SAND99-1257C

CABLE HOT SHORTS AND CIRCUIT ANALYSIS IN FIRE RISK ASSESSMENT[a]

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JUN 09 1999
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ABSTRACT

Under existing methods of probabilistic risk assessment (PRA), the analysis of fire-induced circuit faults has typically been conducted on a simplistic basis. In particular, those hot-short methodologies that have been applied remain controversial in regards to the scope of the assessments, the underlying methods, and the assumptions employed. To address weaknesses in fire PRA methodologies, the USNRC has initiated a fire risk analysis research program that includes a task for improving the tools for performing circuit analysis. The objective of this task is to obtain a better understanding of the mechanisms linking fire-induced cable damage to potentially risk-significant failure modes of power, control, and instrumentation cables. This paper discusses the current status of the circuit analysis task.

I. INTRODUCTION

Hot shorts are electrical faults that occur between any two cable conductors without a loss of the conductor integrity and without a simultaneous shorting of the conductors to the local ground plane. Hot shorts are a unique mode of conductor failure and are distinguished from a short to ground or open circuit fault. While a short to ground or open circuit may render a system unavailable, a hot-short fault might lead to spurious actuations, misleading signals, and unrecoverable losses of plant equipment. These faults may have unique and unanticipated impacts on plant safety systems and on plant safe shutdown capability that may not be reflected in current fire PRAs. To assess the risk significance of hot-short conductor faults, several pieces of information are needed.

First, one must characterize potential cable behavior during the fire. This must include identification of the possible modes of cable conductor failure that might occur, characterization of the cable parameters that will contribute to or mitigate the hot short potential for each failure mode, and assignment of some conditional probability that a given fire-induced conductor fault will occur. Efforts to address these needs through reviews of the available literature and actual fire events are currently under way.

The second factor that must be determined is the impact of a given hot-short failure on plant systems. For example, a hot short in a control circuit may have many potential effects, including simulating the closing of a control switch, application of destructive voltages to a lower voltage circuit, or simply rendering a control circuit path inoperable. Instrumentation circuits might also suffer degradation due to a hot short, but the resulting systems effects might be unique. For example, while various cable faults might render the instrumentation system unavailable, a partial short (loss of insulation resistance without a dead short) between conductors of a low-voltage, current-driven instrumentation signal wire might result in signal bias, producing misleading indications. The paper presents one framework for identifying possible circuit failures resulting from all possible types of fire-induced conductor faults.

Finally, one must consider how to quantify the risk contribution from postulated hot short and other conductor faults. Guidance is needed to direct analysts in the assessment of hot short faults. The paper closes with a number of comments relevant to the development of such guidance.

II. CIRCUIT ANALYSIS FRAMEWORK

To obtain a better understanding of the mechanisms linking fire-induced cable damage to potentially risk-significant failure modes of equipment, models linking fire-induced conductor failure modes to circuit failure modes are

[a]This work was supported by the U.S. Nuclear Regulatory Commission and was performed in part at Sandia National Laboratories. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy under Contract DE-AC04-94AL85000.

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being developed. Key parameters that may significantly affect the likelihood of different circuit failure modes during a fire are being identified. These parameters include the circuit design features, cable physical features, and the layout of the cables in trays. In addition, sources of data are being identified for use in the quantification of the conductor fault models. Each of these parameters is discussed in more detail in the following pages.

The importance of circuit design features is being examined and documented using a Failure Modes and Effects Criticality Analysis (FMECA) approach[1] applied to a spectrum of circuit designs used at existing nuclear power plants. The circuits being reviewed encompass those used for powering and controlling components required for mitigating accidents and thus are those typically modeled in PRA's. In addition, design practices are being examined to identify instrumentation required for actuation and control of mitigating systems and for providing the operators with information on the status of key reactor parameters. Examples of parameters that are being examined include the presence of circuit protection features (i.e., fuses or circuit breakers) and signal lock-in features in the circuit.

The FMECA process is being used to identify possible circuit faults resulting not only from hot shorts but also from different failure modes of cables, including open circuits, shorts to ground, and high impedance shorts to power or ground. Examples of potential circuit faults arising from fire-induced cable failures include low currents to signal processors, spurious energization of a relay, and loss of power to portions of a control circuit. The FMECA process also identifies the corresponding circuit failure modes resulting from the identified circuit faults. Examples of circuit failure modes resulting from the circuit faults include complete loss of function, an incorrect instrumentation reading, spurious activation of a component, and the inability to change the state of a component. The FMECA will also indicate when the circuit failure mode can result in different component faults that are dependent upon the system design. For example, an air-operated valve can be designed to fail either open or closed when the power to the controlling solenoid valve is lost. Thus, the parameters affecting whether a fire results in either energizing or de-energizing a solenoid-operated valve (SOV) have to be examined.

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

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

To illustrate the insights that can be obtained from a circuit FMECA, a portion of the FMECA for a simple SOV control circuit (shown in Figure 1) is provided in Table 1. The FMECA is for Conductor 2, which runs from the main control panel to the valve through two separate areas. The FMECA addresses all possible Conductor 2 faults external to control cabinets (i.e., an open circuit, a short to ground, and hot shorts to both internal circuit conductors and external conductors). A criticality ranking for each conductor fault is provided in Table 1. The definitions for the criticality rankings are provided in Table 2. Table 2 also provides a summary of the number of conductor faults for the circuit for each criticality ranking.

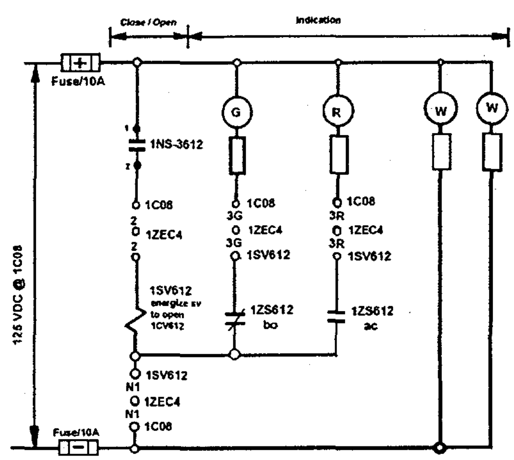

Figure 1. Example solenoid-operated valve control circuit.

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

- many of the identified conductor faults result in the inability to open the SOV,

Table 1. Example FMECA – SOV Conductor 2.

Identification	Failure Modes	Effects	Criticality
Conductor 2 Positive dc power lead	1) Open circuit	Valve inoperable	5
	2) Short to ground	None	0
	3) Hot short to +125 Vdc source	Valve spuriously opens	9
	4) Hot short to -125 Vdc source	+ fuse will blow when HS contacts 1-2 are closed, valve inoperable, loss of position and power indication	7
	5) Shorts to 3R	None	0
	6) Shorts to 3G	Fuse will blow when HS is closed, valve inoperable	7
	7) Shorts to N1	Fuse will blow when HS is closed, valve inoperable	7
	8) Shorts to 3R & 3G	Spurious OPEN indication light, fuse will blow when HS is closed, valve inoperable and loss of position and power indication	6
	9) Shorts to 3R & N1	Spurious OPEN indication light, fuse will blow when HS is closed, valve inoperable and loss of position and power indication	6
	10) Shorts to 3G & N1	Fuse will blow when HS is closed, valve inoperable and loss of position and loss of position and power indication	7
	11) Shorts to 3R & 3G & N1	Spurious OPEN indication light, fuse will blow when HS is closed, valve inoperable and loss of position and power indication	6

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

III. CABLE CONFIGURATION EFFECTS

The cable configuration is an important factor to be considered in a circuit analysis since the potential for a fire-induced circuit fault is dependent upon the proximity of the individual conductors of the control circuit. For example, the potential for a hot short would likely be greater if multiple portions of the same control circuit are contained within the same cable, as opposed to being separated in different cables. Even if portions of the control circuit were located in separate cables, a potential for hot shorts would still exist if one conductor in the cable was energized. That potential would seemingly be greater as the number of conductors in the cables increases. Similarly, whether the cables have ground wires obviously would affect the potential for the different types of cable faults. An important part of this research effort is to: (a) determine if there is a strong technical basis supporting the previous expectations, and (b) identify other cable design factors that may also be important in determining the potential for different cable faults.

The physical location of a cable in a cable tray and cable protection features will also likely be factors that must be addressed in assessing the potential for hot shorts during a postulated fire scenario. The loading of a cable tray would likely be a consideration since the number of cables in the tray and their function could increase the probability for various cable faults. The location of the cable of interest within the tray may also be important. For example, the potential for a high-impedance short to ground may be greater for a cable located at the bottom of the tray. Obviously, whether a cable is enclosed inside a conduit would also affect the potential for certain cable faults. If

Table 2. Conductor fault criticality ranking.

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

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

cables are strapped to a tray to prevent movement; then the potential for a particular circuit fault may be reduced since the associated conductors may not be able to contact each other. These and other cable parameters and tray configuration considerations will be identified and included as parameters in assessing the likelihood for fire-induced circuit faults.

Other environmental factors resulting from a fire also need to be considered in establishing the potential for fire-induced circuit faults. One major environmental factor is the use of water to suppress a fire. Since this can cause electrical shorts, the potential for circuit faults resulting from shorts should consider the operation of automatic water suppression systems and manual fire suppression actions.

The results of the above efforts can be combined to develop guidelines for identifying potentially risk-significant fire-induced power, control, and instrumentation faults. These guidelines would be qualitative in nature and consist of screening criteria that identify circuit features, cable types, cable layout, and other environmental factors affecting circuits that could be important to fire risk.

IV. CONDUCTOR FAULT LIKELIHOOD

In order to quantify the risk impact from fire-induced conductor faults, the conditional probabilities for such faults must be established. Currently, there are no probabilities that can be traced to experimental results or data analysis. A common value used in fire PRAs for the mean conditional probability of a hot short given cable damage from a fire is 6.8E-2. This value is the mean value of a distribution proposed in NUREG/CR-2258[2] and represents a judgement of the report authors based on empirical evidence available at that time. In some fire PRAs, the square of this value has been incorrectly used to determine the probability of two hot shorts due to the same fire.

Better estimates of conductor fault probabilities conditional on fire damage are required in order to provide a reasonable estimate of the risk from fires. Ideally, complete probability distributions would be used to model the uncertainty for each conductor fault type under various circuit design, cable type, and cable layout conditions. In addition, probability distributions for multiple conductor faults caused by a single fire are also required. Since the duration of the conductor fault can be important to the associated circuit failure and its impact on a systems operation, distributions for the duration of conductor faults are also required for fire risk evaluations.

Data on conductor faults during fires are somewhat limited. There are some pertinent experimental data involving cable fire tests. This includes experimental work performed by Sandia National Laboratories (SNL),[3,4] Factory

Mutual Research Corporation,[5] the Republic of Germany,[6] and by Lawrence Livermore National Laboratory.[7] In addition, actual fire events can provide useful data. A potential major source of data is the Browns Ferry fire[8] which included spurious initiation of components, spurious control room annunciation, spurious indication light behavior, and loss of many safety-related systems. This fire damaged over 1600 cables routed in 117 conduits and 26 cable trays. Correlation of the reported events with the circuit designs, cable type, and cable layout could provide a significant source of data for determining the probabilities and durations of fire-induced cable faults. Finally, non-nuclear fire events such as the Hinsdale telecommunication fire[9] may also provide useful data.

As part of the USNRC program to improve fire risk analysis methods, SNL is currently reviewing pertinent experiments and fire incidents for use as fire-induced cable fault data sources. From these data, it is planned to establish probability distributions for single and multiple conductor faults for various circuit, cable, and layout configurations. In addition, the data sources will be reviewed for relevant insights into the behavior of conductors and circuits caused by fire damage to cables.

It should be noted that potential scarcity of data may prevent construction of probability distributions for each unique configuration. In this situation, the probability distributions generated would have to coarsely cover a range of conditions. Thus, parameters significantly affecting the uncertainties in the obtained distributions will be identified and the limitations on the use of the data will be clearly documented.

V. INCORPORATION OF CIRCUIT ANALYSIS INTO A FIRE PRA

Since circuit analysis is a time-intensive process, screening methods are needed to appropriately limit the scope of the circuit analysis to those components important to fire risk. This screening can be performed as part of the fire PRA process.

Quantitative screening of conductor faults may be possible once documented probability distributions for such failures are available. These data may indicate that the potential for certain circuit faults under identified conditions may be small relative to the random failure probability for components resulting in the same effect and thus can be eliminated from fire risk assessments. However, the probability of multiple conductor faults due to a fire will likely limit this screening potential.

ACKNOWLEDGMENTS

This research project is sponsored by the USNRC, Office of Research, Probabilistic Risk Assessment Branch under the guidance of Dr. Nathan Siu and H.W. Woods.

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