Methods of Circuit Analysis for Fire PRA

Jeffrey LaChance

Sandia National Laboratories

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Key Points of Presentation

- Experimental data shows that there are a number of factors that can influence potential for different cable failure modes
- Use of one detailed circuit analysis method (FMECA) provides the connection between the cable fault and the component behavior
- There are circuit design features that can influence the impact of cable failures on component operation
- Experimental data suggests that the probability of hot shorts may be higher than values used in many fire risk assessments (FRAs)
- Review of fire experience indicates that spurious component operations have occurred
- The hot short probabilities used in FRA should be a function of important circuit- and scenario- specific factors
- The evaluation of fire-related risk needs to consider possible combinations of conductor faults and their timing/duration

Outline

- Role of Circuit Analysis in FRA
- Functional Modeling Framework
- Potential Factors Influencing Cable Failure Modes
- Insights from Review of Experimental Data
- Insights from the Application of FMECA to Circuit Analysis
- Important Circuit Design Features
- Cable Failure Mode Probability Distributions
- Risk from Fire-Induced Cable Failures

Role of Circuit Analysis in FRA

- **Objective:**

  To determine the conditional probability of a specified set of component failures, given fire-induced damage of the associated component cables

- **Boundaries:**
  - **power and control cables for**
    - » **all components that can initiate a transient/LOCA**
    - » **all components required to mitigate transients/LOCAs**
    - » **components whose failure can severely degrade a systems operation (e.g., cause a diversion path)**
  - **cables for instrumentation required by operator**
  - **includes both Appendix R and non-Appendix R equipment**

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Functional Modeling Framework

- Characterize potential cable behavior during fires
  - failure modes (open circuit, short to ground, hot shorts)
  - identify parameters that can affect probability of each failure mode (qualitative assessment based on experimental data)
    - » cable physical properties and configuration
    - » electrical function
    - » cable routing/protection
    - » fire conditions
  - assess conditional probability of each failure mode
- Determine effect of cable failure modes on circuits
  - qualitative circuit analysis
    - » circuit design feature impacts
    - » timing and duration effects
    - » information presented to the operator
    - » combinations of cable faults

Functional Modeling Framework (cont.)

- **Determine effects on component/system operation**
  - component fails
  - spurious component operation
  - instrumentation failures
  - spurious instrumentation reading
- **Quantification of risk from fire-induced cable failures**
  - FRA uses screening techniques to focus on important fire scenarios
    - » qualitative screening (use of Appendix R information)
    - » quantitative screening using cable failure mode probabilities
  - additional circuit analysis for unscreened fire scenarios
  - quantification of unscreened fire scenarios

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Cable Failure Modes

- **Open Circuit - loss of electrical continuity of an individual conductor**
- **Shorts to Ground - individual conductor comes into contact with a grounded medium**
- **Hot Short - energized conductor contacts another conductor either in the same cable or an adjacent cable**

Review of Experimental Data

- 26 reports reviewed for detailed information on fire-induced cable failures
  - NRC sponsored cable tests
  - Industry sponsored cable tests
  - Cable tests from other countries
  - Cable tests from cable manufacturer
- Information on fire-induced cable failure modes is more substantial than was expected
  - Electrical monitoring generally designed to identify conductor-to-conductor shorts and shorts to tray but some monitored cable-to-cable shorts and open circuits
  - Variable factors such as type of cables, fire intensities, cable tray loading, tray separation, use of conduits, and room geometry were represented in tests

Potential Factors Influencing Cable Failure Modes

FACTOR	EVIDENCE	RANKING
Cable Physical Properties and Configuration		
Insulation properties	Poor	Likely Weak
Jacket properties	Very poor	Likely weak
Number of Conductors	Good	Significant
Armoring	Good	Significant
Shield wraps	Good	Significant
Drain wires	Good	Significant
Cable age	Very limited	Likely weak
Cable size (wire gauge)	Poor	Likely significant
Cable qualification	Very poor	Likely weak
Electrical Function Factors		
Circuit function / type	Good	Significant
Base ampacity for power circuits	Mixed	Significant
Circuit Voltage	Good	Significant

Potential Factors Influencing Cable Failure Modes

FACTOR	EVIDENCE	RANKING
Cable Routing and Installation Factors		
Cable tray type	Very poor	Likely significant
Conduits	Poor	Likely significant
Air Drops	Mixed	Significant
Raceway loading	Fair	Significant
Maintained Spacing	None	Likely Significant
Protective coatings	Poor	Likely weak.
Raceway orientation	Very poor	Likely significant
Bundling of cables	None	Likely significant
Fire Condition Factors		
Direct flame impingement	Very poor	Likely significant
Convective exposures	Very poor	Likely significant
Exposure duration/intensity	Very poor	Likely Significant
Relative fire elevation	None	Likely significant
Application of suppressants	Poor	Likely significant

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Insights from Review of Experimental Data

- Conductor-to-conductor shorts occurred in many of the tests in both qualified and unqualified cables
- The time of the conductor faults were identified in some of the tests
- Some conductor-to-conductor shorts later shorted to the tray
- One test showed conductor-to-conductor shorts may be more likely at cable terminations
- Cable-to-cable hot shorts happened in one series of tests instrumented to measure their occurrence
- Open circuits were preceded by shorts to ground
- Conductor-to-conductor shorts are likely to quickly progress to include multiple conductors
- "Healing" of both qualified and unqualified cables occurred in some of the tests

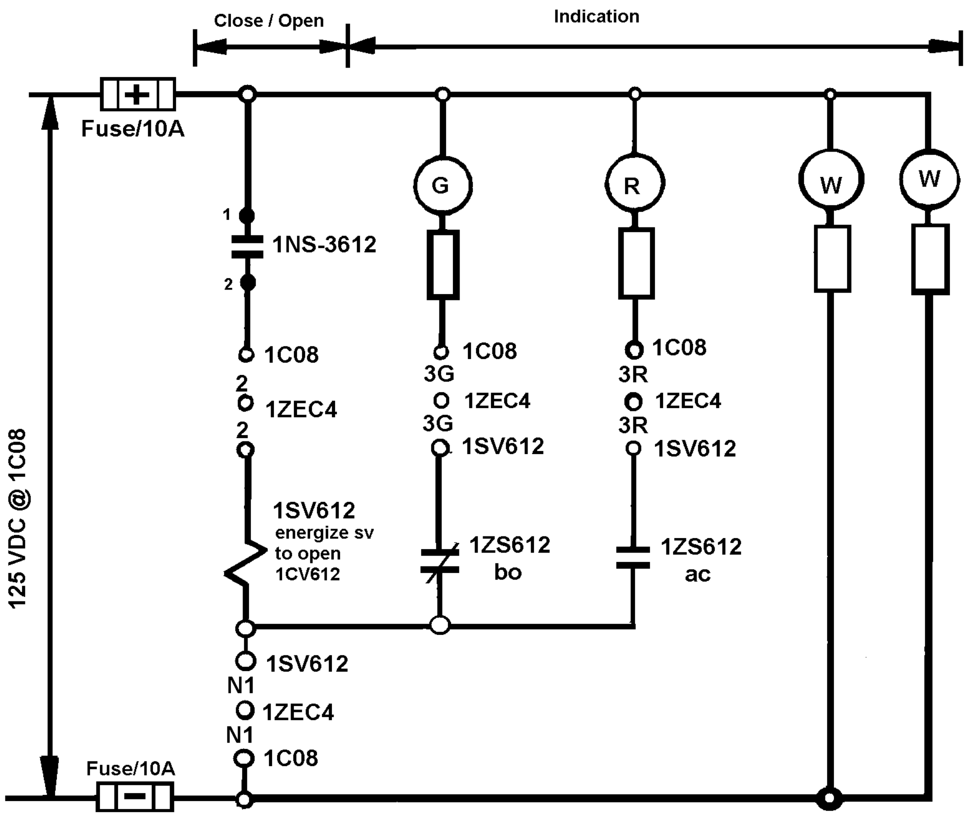
Insights from Review of Experimental Data (cont.)

- Location of cable in tray influenced results from two tests
- Several tests showed location of cables in room relative to fire is important (corner effects important)
- Number of cable failures increased with fire intensity
- Shorting of energized conductors in one series of tests resulted in arcing and ignition of cables
- Thermal aging of cables increased temperature threshold for electrical failure for one type of qualified cable but decreased it for another
- Simulated activation of suppression system in one series of tests resulted in no electrical failures as compared to identical tests without suppression
- Actual use of water suppression in one test resulted in shorts to ground

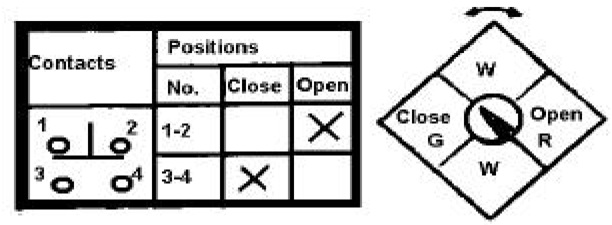
Use of FMECA in Circuit Analysis

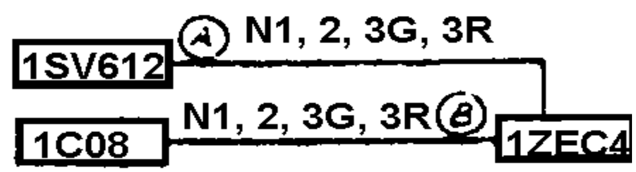
- FMECA more detailed than "hot probe" approach used in some Appendix R analyses
  - Performed for all types of conductor faults
  - Can look at effect of multiple conductor shorts on circuit
  - Identifies circuit impacts dependent upon duration of conductor fault
  - Identifies if indication of conductor fault is available
- Systematic application of FMECA can be used to identify important fire-induced circuit failures and recovery potential
- FMECA, if applied to spectrum of circuits, can be used to identify important circuit designs and features

Example FMECA - SOV



Scheme 1CV612





Block Diagram
Scheme CV612

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

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 from same battery
m = number of +125 Vdc conductors in cable tray from same battery

SOV Circuit Analysis Insights

- Many conductor faults result in inability to open valve
- Only faults to external conductors on same DC circuit lead to spurious valve opening
- Many of the conductor faults would result in some indication prior to attempts to open valve
- Some of the conductor faults would result in some indication after attempts to open valve
- Some of the conductor faults would provide no indication at any time (not critical since no affect on valve operability)
- Many of the circuit failures are dependent on duration of conductor fault

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Unique Scenarios Identified by Other FMECAs

- **MOV scenarios:**
  - spurious valve closure occurs bypassing limit and torque switches causing damage to valve
  - valve spuriously reopens after being closed
  - both the open and closed contactor coils energized leading to phase-to-phase short
- **Pump scenarios:**
  - trip coil energized causing circuit breaker for pump motor to trip immediately when it is closed
  - both open and closed coil for circuit breaker energized causing pump to start and stop repeatedly
- **Auxiliary relay circuit:**
  - 226 out of 301 scenarios result in inadvertent actuation of circuit

Examples of Important Circuit Design Features

- **Component control circuit features:**
  - Limit switch, torque switch, or overload contacts can prevent motor-operated valve damage given hot short (IN 92-18 issue)
  - Open actuation or permissive contacts can prevent some hot shorts upstream of contacts, however, hot shorts in the actuation/permissive circuits can cause multiple component actuations
  - Circuits utilizing control switches and latching relay contact configurations require a brief hot short to initiate and maintain operation of component
  - "Double breaks" (can be control, limit, or torque switches) decrease likelihood of hot shorts (not typical design)
- **Breaker coordination:**
  - Required to prevent propagation of fault currents

Examples of Important Circuit Design Features (cont.)

- **Grounding:**
  - For ungrounded circuits (AC or DC), hot shorts must be from conductors on same power source
  - For grounded circuits, hot short can be from any energized source
  - Multiple shorts to ground in ungrounded circuits on the same power source can have same functional impact as a hot short
- **Control room/alternate shutdown panel transfer design:**
  - Separate power source or parallel fuses for controls eliminates need to replace blown fuses if short to ground occurs before transfer
  - Use of control relay to make transfers (requires power and can fail if fault opens fuse)
  - Use of isolation switches to prevent spurious component operation (same effect as opening breakers)

Cable Failure Mode Probability Distributions

- **Mean probability for a hot short of 6.8E-2 is widely used (Source: NUREG/CR-2258)**
- **Other typical values are 0.1 and 1.0**
- **NUREG/CR-2258 also suggested hot short duration times between 5 and 35 minutes**
- **Existing experimental data was reviewed to establish fire-induced cable failure mode probability distributions**
- **Test data shows:**
  - **mean probability of conductor-to-conductor shorts in multi-conductor cables is approximately 0.3 to 0.7**
  - **conductor-to-conductor short probability in cables with grounded drain wires or armor is approximately 0.05**
  - **very little information on hot short duration**

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Risk from Fire-Induced Cable Failures

- **IPEEEs indicate that most fire scenarios involve fire-induced cable damage**
- **Fire-induced open circuits are clearly important**
- **Importance of hot shorts unclear and documentation of analyses is sparse, particularly**
  - **completeness of PRA models**
  - **consideration of multiple hot shorts**
  - **use of single vs. scenario-specific hot short probabilities**
- **Control system interactions in control room and cable spreading room fires coarsely modeled**

Circuit Analysis/PRA Interface

- **Incorporating circuit analysis into PRA:**
  - provide the link between cable faults and control circuit response and subsequent component behavior
  - examine the impact of combinations of cable faults
  - address the dynamics of the faults (sequencing and duration)
  - address the effects of the faults on component status indications (e.g, indication lights or alarms) and on potential operator actions
  - include the reliability of circuit protection features
  - use appropriate fault probabilities
  - address the potential for component recovery for specific faults
- **Fire quantification studies will provide an opportunity for comprehensive circuit analyses**

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Summary

- Factors that influence fire-induced cable failure modes have been identified
- A relative ranking of the factors has been performed based on an assessment of experimental data and judgement
- An improved circuit analysis approach has been identified
- Experimental data have been collected and will be used to generate probability distributions for different cable failure modes/conditions
- Methods, insights, and data will be used in FRA studies to establish new estimates of fire risk

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