that thermo-plastic cables are more prone to inter-cable hot shorts than are thermo-set cables. I have not attempted to parse my estimates based on raceway loading given weak evidence to date. This factor may be especially important for inter-cable interactions but given a lack of evidence, I consider this a source of uncertainty. I have also indicated that the CPT case is not applicable to inter-cable shorting because it is likely that no analysis would be able to confirm with confidence that no energizing source conductor was present that was not connected though a CPT.

Table 3
Spurious actuation likelihood estimates for multi-conductor cables in cable trays where intra-cable shorts cannot cause a spurious actuation but inter-cable shorts may.

Case/Configuration	Cases without CPTs		Cases with CPTs	
	Best Estimate	**Range***	**Best Estimate**	**Range***
Thermo-set cables	0.1	0.05-0.25	n/a	
Thermo-plastic cables	0.25	0.1-0.4	n/a	
* Range is influenced primarily by the cable-to-circuit wiring configuration but also considers the influence of other test insights and, for some cases, the scarcity of relevant results for the NEI/EPRI tests.				

Non-Armored Cables in Conduit:

This subsection deals non-armored cables located in a conduit. Two subsets of this case are considered similar to the two cases considered above relating to multi-conductor cables in trays.

The likelihood estimates in Table 4 below again assume that internal shorting among the conductors of a multi-conductor cable could lead to spurious actuations (see discussion presented above for the corresponding cable tray case). For this case, I assume a somewhat reduced likelihood of spurious actuation based largely on the IR test results that showed a definite tendency for cables to short to ground when routed in conduits. The industry tests saw vary few cable failures in conduit (just three failure cases). Hence, the evidence for this case is somewhat weak.

Table 4
Spurious actuation likelihood estimates for multi-conductor cables in conduit where intra-cable shorts may cause a spurious actuation.

Case/Configuration	Cases without CPTs		Cases with CPTs	
	Best Estimate	Range*	Best Estimate	Range*
Cases with a grounded conductor present	0.1	0.05-0.3	0.05	0.01-0.1
Cases without a grounded conductor present	0.4	0.1-0.6	0.1	0.05-0.2
* Range is influenced primarily by the cable-to-circuit wiring configuration but also considers the influence of other test insights and, for some cases, the scarcity of relevant results for the NEI/EPRI tests.				

The second subset for this general case is for those cases where an analysis has shown that intra-cable shorts cannot cause a spurious actuation, but that an inter-cable short may (see discussion presented above for the corresponding cable tray case). My estimates for this case are shown in Table 5. In this case there is no direct evidence for the relative behavior of thermo-set versus thermo-plastic cables. I presume that such an impact will be observed similar to that seen for cables in trays. Overall, I expect that inter-cable hot-short interactions should be less likely for conduits than for cable trays given the prevalent ground plane represented by the conduit itself. I also assume that inter-cable interactions are somewhat more likely for thermo-plastic cables than for thermo-set cables, again based largely on the industry tests.

Table 5
Spurious actuation likelihood estimates for multi-conductor cables in cable trays where intra-cable shorts cannot cause a spurious actuation but inter-cable shorts may.

Case/Configuration	Cases without CPTs		Cases with CPTs	
	Best Estimate	Range*	Best Estimate	Range*
Thermo-set cables	0.05	0.01-0.1	n/a	
Thermo-plastic cables	0.1	0.05-0.2	n/a	
* Range is influenced primarily by the cable-to-circuit wiring configuration but also considers the influence of other test insights and, for some cases, the scarcity of relevant results for the NEI/EPRI tests.				

Armored Multi-Conductor Cables:

This subsection deals with various situations related to armored multi-conductor cables. In this case, there is only one possibility for hot shorts leading to spurious actuation; namely, intra-cable conductor-to-conductor shorts. As has been noted above, evidence for armored cables is somewhat weak.

The NEI tests include two tests with armored cables (Tests 1 and 13), one each conducted with and without CPTs in the MOV circuits. For the MOV circuits, there was one device actuation out of a total of 7 cable failures in these two tests. This particular case involved a cable where the minimum bend radius was violated during installation. The SNL IR measurement for Test 1 did not detect any failures, and a wiring fault in the IR system made it impossible to determine the failure mode in Test 13. Hence, evidence for the armored cables is quite limited.

Overall, there is good reason to expect that the likelihood of spurious operation with armored cables is lower than that for general multi-conductors in a cable tray. Nominally, one might anticipate similar behavior between armored cables and conduits given that the armor and conduit both represent prevalent ground planes easily accessible to the conductors. Indeed, the intimacy of this contact is greater for the armored cable. Hence, on should nominally expect a similar, but more pronounced trend. That is, armored cables may be even less likely to cause spurious operations than cables in conduits.

This appears to be nominally borne out by the test data. I would nominally estimate that the spurious actuation likelihood for armored cables might be half that of non-armored cables in conduits. However, I may be conservative in this estimate. Hence, I will allow for a higher level of uncertainty on the down-side for this case. I also assume that the presence or lack of a grounded conductor would have little impact on this case because the armor itself will likely be predominant. Table 6 summarizes my opinions for the armored cable case.

Table 6
Spurious actuation likelihood estimates for multi-conductor cables in cable trays where intra-cable shorts cannot cause a spurious actuation but inter-cable shorts may.

Case/Configuration	Cases without CPTs		Cases with CPTs	
	Best Estimate	Range*	Best Estimate	Range*
Cases with a grounded conductor present	0.05	0.01-0.7	0.01	0.005-0.02
Cases without a grounded conductor present	0.05	0.01-0.7	0.01	0.005-0.02
* Range is influenced primarily by the cable-to-circuit wiring configuration but also considers the influence of other test insights and, for some cases, the scarcity of relevant results for the NEI/EPRI tests.				

Note that I consider inter-cable hot shorts to be virtually impossible for armored cables and am not considering multiple shorts to ground leading to spurious actuation due to a lack of evidence for this case.

Attachment #1 to Nowlen's Report

Introduction

I have concerns regarding the problem statement and formulation for the expert elicitation panel as stated in the original solicitation distributed by EPRI/NEI. During a discussion of my concerns at a research coordination meeting in Palo Alto (4/19-20/01) I was challenged to propose an alternate formulation of the problem for consideration by the panel.

This document presents my thoughts regarding the problem to be addressed by the panel. These thoughts should be viewed as a Awork in progress.≅ I have also borrowed from material provided by Nathan Siu, USNRC/RES, who has voiced similar concerns. I anticipate that interactions with the panel will ultimately refine or revise the proposed problem formulation.

The following discussions include considerable background material. While for some panelists this material may be well known, I feel this presentation is necessary so that all panel participants will appreciate the context within which I have formulated my proposals and the context under which I anticipate that the panel findings will be utilized. I have placed this material at the end of the write-up, but strongly encourage the panel to take the time to read these sections. My position can be viewed properly only in this broader context.

I have already distributed a discussion of circuit analysis terminology that evolved from a public meeting between industry and the USNRC about one year ago. One obvious topic for the panel is to refine (or re-define) the associated terminology. Clearly, use of a common terminology will facilitate future discussion. We took our shot about a year ago with this document using input from industry and NRC. I would encourage the panel to take on the development of a final Acircuit analysis dictionary≅ as well - perhaps even as the first task to be tackled.

Stating the Problem and Establishing the Entry Condition

The expert elicitation is, under either formulation, designed to assess certain factors associated with the response of nuclear power plant electrical systems to fire-induced cable failure. Of particular interest is the likelihood of spurious equipment actuations, although other circuit effects may also be of interest. My concerns are related to the starting point to be assumed by the panel.

I propose that the panel assume, as an entry condition to the problem, that a sufficient fire exposure has occurred such that a fire PRA (or alternate fire damage analysis) would already have predicted fire-induced cable failure (further discussion provided below). The specific objective of the panel would then be to provide expert opinions regarding the likelihood of various circuit fault modes (e.g., no effect, loss of power, spurious actuation, etc.) given failure of an electrical cable. The panel would also identify and, to the extent possible, characterize/quantify those factors that might influence those likelihood estimates.[6] This approach is discussed as a Abase case / modifier≅ approach to the problem in Section 5.3 of the SNL/USNRC circuit analysis test report (which has been circulated to the panel).

The current problem formulation circulated by EPRI/NEI asks essentially this same question, but proposes a different entry point. In the EPRI/NEI formulation, the problem begins with a matrix of thermal environment exposure conditions (e.g., 700EF for 10 minutes). Hence, the panel must also address the likelihood that a given thermal environment (time at temperature) would actually lead to cable failure. Including the failure likelihood question would complicate the problem in the following ways:

> (1) It will require the panel to consider the full range of experimental data relating to cable thermal vulnerability in addition to that relating to cable failure modes. This vastly expands the scope of the applicable literature. For example, equipment qualification data for cables should also be considered.
>
> (2) It introduces a range of fire heat transfer behaviors into the problem formulation that are amenable to, and are typically handled through, direct engineering analysis (fire modeling for example). Such topics are not appropriate for this expert panel even given that the NEI/EPRI tests may shed new light on these behaviors. Rather, these aspects of the EPRI/NEI tests should be seen as fodder for the fire modeling folks.
>
> (3) The question as currently posed distinguishes only two cable types; thermo-set and thermo-plastic. While this distinction is important in terms of thermal failure limits, it is far from concise. That is, among the thermo-set class in particular, cables display a range of thermal vulnerability thresholds.[7] Given the current formulation, this would directly and profoundly impact the likelihood estimates that I am asked to generate. As a panelist, I must either prepare a separate set of probability estimates for each cable type of interest (and there are many), or I must build in my mind a population distribution to represent cables used in practice and then develop a distribution of likelihoods based on that population. I see this as an unnecessary complication that, again, vastly expands the scope of work required.
>
> (4) Utilization of the panel findings would be complicated by the EPRI/NEI formulation in that, as discussed further below, the time-temperature matrix is presented as a surrogate for the fire exposure conditions. As a PRA analyst (or regulator) I have no basis for correlating the step-change temperature conditions to an actual or postulated

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[6] Note that the circuit fault mode influence factors may well include factors associated with the fire exposure. For example, if a panelist concludes that fire intensity or the severity of the exposure environment influences the actual mode of cable failure, then this would be called out as an influence factor.

[7] For example, take an environmental exposure of 700EF for 30 minutes. In my view the likelihood that a XLPE cable would be failed by that exposure approaches unity. In contrast, if the cable has a silicone-based insulation, then the likelihood of failure is essentially zero. Now I still have to estimate the likelihood of the spurious operation given failure.

fire. Real fires present transient exposure profiles, and to use the results one would need to assess an Aequivalent≅ fire exposure condition for a particular application. This, again, takes us back to the need for the application of direct engineering analysis tool (a fire model).

(5) The current formulation does not provide any guidance as to what cable/circuit configurations the panel should consider. For example, the EPRI/NEI tests clearly demonstrated an impact of circuit design on spurious actuation likelihood. Circuit configuration questions must be addressed in my proposed formulation as well, but given the current formulation is more problematic. That is, the question of cable/circuit configuration adds another dimension to the problem that will further expand the scope of the answer. This, combined with the fire exposure-to-cable failure dimensions, included in the EPRI/NEI formulation makes the problem quite broad indeed.

The proposed alternative problem formulation de-couples the problem of the thermal exposure leading to cable failure from that of the cable failure leading to circuit faults. The proposal then focuses the efforts of the panel on only the second part - cable failure leading to circuit faults. As discussed further below, this de-coupling of the problem is fully consistent with fire PRA methods and tools. Hence, it is also fully consistent with the USNRC risk-informed approach. In all likelihood, as formulated by NEI/EPRI, the panelists will need to decompose the problem in any case.

<u>Proposed Problem Formulation and Approach</u>

It is recommended that the panel consider it a given that the cables in question have been exposed to a sufficiently severe thermal environment such that the cables have reached their failure thresholds (see discussion on defining failure below). That is, it should be taken as a given that the cables can no longer ensure the proper operation of their associated electrical circuits. The problem to be addressed by the panel would then be to estimate the likelihood that spurious actuations or other circuit effects might be observed.

The panel should establish a set of representative Abase cases≅ and estimate the circuit fault mode likelihoods for each base case. The exact nature of the parameter variations and combinations among base cases is to be defined by the panel. **Example:** Each base case might reflect a specific combination of fire exposure modes (e.g., plume vs. direct flame impingement vs. radiant heating), cable configuration (conductor count, cable type, armor vs. no armor, etc.), cable routing (e.g., trays vs. conduits vs. air drop), and circuit configuration (e.g., MOV vs. SOV vs. motor/pump controls).

For each base case, the potential range of validity for extrapolation to other similar cases should be assessed. The influence factors relating to extrapolation for each such case should be identified. To the extent possible, the impact of the influence factors should be estimated quantitatively. Additional guidance regarding this approach is provided in Section 5.3 of the SNL/USNRC circuit analysis report. **Example:** Can one extrapolate from a base case involving a ladder-back cable tray to a solid bottom cable tray? If so, under what circumstances would the extrapolation be expected to remain valid? What factors would influence the circuit fault mode likelihood in such an extrapolation and how?

Alternatively, an expanded set of base cases encompassing, directly, variations in the influence factors could be formulated and quantified. That is, under this approach the base cases would be more specific and would need to address more refined variations within the parameter space. At the same time, the number of influence factors and the range of extrapolation for each base case would be sharply limited. The panel should assess the proper balance between the number or base cases identified and the number, and importance, of the associated influence factors.

To facilitate the discussion, it is recommended that the panel should be provided with a specific set of circuit/cable configurations. The circuits should represent a range NPP circuits of potential interest to PRA. Both power and control circuits/cables should be represented. **Example:** An obvious starting point is the EPRI/NEI MOV surrogate circuit as tested in both of its forms (early and late tests). An analogous DC SOV circuit should also be considered. A circuit involving cable-to-cable power circuit shorts should be included. A motor/pump control circuit should be included.

The panel should consider and address uncertainties in their estimates.

The panel should make recommendations regarding additional data needs if such need are perceived to remain.

The panel should identify/endorse/develop a consistent set of circuit analysis related terminology.

PRA Process Background

This section is intended to set the stage for panelists to understand how we got to where we are today, and how the panel findings will be used. The presentation context is fire Probabilistic Risk Assessment (PRA) which leads directly into the USNRC risk-informed regulatory process. That is, the intent of the panel is to support a risk-informed approach to resolution of the circuit analysis - spurious actuation issues. Hence, the PRA context is an appropriate basis for consideration of how the problem posed to the panel should be formulated. The discussion is intended to illustrate how the problem of fire is formulated in fire PRA and how the question posed to the panel fits into this framework. In particular, it is intended to illustrate that the alternative problem formulation I am proposing if fully consistent with the fire PRA / risk-informed approach whereas the current formulation presents problems in this regard.

A nuclear power plant fire PRA is a multi-step analysis quantifying the likelihood that a fire might challenge nuclear safety potentially leading to a core damage accident, failure of containment, and an off-site release of radioactive material. A fire PRA typically considers fires that impact both a single compartment and fires that might impact multiple compartments. For illustration, the following discussion focuses on the single compartment analysis.

The fire PRA will typical begin by screening various plant compartments whose contributions to fire risk can be shown to be insignificant. Those compartments that survive screening then go through a process of detailed fire scenario quantification. The steps of a fire scenario analysis can be characterized in many ways, but typically address the following major tasks:

Step 1: Fire sources are identified and characterized. Characterization includes the nature, location, potential fire intensity, and occurrence frequency. This step typically relies on a plant walkdowns, fire events data, and fire experiments.

Step 2: The impact of each fire source on the environment of the compartment is assessed. This is accomplished using some form of fire modeling tools; typically either a compartment fire model or individual engineering correlations. Consideration typically includes plume, ceiling jet, hot gas layer, and direct radiant heating behaviors.

Step 3: The impact of the fire environment on PRA targets is assessed. PRA targets are plant equipment important to plant safety located within the fire compartment. In particular, the targets of interest include electrical power, control, and instrument cables. In practice the failure assessment may be based directly on the environmental exposure conditions (e.g., plume temperature at the equipment location), or may explicitly consider heat exchange to the target (convection, conduction and radiation). In either case, it is common to assumed cable failure occurs when the environment/target reaches a threshold failure limit; typically either a temperature or heat flux condition.

Step 4: Intervention by detection and suppression is assessed. In this step the timing of PRA target failure is weighed statistically against the likelihood that the fire might be suppressed before failure occurs.

Step 5: The impact of equipment/cable failures on plant safe shutdown is assessed. This step considers the plant damage state induced by the fire and considers the probability that operators might fail to achieve safe shutdown using undamaged equipment and systems. The induced plant damage state may be dependent on the mode of circuit faulting assumed to occur given cable failure. For example, the spurious opening of a valve may lead to a coolant diversion path whereas loss of valve function, so long as the valve remains in its normally closed state, has no impact on system performance.

Step 6: The quantification and uncertainty analysis is completed. In this step the various factors associated with each postulated fire scenario are compiled to estimate the core damage frequency. The impact on containment and potential for off-site release may also be assessed depending on the scope of the analysis.

The differences between the two problem formulations can now be stated in terms of these steps. The expert panel will, under either approach, provide input associated with Step 5, the electrical circuit and plant systems impact analysis.

- Under my proposal all other steps of the analysis are defined as outside the scope of the problem as posed to the panel except to the extent that influence factors might be associated with other steps (e.g., how we got to cable failure might influence the spurious actuation likelihood). I propose that the panel focus explicitly on the impact of electrical cable failures on their associated electrical circuits/systems.
- Under the current EPRI/NEI formulation, Steps 2 and 3 are included, by surrogate, in the problem formulation. The matrix of time-temperature exposure conditions given in Panel Question 1 serves as a surrogate for the estimation of fire exposure conditions (Step 2

output). The panel must then assess the likelihood that the environment leads to cable failure (Step 3) and the likelihood that cable failure leads to spurious actuation (Step 5).[8]

Cable Background

In formulating the problem for the panel, it is appropriate to keep in mind the larger problem that we are attempting to address. That problem is associated with how electrical circuits will respond in a fire. In particular, we are dealing with electrical cables and their failure. Hence, this section provides a background discussion relating to the regulatory positions regarding cable failure and the ultimate purpose of an electrical cable. These lead one to a logical definition of what we mean by cable failure. The discussion then continues with a background discussion of the basis for cable failure thresholds that have been used to support PRA. The background is intended to establish a common ground for understanding what is meant by the failure of a cable.

The failure of an electrical cable is defined in the regulatory context (e.g., in the context of Appendix R - free of fire damage) as the inability to perform its design function. The purpose of an electrical cable is to provide an electrically insulated path for the flow of electrical current. Hence, one can infer that cable failure means that the cable insulation cannot maintain a sufficient level of electrical isolation so as to ensure the proper operation of the associated electrical circuit.

The counter-concern has been voiced that such a definition is insufficient. I would argue that such a definition is sufficient for the panel to proceed. Indeed, I am reluctant to establish a pre-defined threshold of failure in the context of, for example, cable insulation resistance (IR) or leakage current. The threshold of failure for a power circuit in such terms would most certainly differ from the criteria applicable to an instrument circuit. This may be a factor to be posed for the panel. Note that the USNRC has attempted such definitions in the past and their criteria might form the basis for such consideration.[9]

For the purposes of fire PRA, cable failure thresholds are commonly taken from experimental data wherein cables are exposed to a fire, or a simulated fire environment, and monitored for electrical integrity. Numerous cable test programs have been reviewed in Appendix A of the SNL/USNRC circuit analysis letter report provided to the panel as background material. Typical examples of fire damage testing methods and criteria cited in that review include the following:

- In tests sponsored by Nuclear Energy Liability - Property Insurance Association of Hartford Connecticut, seven-conductor power/control cables in cable trays were energized using a two-phase plus neutral/ground AC power source (three conductors on each phase, and the seventh conductor grounded) and exposed to a gas ribbon burner fire. The voltage of the

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[8]It is also noteworthy that under the EPRI/NEI formulation, Step 4, the suppression analysis, is apparently bypassed. That is, the environmental exposures are considered givens and are not subject to a probability of occurrence. Hence, in the bigger picture, some assessment of suppression intervention before failure will be needed.

[9] In a letter from S. Black, USNRC, to W.J. Cahill Jr., Texas Utilities Electric, dated October 29, 1992, the USNRC established criteria for assessing the acceptability of cable performance during raceway fire barrier tests. The criteria required a minimum cable IR performance of 1 M-ohm per 1000 feet of cable. For cables rated at over 1 kV, an additional 1 M-ohm per 1000 feet IR for each kV of voltage rating was also required.

source is not specified. Failure was indicated by separate indicating lights that illuminated upon a phase-to-phase or phase-to-neutral/ground short circuit.

- In tests sponsored by EPRI (EPRI NP-1675) seven-conductor cables were energized using a 10 VDC power source. Each conductor was energized to a different voltage potential using a voltage divider circuit. Cables were then exposed during cable tray fire tests, and the voltage on each conductor was monitored. Failure can be inferred based on changes in the conductor voltage.
- In tests sponsored by the USNRC (NUREG/CR-5546), three-conductor power/control cables were energized using a 208 VAC 3-phase source, and then exposed to elevated temperatures in an air-oven. The cables were monitored for leakage current throughout the exposure. The cable failure times cited were based on exceeding a leakage current 2 A (which would open a fuse in the energizing circuit). It was common to observe leakage currents as high as 15 mA before a precipitous current increase and failure.
- In tests performed by IPSN in France, three-conductor power cables were energized using a 3-phase 380 VAC power system with an imposed baseline current of 0.48A in each conductor. Failure was based on any differential current exceeding 300 mA beyond the imposed baseline current. Failures noted distinguished between hot shorts (conductor-to-conductor) and shorts to ground (conductor-to-ground). Control cables have also been tested using similar approaches and criteria.
- In the recently completed EPRI/NEI fire tests three measures of cable performance were implemented. First, a surrogate Motor Operated Valve (MOV) circuit was implemented. For this circuit, cable failures can be inferred based on the observed circuit effects (i.e., blown fuses, spurious actuations, circuit re-energizing, etc.). Second, the EPRI/NEI test data includes monitoring of leakage currents and voltages on critical conductors. Hence, cable failure can be inferred based on these measures as well. Third, through USNRC sponsorship, a system was installed to monitor conductor-to-conductor and conductor-to-ground insulation resistance. Failure for this approach can be inferred based on the observed insulation resistance behavior. (The data from the latter system will be made available to the panel at a future date.)

When an electrical cable fails, one or more modes of cable failure may be observed. The most commonly identified modes of cable failure include:

- open circuit - a loss of electrical continuity of an individual conductor
- short to ground - one or more individual conductors coming into electrical contact with a grounded conducting medium
- hot short - one conductor coming into electrical (or physical) contact with a second conductor without a simultaneous short to ground, either involving the conductors of a multi-conductor cable (an internal hot short) or between conductors in separate co-located cables (an external hot short)
- loss of insulation resistance - insulation resistance (IR) degradation allows leakage currents to develop between conductors, or between a conductor and ground

Given these modes of cable failure, it is proposed that the problem posed to the panel address how cable failures might be manifested as circuit faults.

Again, with a view towards the bigger picture, another aspect to consider is the circuit fault modes that may be of interest. This section provides a brief discussion of circuit fault modes and why different fault modes are of interest.

Given that a cable failure has occurred, the associated electrical circuit may experience some mode of circuit fault. Depending on the mode of cable failure, different circuit fault modes may be manifested. In the context of a fire PRA, different circuit fault modes might have different risk implications. For example:

- a hot short between an energized conductor and a conductor leading to an actuation device might lead to spurious actuation of the circuit;
- an energized conductor shorting to ground might cause a blown fuse and a loss of motive power for the circuit;
- certain cable failures may have no impact on the circuit.

Additional examples derived from the analysis of representative plant circuits can be found in Appendix B of the SNL/USNRC circuit analysis report.

Attachment #2 to Nowlen's Report

Summary tables of cable failure and circuit fault results for the NEI/EPRI fire tests

Table 1
Circuit fault results for industry tests involving thermo-set cables in cable trays.

Test	CPTs (y/n)	Circuit	Wiring Config.	Failures (y/n)	Sub-circuit target	Actuation (y/n)	Source if actuated	Notes
2	n	1		n	1			No Failures
					2			
					3			
		2		n	1			
					2			
					3			
		3		n	1			
					2			
					3			
		4		n	1			
					2			
					3			
3	n	1	AB	y	1	y	intra	
					2	y	??	
					3	y	inter - 1/C	
		2		y	1	n		
					2	n		
					3	n		
		3	SC	y	1	y	??	
					2	y	intra	actuated during spray
					3	y	inter - 1/C	actuated during spray
		4		y	1	n		
					2	n		
					3	n		
5	n	1		n	1			No Failures
					2			
					3			
		2		n	1			
					2			
					3			
		3		n	1			
					2			
					3			
		4		n	1			
					2			
					3			

Table 1 (cont)
Circuit fault results for industry tests involving thermo-set cables in cable trays.

Test	CPTs (y/n)	Circuit	Wiring Config.	Failures (y/n)	Sub-circuit target	Actuation (y/n)	Source if actuated	Notes
7	n	1	SC	y	1	y	intra	
					2	y	??	
					3	n		
		2		y	1	n		
					2	n		
					3	n		
		3	AB	y	1	n		
					2	y	intra	
					3	n		
		4		y	1	n		
					2	n		
					3	n		
8	n	2		n	1			(circuit 1 in conduit)
					2			
					3			
		3		y	1	n		
					2	n		
					3	n		
		4		n	1			
					2			
					3			
9	n	1	SC	y	1	y	??	
					2	y	intra	
					3	n		
		2	CG	y	1	y	??	
					2	y	intra	
					3	n		
		3	AB	y	1	y	??	
					2	y	intra	
					3	n		
		4	??	y	1	n		
					2	n		
					3	y	inter - 1/C	
10	n	1		y	1	n		Vertical Tray! Circuit 4 was an Air Drop Cable
					2	n		
					3	n		
		2	CG	y	1	y	intra	
					2	n		
					3	y	inter - 1/C	
		3		y	1	n		
					2	n		
					3	n		
		4	??	y	1	n		
					2	n		
					3	y	inter - 1/C	

Table 1 (cont)
Circuit fault results for industry tests involving thermo-set cables in cable trays.

Test	CPTs (y/n)	Circuit	Wiring Config.	Failures (y/n)	Sub-circuit target	Actuation (y/n)	Source if actuated	Notes
11	n	1		Partial	1			Only failure was fuse blow on one of two single-conductor source cables
					2			
					3			
		2		n	1			
					2			
					3			
		3		n	1			
					2			
					3			
		4		y	1	n		All circuit fuses blew by end of test
					2	n		
					3	n		
12	y	2		y	1	n		
					2	n		
					3	n		
		3		y	1	n		7/C to 1/C inter-cable hot shot - chatter only
					2	n		
					3	y	inter - 7/C	
		4		y	1	n		
					2	n		
					3	n		
15	y	1		y	1	n		
					2	n		
					3	n		
		2	??	y	1	n		
					2	y	intra	
					3	n		
		3		y	1	n		
					2	n		
					3	n		
17	y	3		n				Vertical Tray!
		4		n				

Table 2
Circuit fault results for thermo-plastic cables in cable trays.

Test	CPTs (y/n)	Circuit	Wiring Config.	Failures (y/n)	Sub-circuit target	Actuation (y/n)	Source if actuated	Notes
4	n	1		y	1	n		
					2	n		
					3	n		
		2		y	1	n		1/c to 1/c hot short
					2	n		
					3	y	inter - 1/c	
		3		y	1	n		1/c to 1/c hot short
					2	n		
					3	y	inter - 1/c	
		4	NAB	y	1	y	inter - 1/c and intra	possible 1/c to 7/c hot short
					2	y	??	
					3	y	inter - 1/c and 7/C	possible 7/c to 1/c hot short
6	n	1	SC	y	1	y	??	
					2	y	inter - 1/c	1/c to 7/c hot short
					3	y	inter - 1/c	1/c to 1/c hot short
		2	CG	y	1	y	intra	
					2	n		
					3	y	inter - 7/C	7/C to 1/C hot short
		3		y	1	n		
					2	n		
					3	n		
16	y	1		y	1	n		
					2	n		
					3	n		
		2		y	1	n		
					2	n		
					3	n		
		3		y	1	y	intra	
					2	y	intra	
					3	n		
17	y	1		y	1	y	intra and inter - 1/C	1/C to 7/C inter-cable hot short after fuse blow on intra-cable source caused second actuation on 1-1 Vertical Tray!
					2	y	??	
					3	n		
		2		y	1	n		
					2	n		
					3	n		

Table 3
Circuit fault results for thermo-set cables in conduit.

Test	CPTs (y/n)	Circuit	Wiring Config.	Failures (y/n)	Sub-circuit target	Actuation (y/n)	Source if actuated	Notes
8	n	1	SC	y	1	y	intra	
					2	n		
					3	y	inter - 1/C	
12	y	1		n				no failure
15	y	4	??	y	1	n		no actuation
					2	n		
					3	n		

Table 4
Circuit fault results for thermo-plastic cables in conduit.

Test	Circuit	CPTs (y/n)	Wiring Config.	Failures (y/n)	Sub-circuit target	Actuation (y/n)	Source if actuated	Notes
16	1	Y	4	y	1	n		
					2	n		
					3	n		1/c target

Table 5
Circuit fault mode results for the two armored cable tests.

Test	CPTs (y/n)	Wiring Config.	Circuit	Sub-circuit	Cable Fail (y/n)	Device Actuation	Actuation (source)	Notes
1	n		1	1	y	n		
				2				
		CG	2	1	y	y	intra	Cable installation violated bend radius
				2		y	intra	
			3	1	y	n		
				2				
			4	1	n			
				2				
13	y*		1	1	y	n		
				2				
			2	1	y	n		
				2				
			3	1	y	n		
				2				
			4	1	y	n		
				2				

* conflicting information in NEI documentation - use of CPT verified per discussion with W. Walker of Entergy on 11/5/01

Table 6
Summary of overall test results - this matrix identifies each test in one of three categories: tests with no cable failures observed, tests with at least one cable failure but no device actuations, and tests with at least one device actuation observed (Tests 14 and 18 excluded).

Test	CPTs (y/n)	No Failures	Failures but no device actuations	At least one device actuation
1	N			X
2	N	X		
3	N			X
4	N			X
5	N	X		
6	N			X
7	N			X
8	N			X
9	N			X
10	N			X
11	N		X	
12	Y			X
13	N		X	
15	Y			X
16	Y			X
17	Y			X

Appendix B-5 Report of Gareth W. Parry

August 21, 2001

To: Robert Budnitz

From: Gareth Parry

Subject: Analysis of the EPRI/NEI Test Data

Problem Definition

The parameter to be estimated, p_{SA}, is contained in the equation:

$$\Delta CDF = F_f * p_E * p_{AS} * p_{DM} * p_{SA} * \Delta P_{CCD}$$

On the basis of an NEI presentation at NRC, August 8, 2001, it appears as if this equation will be used to evaluate the change in CDF from spurious actuation associated with a specific component, or pair of components. For the single component, the problem is well defined, and the EPRI data can be used to estimate a p_{SA}, as discussed below. Furthermore, the associated OP_{CCD} can be evaluated uniquely.

The use of the same parameter, p_{SA}, to calculate the contribution from two spurious actuations is more problematic, however, as discussed later.

The equation written as above is Fred Emerson's original form of the equation, where the parameter represents the probability of spurious actuation for a given combination of fire temperature and duration, i.e., it is the probability of damage to such an extent that it leads to spurious actuation. Dan Funk proposed a modification of the equation to include an extra term M that accounts for the probability of damage.

$$\Delta CDF = F_f * p_E * M * p_{AS} * p_{DM} * p_{SA} * \Delta P_{CCD}$$

In this formulation, the parameter, p_{SA}, represents the probability of spurious actuation given cable damage. It is this definition of the parameter that I address. I have taken as an operational definition that a cable is damaged if it leads to a short to ground or a sufficient short between conductors to permit actuation. This is the only definition I can use to make sense of the data without having a more detailed understanding of electrical circuits. Therefore, any conclusions I draw are valid if, and only if, the circuits analyzed in the tests are truly representative of real nuclear power plant circuits.

There was a suggestion from Steve Nowlen that we use a base case/modifier approach to the estimation of p_{SA}. In my opinion, the data is not adequate to give anything more than anecdotal support for certain proposed influences. However, since the value I estimate for p_{SA} is relatively high, making minor changes is unlikely to have a significant impact on risk insights.

Observations

Observations made from consideration of the data concerning armored cable and in-conduit tests are not generally taken into account here, since these cables are likely to behave differently, having a more likely path to ground.

2. It is more likely that the two devices in the same bundle are both actuated rather than just one (8 cases of two actuations (tests 3, 4, 6, 7, 9, 16, 17) versus only 3 cases of one actuation per damaged cable (tests 6, 10, and 15)). Interestingly, all three cases where there was only one actuation are all center grounded, though in test 9 the center grounded cable resulted in two actuations. The quantity of data is small so there may not be any significance to this observation. From the measured voltages and currents in the test data, it appears that, in many cases, there is clearly a potential for shorting between several of the conductors within the cable. This is also seen in the SNL tests. The ordering or degree of shorting is not predictable, and therefore, we have to treat this in an aleatory way, i.e., as a random process. On this basis, there is a reasonable likelihood of actuation, which increases with the number of conductors connected to actuation circuits. However, if the circuits perform different functions for the same equipment (e.g., close, open) it is not clear what this will do to the component.

3. The time between hot shorts and grounding, when hot shorts appear first, is generally short. There does not seem to be any distinctive correlation with the wiring scheme (center-grounded, actuation biased, etc.). In any case, unless it could be established that the schemes were all of the same type, knowing this would not be helpful. It is something that would have to be treated as a randomizing factor. Location in the tray does not seem to correlate either, though this was not a factor that was varied significantly (only one test had four rows of cables for example). Again though, for a generally applicable probability, this should be a randomizing factor, since the position in the tray will not be known a priori in general.

4. The Sandia report suggests that thermoset insulated single conductors tend to short to ground before shorting with each other. Of the live single conductor cables in tests 3, 7, 9, 10, 11, 15, 16, and 17, 41 shorted to ground and only 5 found an actuation cable to short to. Of the thermoplastic cables in tests 4 and 6, 10 conductors shorted to ground while 4 shorted to an actuation circuit. This supports the SNL observation. While the statistics cannot be used directly since the tests are biased by the number of cables, the general observation can be made that it appears that thermoplastic cables are more likely to have cable-to-cable interactions than are thermoset cables.

5. The Sandia report also shows that in several cases there were cable(1C) to cable(7C) shorts early, as early or earlier than conductor to conductor shorts. This was seen in the EPRI data for the thermoplastic cables (tests 4 and 6). Again, this supports the observation in item 3 above concerning thermoplastic cables.

Conclusions Based on the EPRI tests

1. Using data from tests 3, 4, 6, 7, 8 (excluding the conduit), 9, 10, 15 and 16 there were 10 cases of one or more actuation versus 17 cases of grounding in the 7-conductor cables. Therefore, a simple relative probability of intra-cable shorting leading to actuation versus grounding for cables routed in cable trays is 10/27 ~ .37.

   This estimate is in general agreement with the estimates provided in the SNL letter report: Circuit Analysis - Failure Mode and Likelihood Analysis.

   For the type of exposure in these tests, the probability of one or more spurious actuations caused by shorting within a cable, given damage has begun is on the order of .37. The uncertainty range is not great. It is not reasonable to propose an upper limit of 1, but equally, there does not appear to be any reason to believe that the probability will be very low. Because there were two conductors connected to actuation devices in each cable versus one grounded conductor, this estimate might be a little conservative if it is more typical to only have one actuator connected. However, the fact that there are typically multiple shorts within the cable means that the probability of a spurious actuation is still not likely to be very low. If there were only one active cable, one ground, and one actuator cable, the likelihood of the hot short occurring first based on random ordering is on the order of 1/5. It is difficult to be precise because one would have to consider multiple shorts in a variety of sequences.

2. The tests were not designed to test the possibility of spurious actuations from shorts between multi-conductor cables, except for tests 14 and 18. The cable assemblies were generally surrounded by dead cables. The majority of tests did have the capability of addressing the limited case of co-located 1C cables. Some evidence of inter-cable shorting was seen in tests 14 and 18, and for thermoplastic cables shorts between 1C and 7C cables was seen in tests 4 (SNL) and 6 (SNL and cable #2). It does appear that thermoplastic cables are more likely to result in inter-cable shorts, with a reasonable physical explanation based on the nature of the response of the insulation to heat, to back it up.

   Tests 14 and 18 provide strong anecdotal evidence that intra-cable interactions occur before inter-cable interactions. The French test discussed in Section5.2.4 of SNL letter report: Circuit Analysis - Failure Mode and Likelihood Analysis, gave a similar conclusion. In test 14 however, intra-cable interactions in cable 1 occurred at about the same time as cable 2 interacted either with it or with cable 3. The EPRI report explains this with the statement that cable 1 was more resistant to failure than cable 3. It does not explain why, whether this was due to its placement in the tray, or the composition of the insulation for example.

3. From tests 3, 4, 6, 7, 8, 9, 10, 12, there were 12 actuations of the single cable DA from a possible 32 actuations, where some cable damage (shorting or grounding) was seen. While a probability of actuation given damage can be estimated as 12/32 ~ .375, this is the probability of an actuation cable finding a live short, versus shorting to ground. This probability is not, however, directly useful since it is dependent on the number of possible donors, and in particular on the geometric arrangement of the test specimens. Of these 12, 10 were caused by shorting between single conductor cables in the same group, and 2 from a conductor in the 7C cable. I'm speculating that the higher probability of 1C to 1C shorting

compared with 1C to 7C shorting, despite the initial geometrical separation may be something to do with the relative thickness of the insulation.

4. It is not possible, on the basis of the EPRI data, to estimate a probability of inter-cable interactions leading to spurious actuations that would be generally applicable. This mechanism of failure is relevant since it provides an additional way of causing spurious actuations or grounding for each specific cable. Tests 14 and 18 (thermoset cables) show that inter-cable interactions generally occur later than intra-cable interactions. Thus cable-to-cable shorts may not be particularly significant; the cable damage will have already either resulted in a short to ground or a hot short. The conclusions may not be so straightforward for thermoplastic cables, where inter-cable interactions are expected to be more significant.

5. Based on the evidence in the tests, the parameter p_{SA}, for multi-conductor cables in cable trays, is estimated to lie in the range (.5, .2), with a best estimate of .37.

6. The little evidence there is for cables in conduit suggests that the likelihood of an initial ground is considerably higher. See section 7.2.2 in SNL report. The EPRI data is inconclusive, and not clear. The report says for Test #15 the only actuations occurred in conduit. The summary table identifies the actuation as cable 2 in the tray. However, as the results for Test #8 show, hot shorts cannot be ruled out for cables in conduit.

<u>The Case of Two Spurious Actuations</u>

Although not requested of the expert panel, it appears that there is also interest in considering two simultaneous spurious actuations. The parameter, p_{SA}, evaluated above does not apply, unless the two actuators are routed through the same cable, since it is based on the intra-cable test data. If two cables fail, there is no reason not to treat the probabilities as independent, since the factors that govern whether actuation occurs before grounding, are, as much as can be determined from the limited data, random. However, the coupling factor between the two spurious actuations would be that both cables be damaged by the same fire..

<u>The Case of Multiple Spurious Actuations</u>

Focusing on one component may be non-conservative. In general, the impact of associated circuits would have to be addressed through the following equation:

$$\Delta CDF = F_f * p_E * M * p_{AS} * p_{DM} * \sum_i (p_{SA} * \Delta P_{CCD})_i$$

where the terms have the original interpretation, but the newly included summation is over the different combinations of possible spurious actuations. In other words, to properly evaluate the impact on risk of spurious actuations is an evaluation of the likelihood of groups of spurious actuations, p_{SA}^i, each of which is associated with a change in CCDP, ΔP_{CCD}^i. Each group of spurious actuations affects different cutsets and different accident scenarios.

If this general equation has to be used, the probability evaluated here will not apply. The joint probability of more than one spurious actuation will be a function of many factors, including the relative placement of the cables within the tray, whether the cables are connected to more than one actuator, the type of insulation, etc.

In the case of the more general problem of addressing all spurious actuations, if there are correlations between cable failures, they could have a significant impact, since they can lead to multiple spurious actuations. Cable failures will be correlated if they see the same thermal insult. It may be arguable that the most significant coincidences of spurious actuations are not likely. Consider the spurious actuations of two redundant components. The actuation circuits will not be run in the same cable, and probably not in the same tray. Therefore, the cables would see different conditions and may not respond in the same way. Spurious actuations of multiple components whose cables run in the same tray are more likely and more correlated. However, it is also likely that they will not have the same compounding effect that simultaneous actuation of redundant components would. This, however, is beyond the scope of the expert panel.

Appendix B-6 Report of Mark H. Salley

EPRI/NEI Expert Panel Input Regarding
Fire Induced Cable Failure and Resulting Spurious Actuations

Mark Henry Salley
NRC/NRR

Introduction

I have had the opportunity to view Gareth Parry's "Analysis of the EPRI/NEI Test Data" dated August 21, 2001, and Steve Nowlen's "Fire-Induced Cable Failure Spurious Actuation likelihood Estimates" Revision 0. In principle, I believe both Experts opinions are reasonable:

Mr. Parry has devised a single "best estimate" of 0.37 likelihood of spurious actuation given the limited amount of testing results and numerous variables included. If only a single value is to be used for all control circuit scenarios, Mr. Parry's single value is reasonable average (although I would not go so far as to say "conservative/worst case/bounding" by any case, due to the effects of material properties of the cable polymers and circuit arrangement.)

Mr. Nowlen's approach is somewhat more specific to some of the variables included in the testing. His specific values (Tables 1 through 6) provide a higher degree of accuracy if certain variables are known. Mr. Nowlen also does an excellent dissertation on all the unknowns going into the evaluation. His results and estimates are believable.

My evaluation lies somewhere between both their evaluations and hopefully adds some additional insights to the problem. The values used to form my opinion are derived from the "raw" test data and Omega Point Laboratories (OPL) "*Draft Report for the Use of the EPRI Expert Panel Special Testing, Cable Tray Testing within a Steel Enclosure*" Project No. 16333 - 108003, dated July 23, 2001. Based on this information I have constructed Table 1 to support my evaluation.

Table 1
EPRI CABLE FIRE TEST SUMMARY - PROJECT 16333-108003, 2001

Test No.	Cable Insulation Type	Approximate Fire Size (kW)	Approximate Surrounding Air Temperature at Failure (Note 1) °F (°C)	Maximum Cable Temperature at First Failure °F (°C)	Average Cable Temperature at First Failure °F (°C)	Time to First Failure (Minute)	Number of Spurious Actuations # Possible/4	Number of Shorts # Possible/16
1	Armored/Thermoset	350	700 (371)	700 (371)	575 (302)	36	1/4	3/12
2	Thermoset	70	630 (332)	680 (360)	490 (254)	45 (Note 2)	Note 3	Note 3
3	Thermoset	145	520/660 (271/349)	785 (418)	430 (221)	44	3/4	10/12
4	Thermoplastic	145	350/700 (177/371)	390 (199)	200 (93)	3	4/4	12/12
5	Thermoset	200	620/750 (327/399)	660 (349) (Note 3)	530 (277) (Note 3)	(Note 3)	Note 3	Note 3
6	Tefzel/Thermoplastic	200	550/530 (288/277)	465 (241)	445 (229)	32	3/4	12/12
7	Thermoset	350	800/750 (427/399)	680 (360)	620 (327)	36	2/4	9/12
8	Thermoset	145	560/450 (293/232)	770 (410)	530 (277)	57	2/4	5/12
9	Thermoset	145	840/375 (449/191)	950 (510)	500 (260)	6	2/4 (Note 4)	6/12

EPRI CABLE FIRE TEST SUMMARY - PROJECT 16333-108003, 2001 (Con't)

Test No.	Cable Insulation Type	Approximate Fire Size (kW)	Approximate Surrounding Air Temperature at Failure (Note 1) °F (°C)	Maximum Cable Temperature at First Failure °F (°C)	Average Cable Temperature at First Failure °F (°C)	Time to First Failure (Minute)	Number of Spurious Actuations # Possible/4	Number of Shorts # Possible/16
10 (Note 5)	Thermoset	200	950/860 (510/460)	990 (532)	620 (327)	2 (Note 6), 57	2/4	9/12
11	Thermoset	145	775/450 (413/232)	591 (311)	504 (262)	57 (Note 7)	0/4	3/12
12	Thermoset with CPT	145	500/360 (260/182)	700 (371)	440 (227)	13	1/4	12/12
13	Armored/Thermoset with CPT	350	750/725 (399/385)	713 (378)	609 (321)	25	0/4	4/12 (Note 8)
14	Thermoset with CPT	145	Note 9	825 (441)	Note 9	Note 9	Note 9	Note 9
15	Thermoset with CPT	350	1000/850 (538/455)	990 (532)	925 (496)	46	1/4	12/12
16	Thermoplastic with CPT	145	400/350 (204/177)	440 (227)	280 (138)	3	1/4	12/12
17 (Note 5)	½ Theromset and ½ Thermoplastic with CPT	200	850/440 (454/227)	460 (238)	285 (141)	7	1/4 (Note 10)	6/12
18	Thermoset with CPT	250	Note 9	960 (516)	Note 9	103	Note 9	Note 9

Note 1: This temperature is an approximation of the east and west thermocouple trees at the height of the cable tray.

Note 2: Voltage on conductor DA1 begins to rise, but insulation does not fail.

Note 3: The test never developed temperatures high enough to cause creditable cable damage.

Note 4: Two spurious activations occurred within the same circuit (DA1-2 followed by DA 1-1). Only counted as 1 spurious actuation.

Note 5: Cable trays were in the vertical position.

Note 6: Device begins to chatter at 2 minutes, but does not lock in.

Note 7: Circuit DA3 spikes, but does not spuriously actuate or blow.

Note 8: All the fuses that blew were main fuses.

Note 9: No other data provided.

Note 10: Circuit DA 1-1 spurious actuated two separate times. Only counted as 1 spurious actuation. This was believed to be the thermoplastic cable.

CPT = Control power transformer 150 VA.

Analysis

1) A key parameters to the analysis (and major sticking point for the start of this Expert panel) is "what degree" of a thermal insult could lead to the cable damage and resultant probability of spurious actuation. Many of the evaluators proceeded along with the assumption that, "Given cable damage, what is the probability of spurious actuation." Before we can proceed with this assumption, its worth taking a moment and looking at the cable failure criteria. The conventional wisdom used today in evaluation methods such as EPRI "FIVE" use the threshold values of 700°F for "garden variety" IEEE 383 qualified cables and 400°F "garden variety" Non-IEEE 383 qualified cables. Understanding a little more about the material properties of electrical cables we can consider the IEEE 383 qualified cables as the "Thermoset" cables used in the testing while the Non-IEEE 383 cables would be those of "Thermoplastic" construction. Also, to simplify the evaluation, we can simply perform the evaluation using the temperature profiles rather than attempting to calculate the heat transfer from the given fire size and the physical effects/parameters of the test assembly (cable location, energy lost to the enclosure, and the thermochemistry of the fire, etc). Reviewing this data, the cables in Test #2and #5 never were raised to a high enough temperature for the thermoset insulation to thermally break down and lead to potential spurious actuations. As such these test will be excluded from the analysis. Looking at the Armored/Thermoset cable performance (Tests 1 and 13) the cables first failed at 700 and 713 °F measured on the cable. The other Thermoset cables (Tests 2,3, 5, 7, 8, 9, 10, 11, 12, 14, 15, 18,) first fail at 680, 785, 660, 680, 770, 950, 990, 591, 700, 713, 825, 990, and 960 °F respectively with the temperature measured on the cable jacket. Its worthwhile noting that four of the Thermoset cable tests first failed below the assumed 700 °F, one at 700 °F and eight at above the assumed 700°F value. While the 591°F appears a bit low, 660 to 680 °F may be a better, more conservative value for "garden variety" Thermoset insulation failure when exposed to fire environment. For the Thermoplastic cables, (Tests 4, 6, 16, and 17) the cables first failed at 390, 465, 440, and 460 F. Based on this information, the 400 F used for "garden variety" Thermoplastic cables is reasonable.

2) In order to evaluate the spurious actuations, it may be best to group the tests based on their physical parameters. For all these analyses, it will be assumed that the maximum number of spurious operations will be four per test based on the number of operating devices. Further, each device will only be counted once, such that for circuits that cycled in and out, or were energized at different times by different cable combinations, they will only be counted as one spurious operation. The introduction of a Control Power Transformer (CPT) into the circuit also showed a significant difference, and those tests will be grouped together. Tests #14 and #18 were alternately connected than the others and did not have actuation devices. As such, they will be excluded with Tests #2 and #5 (for reasons previously stated.)

<u>Armored Thermoset cable without CPT.</u>

Test #1 was the only test in this configuration. One spurious actuation (SA) out of a possibility of four, therefore, given this one data point, the probability is suggested at 0.25.

Armored Thermoset cable with CPT.

Test # 13 was the only test in this configuration. No SA occurred, and as such with this single data point, no probability can be established. It is suggested to use the value developed in the non-CPT circuit above. It is also worthwhile noting that in only this test, all four main fuses activated removing power from the circuit. This would suggest that the conductors failed first to the (grounded) metal jacket resulting in the blown fuses.

Thermoplastic cable without CPT.

Tests # 4 and 6 were tested in this configuration. Test #4 had all four circuits SA. Test # 6 had three of the four SA. This would suggest a probability of seven out of eight or 0. 88.

Thermoplastic cable with CPT.

Tests # 16 and 17 were performed in this configuration. Each test had one of the four circuits SA. However Test # 17 only had two circuits connected to activation devices. The suggested probability of one out of four, and one out of two, or 0.38.

Thermoset cable without CPT.

Tests # 3,7, 8, 9, and 11 were performed in this configuration. Test #3 had three of the four circuits SA, Test #7 had two of the four circuits SA, Test #8 had two of the four circuits SA, Test #9 had two of the four circuits SA, and Test #11 had none of the four circuits SA. This gives an average of nine of the twenty potential circuits SA or 0.45.

Thermoset cable with CPT.

Tests # 14, 15, and two circuits in Test #17 were performed in this configuration. Test #14 did not have data provided for the test. Test #17 did not either of the Thermoplastic circuits SA. Test #15 only had one of the four circuits SA. This suggests a probability of one out of six or 0.17.

Conclusions

The following table (Table 2) provides the conclusions from my evaluation. It must be cautioned that these values were obtained from a VERY SMALL population of testing, and should be used only for first order approximations. The CPT values are also bound by the “tight” electrical configuration of the 150VA CPT on a nominal 120V circuit. This application may be bound, for example, by NEMA size 1 starters which are limited to typically a maximum 7.5 HP motor. For circuits with a higher range, it is suggested to use the non-CPT values.

The “time” factor i.e., how long before cable damage, is also important, but beyond the scope of this evaluation. Cables have a mass that will have to be heated, and the position of the cable in the tray would have to be evaluated. However, just as big a variable in the overall analysis would be the fire growth rate. The fire “sizes” used in the testing were not very large, and for the most part “steady-state”, very different than a real fire which most FPE analyze using methods like T^2 growth rates.   So, to simplify this analysis, when the cable reaches its damage temperature, damage should be assumed.

Credit for suppression systems and activities should also remain separate from this evaluation. Their effectiveness and probabilities for success/failure are another evaluation altogether (e.g., human factors, system design, etc.).

This analysis is much more simplified i.e., given a fire that can produce a thermal insult to the cable in question, does it raise the cable•s temperature such that cable damage can occur, and if so, what is the probability of the control circuit having a spurious actuation.

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Appendix B-7 Report of R. Brady Williamson

October 4, 2001

Memorandum

To: Robert J. Budnitz,
From: Brady Williamson
Subject: EPRI Cable Testing

Introduction

As I have discussed with you by telephone, I have had a difficult time understanding what the data means in these fire tests. The arbitrary uses of different door opening heights was one of the features that has made analysis of the data so difficult. The actual fire scenarios created in each experiment are not well documented. There are however several conclusions I can make from my analysis of the information provided up to this point in time.

In discussing my findings I will use a ranking scale of 1 to 7 with the following meaning:

1 means very, very low probability of a false actuation given a fire (10^{-5})

2 means very low probability of a false actuation given a fire (10^{-4})

3 means low probability of a false actuation given a fire (10^{-3})

4 means 1% probability of a false actuation given a fire (10^{-2})

5. means 10% probability of a false actuation given a fire (10^{-1})

6. means 50% probability of a false actuation given a fire ($5*10^{-1}$)

7. means 100% probability of a false actuation given a fire (1)

The word "fire" in my rankings above means a fire which has reached sufficient size that there is a well-developed "hot-layer" in the fire compartment, and the cable is either directly exposed to the flame or is in the hot-layer. I assume that the fire is under-ventilated, and thus some combustion which could take place inside the fire compartment does not take place there.

I will use a three number set for each case. The *first number* gives my estimate of the least probable effect, the *second number* gives my estimate of the most probable effect, and finally the *third number* gives my estimate of the worst probable effect.

Thus (2, 4, 6) means:

a. My estimate of the least probably effect is that there is a very low probability of a false actuation given a fire (10^{-4}),

b. My estimate of the most probably effect is that there is a 1% probability of a false actuation given a fire (10^{-2}), and

c. My estimate of the worst probably effect is that there is a 50% probability of a false actuation given a fire ($5*10^{-1}$).

Thermoplastic Cable vs. Thermosetting Cable

This is probably the most distinctive finding of the research conducted on this topic. Thus if one does not make any distinction about other details which will be presented below and only focuses on the "nature" of the cable, (i.e., *thermoplastic cable vs. thermosetting cable)*, then I find:

Given *thermoplastic cable* then: (3, 5, 6)

Given *thermosetting cable* then: (1, 3, 4)

The Effects of Temperature

I have read Fred Mowrer's report[10], and I agree with his findings. Temperature seems to be the most important parameter, but it still leads to the same view that I expressed in the previous section. Thermoplastic cable is much more reliable than thermosetting cable. (I did not single out "armored" cable, but as Fred shows it is almost as good as thermoset cable.)

It is not unusual for the upper layer in a fire to reach 400ºF, and thus the (3, 5, 6) rating I gave thermoplastic cable. Note that my evaluation starts with "given a fire". Fires are not easy to quantity in a probabilistic fashion. The EPRI test series has some severe limitations, but it does show the distinct difference between thermoplastic and thermoset cable.

[10] F. W. Mowrer, "NEI/EPRI Expert Elicitation Panel Report (Supplement 1)" 10-25-01.

Table 2
Results

Cable Insulation and Control Circuit Type	Probability of Spurious Actuation	Cable Temperature to Cause Actuation °F (°C)
Armored Jacket w/ Thermoset Insulated Conductors, with/without CPT	0.25	700 (371)
Thermoplastic w/o CPT	0.88	390 - 400 (199 - 204)
Thermoplastic with CPT	0.38	390 - 400 (199 - 204)
Thermoset w/o CPT	0.45	660 - 680 (349 - 360)
Thermoset with CPT	0.17	660-680 (349 - 360)

C
PEER REVIEWERS' REPORTS

Appendix C-1 Peer Review Report of Dennis W. Henneke

Appendix C-2 Peer Review Report of Neil E. Todreas

Appendix C-1 Peer Review Report of Dennis W. Henneke

Dennis W. Henneke

Independent Review of
"Spurious Actuation of Electrical Circuits
Due to Cable Fires: Technical Integrator's Report,"
Version 8, March 2002.

1.0 INTRODUCTION

The purpose of this report is to provide an independent peer review of the technical results documented in the "Spurious Actuation of Electrical Circuits due to Cable Fires" Technical Integrator's Report," Version 8 (this is referred to below as the "Report" or the "Final Report"). The peer review report contained below is one of two peer reviews for the Final Report. A draft of this peer review report was provided as part of the comments on the version 5 of the Report.

2.0 BACKGROUND

Per the Report, the peer review is to provide an evaluation of "both the process and the technical product." The background for development of the technical product is not repeated here, but can be found in the Final Report.

Peer reviewers participated in the process by receiving and reviewing information provided to the entire panel, and participating in conference calls. In general, peer reviewers did not ask many questions or provide opinions during either the conference calls or through the many e-mails that were sent out during the process. As such, we generally just watched over the process, and remained independent. However, to ensure the final technical product was adequate, the peer reviewers had to perform much of the same data review and analysis of the information and data provided as was required of the panel members. This helped ensure the final technical product was within the uncertainty of the expected value.

3.0 RESULTS

Discussions on the results provided in the Final Report are provided below. These include discussion on the expert panel process, the technical results, and a discussion on conservatism in the final results. The discussion on conservatism is provided below as a point of information, but is not considered to affect the final usefulness of the final results.

3.1 Process

The process involved the dissemination of information via e-mail, mail, and numerous conference calls. This process is described in the Report, Sections 2.1 to 2.7. Although the process was somewhat disorganized, and took longer than expected, there were no issues resulting from the process that would greatly affect the results. The process developed, and information provided, should be sufficient to provide the experts with all of the tools needed to evaluate the technical questions requested.

That said, it is surprising that the resulting reports from most of the experts did not produce what was asked by the task leader, and what was agreed upon as the "technical question." This point was noted in the Final Report. The Technical Question was:

> Under what conditions could a serious fire affecting cabling in a nuclear power plant cause the spurious actuation of electrical/electronic circuits that could affect the plant's safety? and What is the probability of such actuation conditional on those conditions?

For example, a condition that affected spurious actuation was the inclusion of CPTs (Current Power Transformers). 5 of the 6 experts did not address this influence factor. Other influence factors ignored by a majority of the experts include: failure mode (Inter or Intra-cable), Number of Conductors, and Conduit or armor. Additionally, 5 of 6 experts did not use or present significant data analysis in support of their conclusions. These facts, combined with the 4 additional experts who did not submit any report or estimate, results in a less supported product. In many cases, this leaves the technical integrator with no choice but to base the final estimates for the technical product on the one expert who did try to perform both the data analysis and quantify influence factors.

This is probably not a big issue for areas where there is significant data from the tests. Where significant data exists, independent data analysis by 2 or 20 experts should result in similar results. However, extrapolated estimates where there is little or no data are most likely highly uncertain. Analysis by most of the experts would have helped reduce the uncertainty in many areas, and solidified the product from the process.

The expert panel was provided several drafts of the report, resulting in comment, feedback, and eventually buy-in of the final product. This review and feedback process, although somewhat different that the original design of the panel process, did provide some assurance that the final results of the Report are supported by the experts.

In summary, the process performed in support of the Report was performed as expected, and although many of the experts did not provide the expected analysis results, the Report findings are supported by the experts and the expert panel process.

3.2 Technical Product

In general, the Technical Product provided in Draft 5 of the Report is considered adequate and well supported by experimental data.

The technical product is mainly provided in Tables 7-1 and 7-2 of the Report. These tables are supported through separate discussion in the Report, including the sections referenced in the tables. In addition, there is discussion on other areas, such as damage temperature, as presented in Figure 1.

As mention in the introduction above, a draft of this independent review was provided to the technical integrator. This draft included both major and minor comments of the draft report. Review of the Final Report indicates that all major comments have been incorporated, and there are no outstanding comments that affect the technical accuracy of the final results.

3.3 Conservatism In the Final Results

Based on a review of the panel member reports and the experimental/test data, the final results presented both in Figure 1 and in Table 7-2 are considered conservative. Discussions on both technical products are provided below. This conservatism is noted here as a point of information, but is not considered to affect the final usefulness of the final results. As shown below, the expected results, and the recommended values as provide in the Report are reasonably close.

3.3.1 Figure 1 Conservatism

The values in Figure 1 are mainly supported analysis from a single expert. The figure represents temperature versus damage probability. Several of the tests resulted in cables within the range of the figure, which were not damaged, and remained operable throughout the test. Judgement was used to incorporate these into the figure. However, it is unknown what temperature these cables would have failed. In the Armored cable tests, for example, several of the cables did not fail. With un-failed cables the Figure 1 curve should have not been extended to show all cables failed, thus either lowering the curve to show lower probabilities, or by moving the curve to the right to show all cables failed at some higher temperature than the test provided. Overall, there is probably a 10-20% (estimated) error in the final results, based on the number of operable cables for each type.

3.3.2 Table 7-2 Conservatism

The values in Table 7-2 are mainly supported by data analysis from a single expert and additional analysis by the technical integrator. Other experts provide some support for portions of the table. The data analysis of the test data shows values slightly lower than the reported results, for a little over half of the results. For example, the T-set and T-plastic intra cable results show 0.25 based on the test data and 0.3 in Table 7-2. This is only a 25% difference, and within the range as specified in Table 7-2. However, when looking at multiple circuit failures, this difference can propagate. For example, a combination of three failures would result in 0.015 based on the data, and 0.027 based on Table 7-2 – or a 73% difference.

The data results provided by one of the experts is derived using one of several possible ways to analyze the data. In general, the data segregates the failures based on 4 cables per test, with any circuit failure in the 3 circuits per cable counted as a circuit failure. Thus the numerator in the failure rate is the number of failures in any cable (any of the 3 circuits per cable), divided by the total number of cables. If the data were analyzed as 12 circuits per test rather than 4, the resulting failure data would be slightly lower for most categories in Table 7-2. For example, if there were 3 circuit failures in one test, and 2 were on cable 1, the method used by the expert would get a value of 0.5 (2 cables failed in 4), while the alternate counting method would result in 0.25 (3 circuits failed in 12). Based on discussions during the expert review process, it is generally agreed that the method used by the expert would represent what we would see in the plant for MOVs with multiple circuits in a single cable. However, some components or circuits may only contain a single circuit per cable that can result in a circuit failure. Thus the lower value would be more applicable.

The point of the above discussion is that the data analysis provided by the single expert is reasonable, but probably represents an upper bound to the types of circuits we would see in the plant. The results provided in Table 7-2 are generally above the data analysis results, and are thus considered conservative in two areas; a) Table 7-2 results are slightly above the supporting data analysis, and b) supporting data analysis is probably an upper bound for cables with less than 3 circuits per cable.

As stated above, the difference in all cases reviewed is within the range as specified in Table 7-2. For example, the 0.3 value above has an assigned range of 0.1 to 0.5, with data results providing a 0.25 value and alternate data results in the range of 0.18. Based on this, the final results are considered acceptable, but conservative by 20% to 50%.

4.0 CONCLUSIONS

Based on an independent peer review of the process and the technical product provided in Revision 8 of the Final Report, the technical results are considered adequate and accurate, with conservatism. Although many of the panel members (technical experts) did not provide comprehensive responses to the technical question, the final results reasonably represent the test data.

Appendix C-2 Peer Review Report of Neil E. Todreas

Peer Review Report of Neil E. Todreas
on the Project
"Spurious Actuation of Electrical Circuits Due to Cable Fires"

CHARGE

The charge to the Peer Reviewers, issued was to evaluate both the process followed and the technical product.

SCOPE OF REVIEW I CONDUCTED

In executing the Peer Review function I received all documentation made available to the Experts as well as their own reports and was invited to participate in all Project telephone conferences. My actual participation was in about half these conversations due to schedule conflicts. However the Technical Integrator prepared and circulated a report of all telephone conferences.

My technical competence is in the area of reactor engineering more specifically the design and safety aspects of energy extraction. While, I am generally conversant with the impacts of fire technology on reactor safety, I am not an expert in this area nor importantly on the possible effects of fires on plant electrical/electronic circuits which could affect plant safety. My evaluation and comment is focused primarily on the integrity of the process by which this Project was executed. I close with comment on the Technical Product of the Project.

EVALUATION OF THE PROCESS OF THE PROJECT

1) The Project conduct proceeded through a number of sequential, distinct steps modeled after the “SSHAC methodology” described in NUREG/CR-6372. These included

   - Problem definition
   - Expert Reporting
   - Technical Integrator Draft Report
   - Expert Review of Technical Integrator Draft Report
   - Technical Integrator Revised Report
   - Expert Review of Technical Integrator Revised Report
   - Technical Integrator Final Report

In executing these steps several key principles were followed

- The definition of the "technical question" to be answered by this Study was formulated with extreme attention. This effort was successfully directed to developing relevant subsidiary questions. The Experts individually confirmed that one or more of these questions could be answered based on their expertise.

- The Technical Integrator's reports was subject to review and comment by the Experts at the key stages of its preparation i.e. first draft and final report.
- The Technical Integrator was informed but not bound by the opinions offered by the Experts. The Technical Integrator in the end was solely responsible for the overall evaluations and the final Project report.

2) Discussion of Potential Issues in the Conduct of the Study

In this section I identify and discuss factors I observed which might have the appearance or potential of impacting the integrity of the Project.

2.1 Independence of Process from the Customer and the Regulator

Both the Project managers (R. Kassawara, EPRI in coordination with F. Emerson, NEI) and the regulatory coordinator (N. Siu) participated as they were available in the group telephone conversations and in some exchange of correspondence. Their interactions were not framed or expressed in any manner to influence the integrity of the technical evaluations performed. Other members of the regulatory research staff, G. Parry and M. Salley, participated with the Group, but their role was as technical experts. Their participation was expressed through their reports and comment on the Technical Integrator’s product. Therefore their status as regulators was not a factor which otherwise impacted the conduct of their interaction with the Group.

The NEI (Fred Emerson) also oversaw the execution of the Omega Point tests and provided the Group initially with synopses and subsequently with full reports of the test data. Emerson's interactions with the Project regarding these tests were also not framed or expressed in any manner to influence the integrity of the technical evaluations performed.

2.2 Expert S. Nowlen's Additional Relationship with the Test Data

Steve Nowlen, SNL led a team of two other SNL investigators in obtaining additional information on insulation resistance in certain cables during each of the Omega point tests. This activity was sponsored by the USNRC. Nowlen also served as a Technical Expert and consequently evaluated all the Omega Point test data. From review of his report and limited telecons that we were both present, I detected no bias in his contributions to the group by virtue of his implied ownership of a segment of the test data. On the contrary, I believe his familiarity with the Omega Point program was beneficial to the Group by virtue of the insights into the test program that his participation in the insulation resistance measurements offered.

2.3 Deviations from the Proposed Project Methodology

The central step in the Project (per the Technical Integrator, pg 7 of the Final Report) was the evaluation by each Expert of the relevant technical information. It was expected that the Technical Integrator draft report was not to be available to the Experts prior to receipt by the Technical Integrator of the Expert’s reports.

This procedure was followed by all Experts who submitted reports with the exception of M. Salley, USNRC who had the Technical Integrator draft report (as of 4 December 2001) prior to submitting his own report (received by the Technical Integrator on 3 January 2002.)

The Technical Integrator did review and consider the Salley report in the preparation of his final report. The Technical Integrator has informed me upon my inquiry that while he considered Salley's input useful he felt that no changes were necessary to his final report based on the Salley input. Thus Salley's input, while not provided in the prescribed Project manner, was useful to the Technical Integrator in confirming his judgements but did not offer the Technical Integrator new insights leading him to modify or supplement his draft Report.

2.4 Contraction of the Group of Experts Finally Participating in the Project

At the outset ten Experts were recruited and started this Project. At the end of the process only six Experts (Salley is excluded in this count) submitted independent evaluations to the Technical Evaluator. The attrition raises two questions which need to be addressed:

1. Did the dropouts occur for any reason which reflects on the integrity of the Project process?
2. Is the resulting Group of six Experts sufficient in breadth and depth of technical expertise to confirm the adequacy of the technical underpinning of this Project?

Answers: 1) Dropouts - 3 expert utility participants did not submit reports. The Technical Integrator responding to my inquiry stated that these participants were unable to ultimately participate because the time period they had set aside for this activity was passed by as the Group worked to define the specific questions to be addressed. When these were established and work could have begun, these three individuals had other commitments which precluded their return to this job. None of the three contacted me with concerns about the conduct of this Project as the reason for their action nor did I sense any basis for such a concern.

2) Adequacy of Composition of the Participating Experts - The affiliation and field of expertise of the 6 experts who did complete the study are given in the Table below. Included is a seventh, M. Salley, a participant whose contribution was not prepared in the fully independent manner as the other 6 (this difference in process is covered in Section 2.3 above). A similar Table for the 3 Experts who dropped out is also given below.

Comparison of these Tables confirms that the participating experts did possess as a group the expertise across the full range of needed subject areas - Cable, Electrical, Nuclear Safe Shutdown, Fire, Testing, PSA, Fire Protection - and the experts who dropped out would have deepened the coverage in certain areas but were not needed to otherwise expand the range of subject areas. It is noted that Salley uniquely covers Fire Protection. I, however, do not consider the actual circumstances of his preparation of his report as sufficient grounds to disqualify him as an Expert participant and conclude that the Fire Protection area was adequately covered by the Expert Group.

Participating Experts	Affiliation	Field of Expertise
Funk, D.	Engineering Consultant	Cable/Electrical/Nuclear Safe Shutdown
Leake, H.	Utility	Nuclear Safe Shutdown
Mowrer, F.	University	Fire / Testing
Nowlen, S.	National Laboratory	Fire / Testing
Parry, G.	Regulator	PSA
Williamson, B.	University	Fire / Testing
Salley, M.	Regulator	Fire Protection / Testing

The analogous information for the three dropouts is

Dropout Experts	Affiliation	Field of Expertise
Brown, K.	Utility	Cable / Testing
Circle, J.	Utility	Fire PSA
O'Connor, T.	Utility	Fire Protection

Evaluation of the Technical Product of the Project

I find the technical product encompassing the Technical Integrator's final report and the Expert reports as constructive and useful responses to the question under study, the determination of P_{SA}, the overall probability of spurious actuation.

I have no technical critique to offer regarding these individual efforts. My observations deal with the usefulness of the final product from now viewing the project in hindsight. The end product, Tables 7.1 and 7.2 together with the Expert reports do provide a far more specific basis upon which to evaluate/estimate PSA than has previously existed. However, as the Technical Integrator's report emphasizes there are uncertainties with the probabilities deduced for the cases where even extensive data was available (the Base Case). For cases where only limited data was taken (the variants on the Base case including electrical configuration issues and configuration influence factors; pgs 31-38) uncertainties are even greater.

Two factors contributed to these uncertainties. The first factor is the scope and conduct of the test program. The scope was in fact broad and of course necessarily bounded. Hence, all variables of interest could not be fully explored. On the other hand, the uncertainties introduced by the vertical variation in the external ventilation configuration and the lack of use of a Control Power Transformer (CPT) in early tests were avoidable and introduced unfortunate limitations on the subsequent interpretation of the data.

The second factor was the manner in which the data was evaluated and conclusions drawn. The Project process essentially led to individual evaluations exchanged in a very structured manner. While that process did achieve maintenance of independence among the Experts and Technical Integrator throughout the process, it occurred at the expense of more fully coordinated, consistent evaluation of all the Project data. Certainly in some areas, detailed Expert evaluations together with subsequent Technical Integrator evaluation achieved the desired in-depth review. However, this was not the case across the spectrum of technical areas. In my judgement, evaluation of the data by a technical team lead by the Technical Integrator or his equivalent which periodically met and always worked in a continuing collaborative and hence synergistic manner might likely have achieved greater insight into the data and the answers to desired probabilities. The collective evaluation of such a group could then have been subjected to a peer review as desired by the sponsors.

SUMMARY

I believe the integrity of the Project was maintained throughout its duration. The Project was executed with careful attention to the selected process and produced a result based on the Expert and Technical Integrator evaluations of the available technical information. From my observation these evaluations reflected only the technical judgements of these individuals.

Target:
Nuclear Power

About EPRI

EPRI creates science and technology solutions for the global energy and energy services industry. U.S. electric utilities established the Electric Power Research Institute in 1973 as a nonprofit research consortium for the benefit of utility members, their customers, and society. Now known simply as EPRI, the company provides a wide range of innovative products and services to more than 1000 energy-related organizations in 40 countries. EPRI's multidisciplinary team of scientists and engineers draws on a worldwide network of technical and business expertise to help solve today's toughest energy and environmental problems.

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