U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Module II – Circuit Analysis

Fire-Induced Circuit Failures Research

Joint EPRI/NRC-RES Fire PRA Workshop
June 25-29, 2018

Gabe Taylor – U.S. NRC

Daniel Funk – JENSEN HUGHES

Dane Lovelace – JENSEN HUGHES

A Collaboration of the Electric Power Research Institute (EPRI) & U.S. NRC Office of Nuclear Regulatory Research (RES)

CIRCUIT FAILURE RESEARCH

Objectives

- To provide a status update on the recent research efforts related to fire-induced cable damage and circuit/equipment failures
- Topics covered
  - Circuit Failure Testing
  - Electrical Expert PIRT Panel (NUREG/CR-7150, Vol. 1 / EPRI 1026424)
  - PRA SSHAC Level 2 Expert Elicitation (NUREG/CR-7150, Vol. 2 / EPRI 3002001989)
  - Data Analysis (NUREG-2128)
  - NUREG/CR-6850 Impacts
  - JACQUE-FIRE 3 Working Group (NUREG/CR-7150, Vol. 3 / EPRI 3002009214)
  - Current Transformer (CT) Open Circuit Testing (NUREG/CR-7228)
  - High Energy Arc Fault (HEAF) Testing (NEA/CSNI/R(2017)7)
  - Instrumentation Circuit Testing (NUREG/CR-7244, in publications)

WARNING!

Some of the material in this presentation
has NOT been generically endorsed by the NRC.

The referenced documents in this presentation may be endorsed in future RG updates (in part or full).

NRC may endorse on a case-by-case basis.

CIRCUIT FAILURE RESEARCH

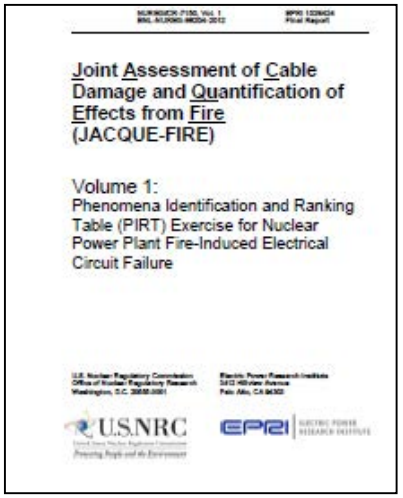
Testing Programs

- Testing programs include:
  - NEI/EPRI 2002
  - NRC/SNL CAROLFIRE 2008
  - NRC/SNL DESIREE-FIRE 2010
  - NRC/SNL KATE-FIRE 2011
  - NRC and OECD HEAF testing (2017, 2018, Phase 2 In Progress)
  - Current transformer testing 2016
  - Instrumentation circuit testing 2018
  - Panel Wiring (Canceled)
  - Performance of Cable Coatings – Completed 2017

CIRCUIT FAILURE RESEARCH

Electrical PIRT Panel

NUREG/CR-7150, Vol. 1 & EPRI 1026424


Joint Assessment of Cable Damage and Quantification of Effects from Fire (JACQUE-FIRE)

Volume 1:
Phenomena Identification and Ranking Table (PIRT) Exercise for Nuclear Power Plant Fire-Induced Electrical Circuit Failure

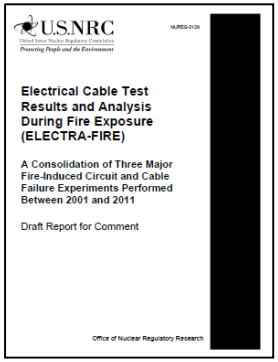
U.S.NRC

EPRI

- PIRT
  - Phenomena Identification and Ranking Table
  - Structured expert elicitation (use of expert judgment)
- Purpose
  - Identify phenomena that influences the failure mode of electrical cables during severe fire conditions
  - If possible, arrive at consensus technical positions on longstanding fire-induced circuit failure issues
  - Provide technical basis for follow-on PRA Expert Panel
- Report - JACQUE-FIRE
  - Results of PIRT *are not* regulatory guidance
  - NRR will establish regulatory positions on the technical results presented in the PIRT Report

CIRCUIT FAILURE RESEARCH

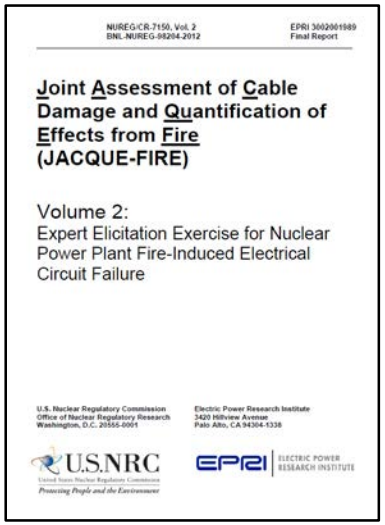
Data Analysis Effort: NUREG-2128



- NRC ELECTRA FIRE
  - ELECTRA-FIRE
    - Electrical Cable Test Results and Analysis During Fire Exposure
  - Objective
    - Consolidate three major fire-induced circuit and cable failure experiments between 2001 and 2011
    - Further refine available test data to obtain additional insights from existing data
  - Scope
    - Evaluate parameters that effect hot-short failure modes and hot-short durations
    - Intra-cable & Inter-cable faults
    - Concurrence
    - Ground equivalent hot shorts

CIRCUIT FAILURE RESEARCH

PRA Expert Panel
NUREG/CR-7150, Vol. 2 & EPRI 3002001989

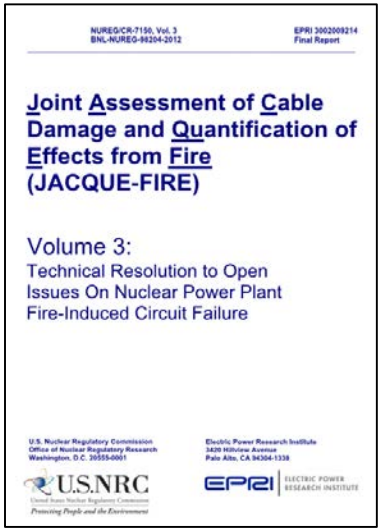


- PRA SSHAC Level 2 Expert Elicitation
  - Following PIRT, SSHAC Level 2 process for use of expert judgment
  - Formal process for soliciting, judging, and weighing input
- Purpose
  - Use expanded data set to revise/develop conditional probabilities of hot short given cable damage
  - Results replace guidance and probability values in NUREG/CR-6850, Task 10
  - Develop hot short duration probabilities for AC and DC control circuits
- Status
  - Final Report Issued May 2014
  - Use of NUREG/CR-7150, Vol. 2 Probabilities and Durations endorsed by NRC Interim Guide Memo (IGM)

U.S.NRC UNITED STATES NUCLEAR REGULATORY COMMISSION Protecting People and the Environment
EPRI ELECTRIC POWER RESEARCH INSTITUTE

CIRCUIT FAILURE RESEARCH

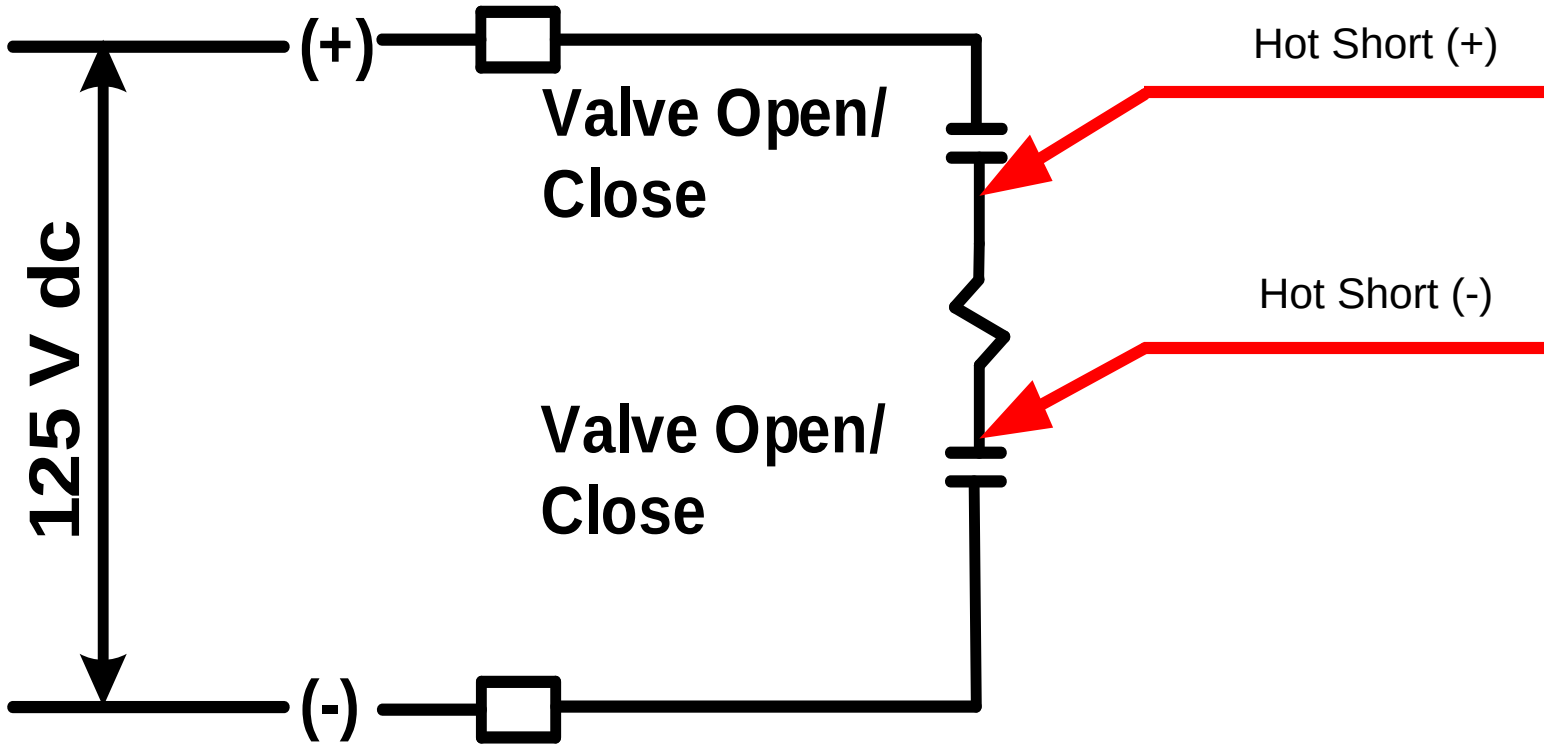
JACQUE-FIRE 3 Working Group
NUREG/CR-7150, Vol. 3 & EPRI 3002009214



- Provide technical basis/positions on outstanding circuit analysis issues
  - Use of the PIRT results (Clarifications to Appendix J of NEI 00-01)
  - Limits on the number of hot-short circuit failures to assume for MSOs
  - Established a NEW class of equipment – “High Impact Component”
  - Update to hot-short classifications for select cases (i.e., plausible, implausible, incredible)
  - Shorting switch criteria and design considerations (New Appendix I to NEI 00-01)
  - Limit on Spurious Operation Duration for certain circuits
  - Clarifications to Volume 1, based on insights obtained from Volume 2 results

U.S.NRC UNITED STATES NUCLEAR REGULATORY COMMISSION *Protecting People and the Environment*
EPRI ELECTRIC POWER RESEARCH INSTITUTE

Which is Proper Polarity?



PROPER POLARITY

Conclusion

- Conclusion
  - AC and DC solenoids and relays used in double break control circuits should be assumed “polarity insensitive,” unless specific manufacturer’s technical data indicates the device is “polarity sensitive”.
  - “Polarity insensitive” means that the coil will operate regardless of the orientation of the applied positive and negative voltage to the coil.

DEVICE ACTUATIONS FROM DIFFERENT POWER SOURCE

- Issue
  - Can an ac power source energize a dc device (solenoid or relay)?
- Conclusion
  - Yes, unless engineering analysis or testing shows otherwise.

HIGH IMPACT COMPONENT

- Definition

  "The set of components whose fire-induced failure could result in immediate and unrecoverable consequences for an operating nuclear power plant, e.g., loss of reactor coolant system inventory, inventory loss with the potential to damage the fuel in less than or equal to one hour, the potential for a release of radiation by bypassing primary containment. As such, this set of components warrants the use of a more conservative circuit failure criteria in the post-fire safe shutdown analysis."

- Consider for "**implausible**" failure modes

HIGH IMPACT COMPONENT CONSIST OF

- High/low pressure interface
  - See Appendix C of NEI 00-01

- Target conductor(s) is(are) associated with cabling for a single component or single signal that due to fire-induced hot short spurious operation, could cause a transient that results in an unrecoverable condition leading to fuel damage.

HIGH IMPACT COMPONENTS

BWR

- Spurious opening of both shutdown cooling suction valves (classified as “high/low pressure interfaces”)

- Spurious opening of multiple Safety Relief Valves (SRVs) and failure (due to “fire damage” effects) of a sufficient number of low pressure make-up systems such that the inventory loss is not bounded by design basis accident analysis.

HIGH IMPACT COMPONENT

PWR

- Spurious opening of the shutdown cooling suction valves (to SDC/LPSI/RHR – the “high/low pressure interfaces”)

- Spurious opening of one or more Pressurizer Power Operated Relief Valves (PORV) and failure (due to “fire damage” effects) of its associated block valve to close or remain closed.

SINGLE BREAK CONTROL CIRCUITS

Table of Plausibility

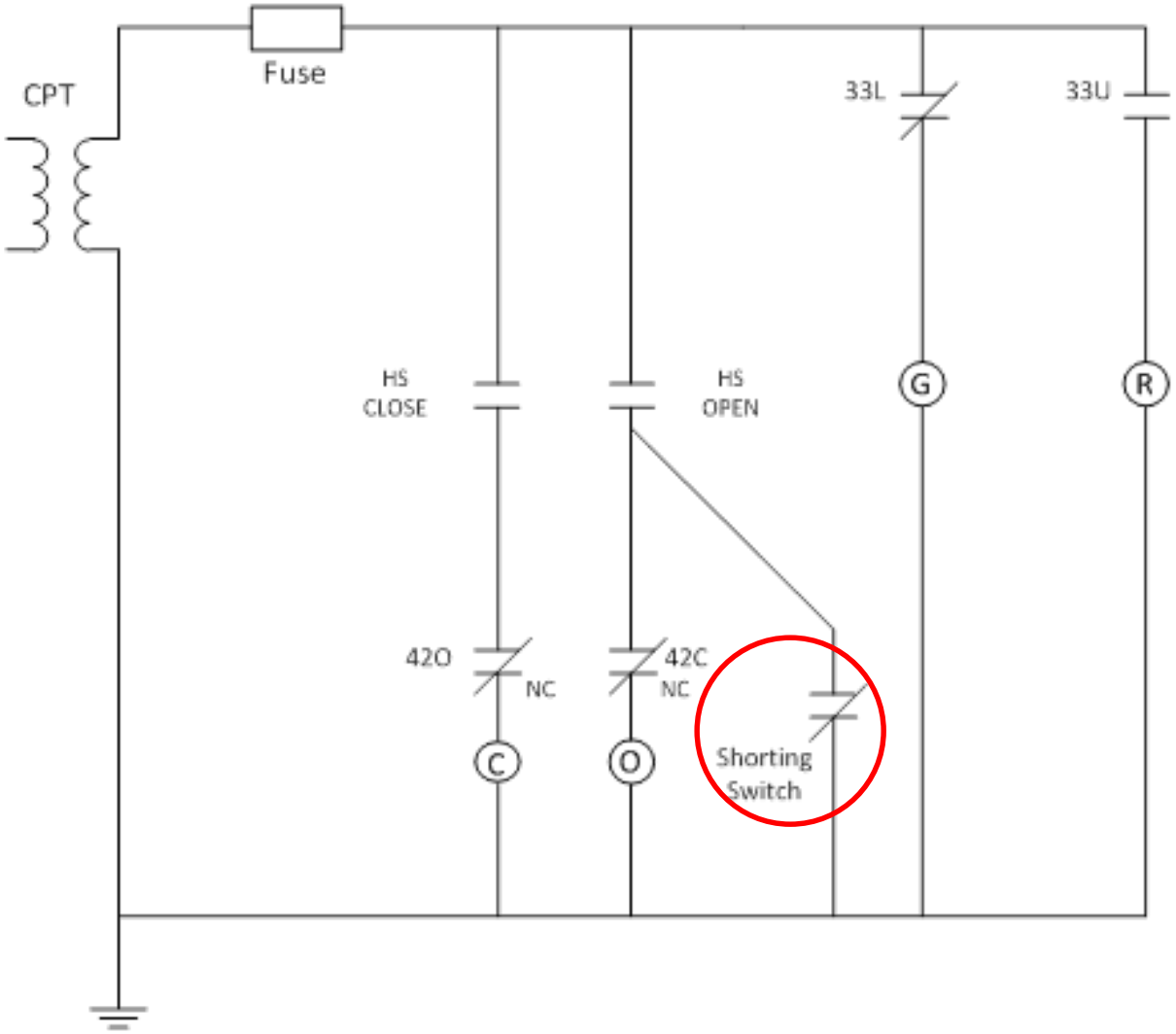
Table 3-1: Failure Modes for Single Break Control Circuits					
Power Supply	**Grounded AC**		**Ungrounded AC (from CPT or Distributed) or DC**		
	Conductor Hot Short Failure Mode				
Target Cable Configuration	**Intra-Cable**	**Inter-Cable**	**Intra-Cable**	**Inter-Cable**	**Ground Fault Equivalent**
Thermoset Insulated Conductor Cable	Plausible	Plausible	Plausible	Plausible	Plausible
Thermoplastic Insulated Conductor Cable	Plausible	Plausible	Plausible	Plausible	Plausible
Metal Foil Shield Wrap Cable	Plausible	Incredible	Plausible	Incredible	Plausible
Armored Cable	Plausible	Incredible	Plausible	Incredible	Plausible

DOUBLE BREAK CONTROL CIRCUITS

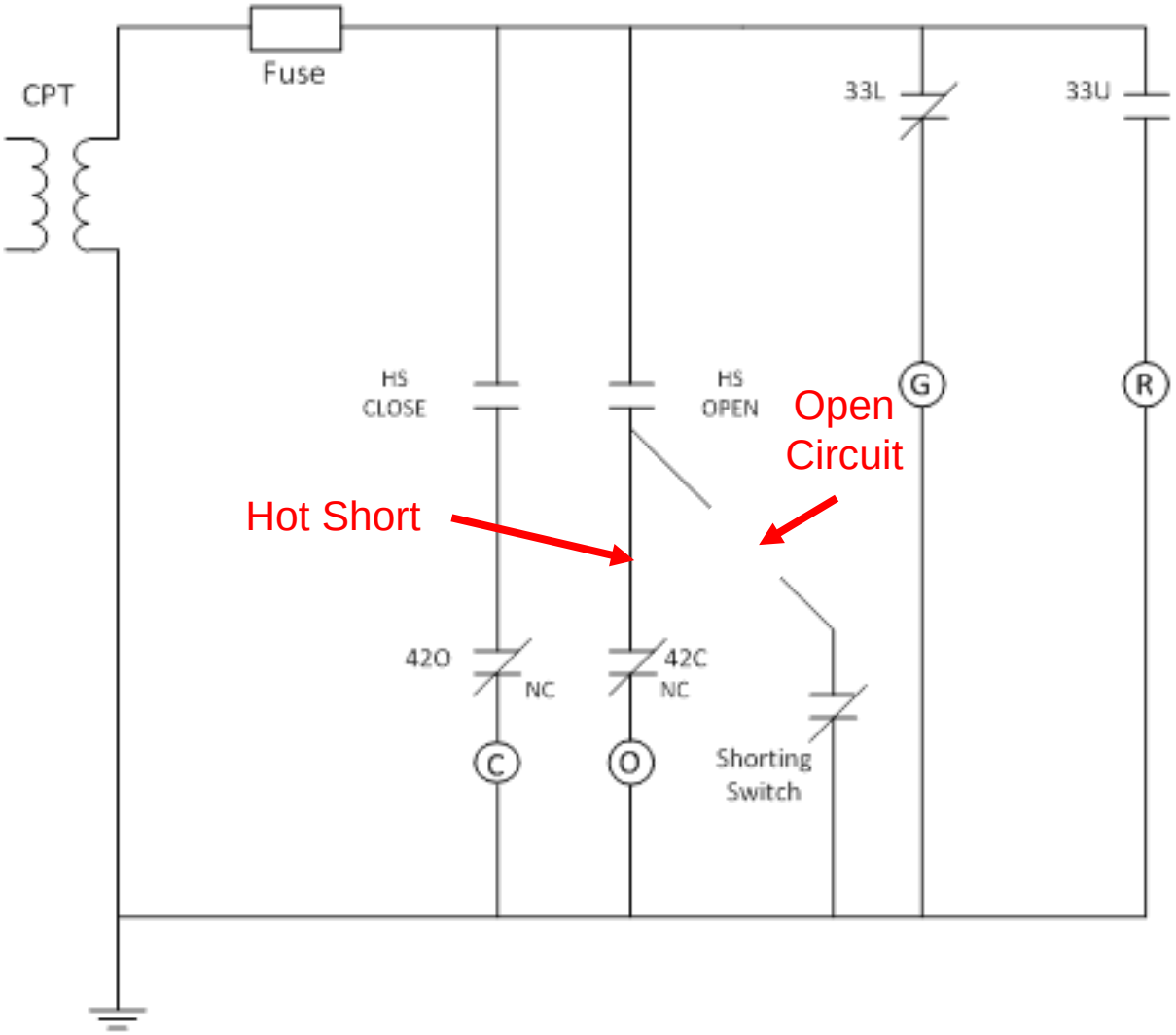
Table of Plausibility

Table 3-2: Failure Modes for Double Break Control Circuits (includes single break control circuits with control power fuses removed) [Ungrounded AC w/CPTs, Ungrounded DC (Ungrounded AC w/o CPTs)]					
Target Cable Configuration	**Intra-Cable & Intra-Cable**	**Intra-Cable & Inter-Cable**	**Inter-Cable & Inter-Cable**	**Intra-Cable & Ground Fault Equivalent**	**Inter-Cable & Ground Fault Equivalent**
Thermoset Insulated Conductor Cable	Plausible	Plausible	Incredible	Plausible	Implausible (latching) Incredible (non-latching)
Thermoplastic Insulated Conductor Cable	Plausible	Plausible	Implausible (latching) Incredible (non-latching)	Plausible	Implausible (latching) Incredible (non-latching)
Metal Foil Shield Wrap Cable	Plausible	Incredible	Incredible	Plausible	Incredible
Armored Cable	Plausible	Incredible	Incredible	Plausible	Incredible

APPENDIX I – SHORTING SWITCH GUIDANCE



SHORTING SWITCH DRAWBACK



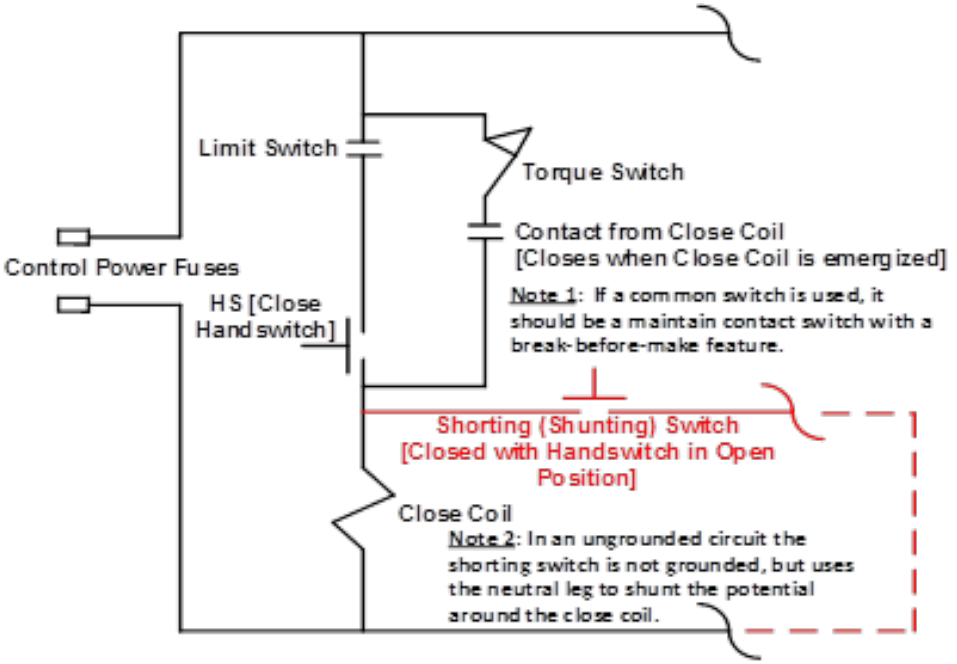
Both open circuit and hot short failures must occur to produce a spurious operation.

CONSIDERATIONS WHEN USING A SHORTING SWITCH

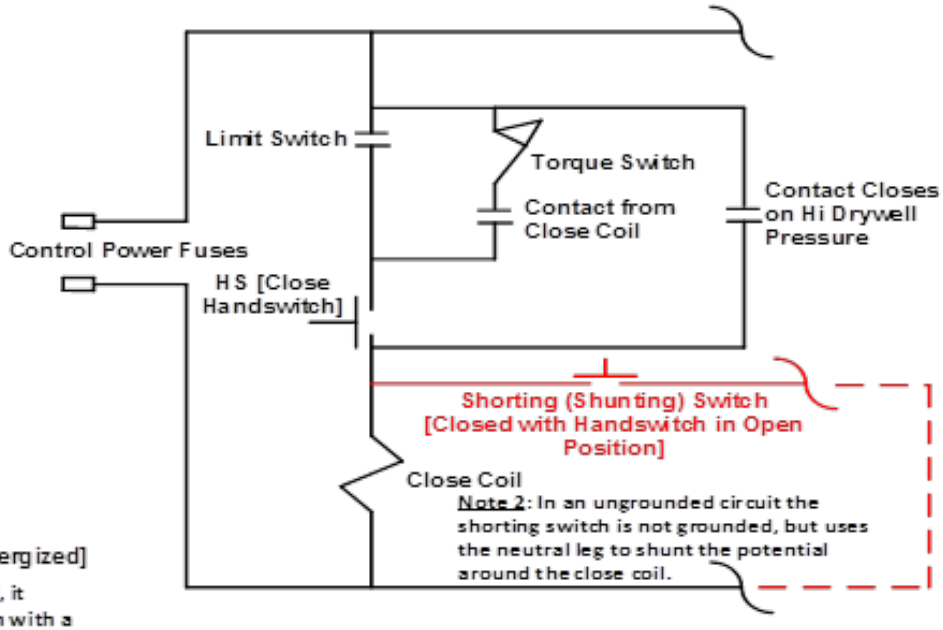
- Licensing Conditions
  - 10 CFR 50, Appendix R
    - III.G.2
    - III.L.7
  - GL 86-10
- Component Classification
- Engineering Evaluation
  - Maintain integrity of switch and other associated components

SHORTING SWITCH DESIGN CONSIDERATIONS

- Good design
  - Break-before-make



a.) Shorting Switch in an Ungrounded DC Manually Operated Valve with Seal-in



a.) Shorting Switch in an Ungrounded DC Automatically Operated Valve with No Seal-in

- Not so good design
  - Circuit with Seal-in design
  - Automatic operation feature

U.S.NRC UNITED STATES NUCLEAR REGULATORY COMMISSION Protecting People and the Environment
EPRI ELECTRIC POWER RESEARCH INSTITUTE

ELECTRICAL DESIGN AND OTHER CONSIDERATIONS

- Minimum pick-up
- Credible source cables/conductors
  - Sometimes referred to as “aggressor”
- Maximum expected voltage / current
- Cabinet fires
- Fire-induced open circuits
- Additional mitigating measures

CURRENT GUIDANCE ON MULTIPLE CIRCUIT FAILURES

- RG 1.189, Rev. 2 took exception to
  - NEI 00-01 Section 3.5.1.1 “Circuit Failure Criteria”
    - Bullet 7 under “Circuits for ‘Important to safe shutdown’ components”
      - Multiple fire induced circuit failures affecting separate conductors in separate cables (where circuit failure is not sealed-in or latched)

- Where defense-in-depth features are present
  - Considered at least 2 separate cables
  - High-low pressure interface → considered at least 3 separate cables
- Where NO defense-in-depth features are present
  - No limit on the number of separate cables

JACQUE-FIRE VOLUME 3 RECOMMENDATIONS

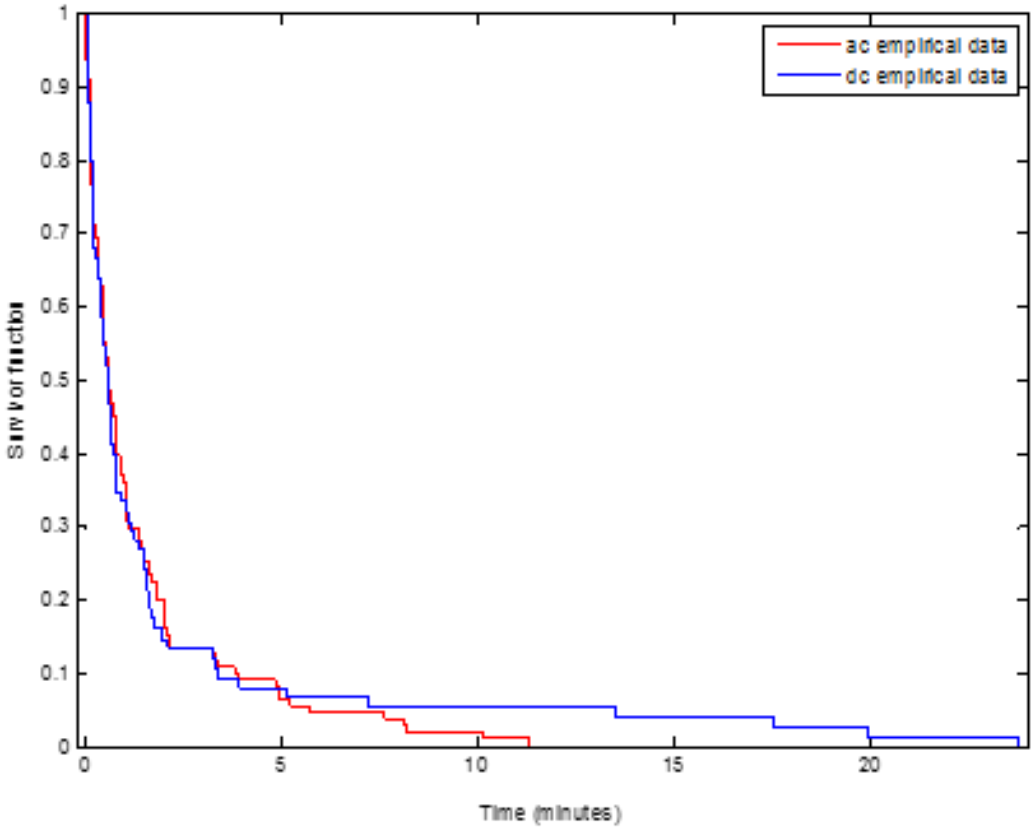
Number of Fire-Induced Failures to Consider (1-1-2-2-4)

- Hot shorts for transient inrush considerations
  - Only consider single inrush, provided supply and load sequencer is not degraded from fire effects
- Inter-cable, non-latching hot shorts with 10 minutes coping time
  - One (Single Break)
- Inter-cable
  - Two
- Non-latching with 10 minute coping time
  - Two
- Selective Sequence
  - Four

DURATION

Recommendation for Deterministic Applications

- ac control circuits
  - 20 Minutes
- dc control circuits
  - 40 Minutes
- Single worst case postulated hot short-induced spurious operation

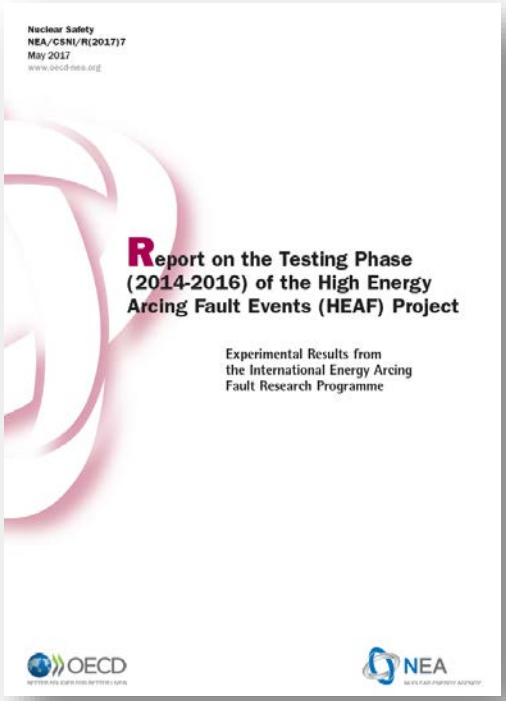


U.S.NRC UNITED STATES NUCLEAR REGULATORY COMMISSION Protecting People and the Environment
EPRI ELECTRIC POWER RESEARCH INSTITUTE

ANTICIPATED REGULATORY FOOTPRINT

- JACQUE-FIRE Volume 3 issued November 2017
- NEI 00-01 has been revised to incorporate JACQUE-FIRE insights (Rev. 4 submitted to NRC)
- RG 1.189 to be revised to endorse NEI 00-01, Rev 4 (in full or in part)

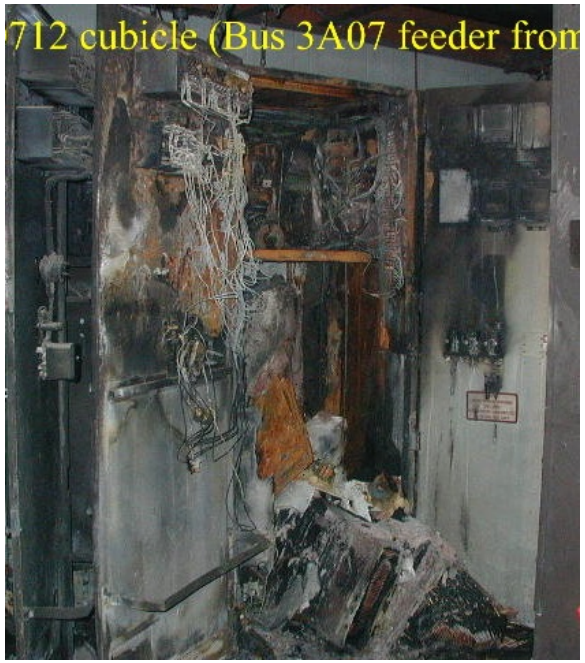
NRC AND OECD HEAF TESTING

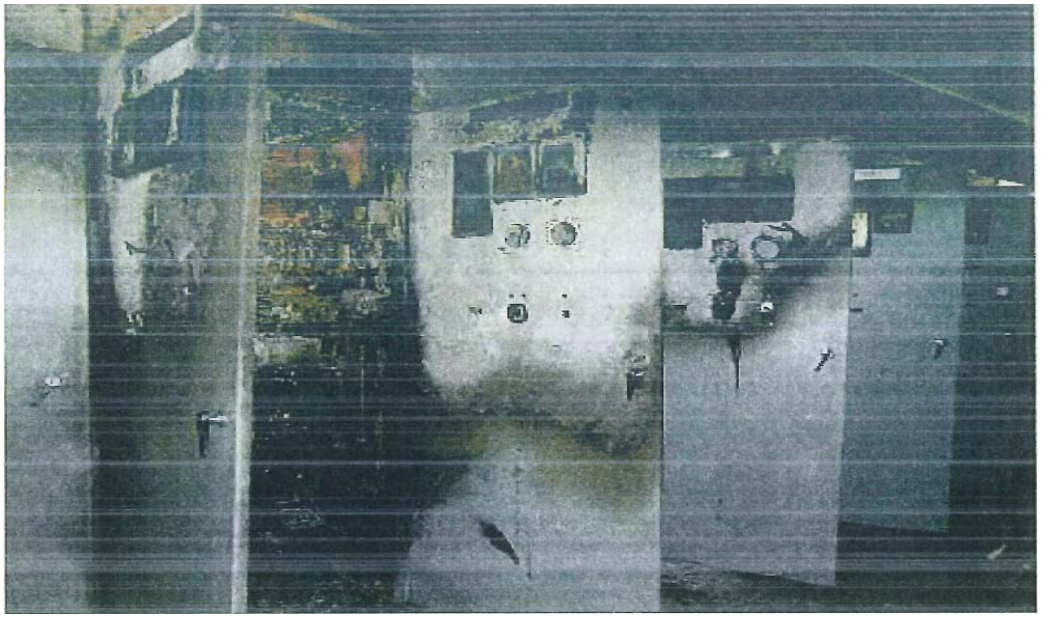


- 2017 Nuclear Energy Agency issued NEA/CSNI/R(2017)7, documenting a series of test performed to investigate high energy arcing fault (HEAF) phenomena
- 26 tests completed
- Several tests involving aluminum exhibited energy releases and byproducts different than non-aluminum tests
- NRC staff identified the involvement of aluminum during a HEAF as a potential Generic Issue
- Additional testing is planned / ongoing.

U.S.NRC UNITED STATES NUCLEAR REGULATORY COMMISSION Protecting People and the Environment
EPRI ELECTRIC POWER RESEARCH INSTITUTE

Examples of HEAFs that have occurred



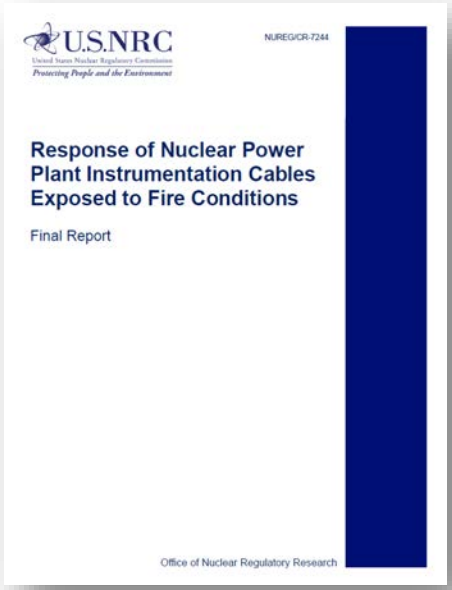


U.S.NRC UNITED STATES NUCLEAR REGULATORY COMMISSION *Protecting People and the Environment*

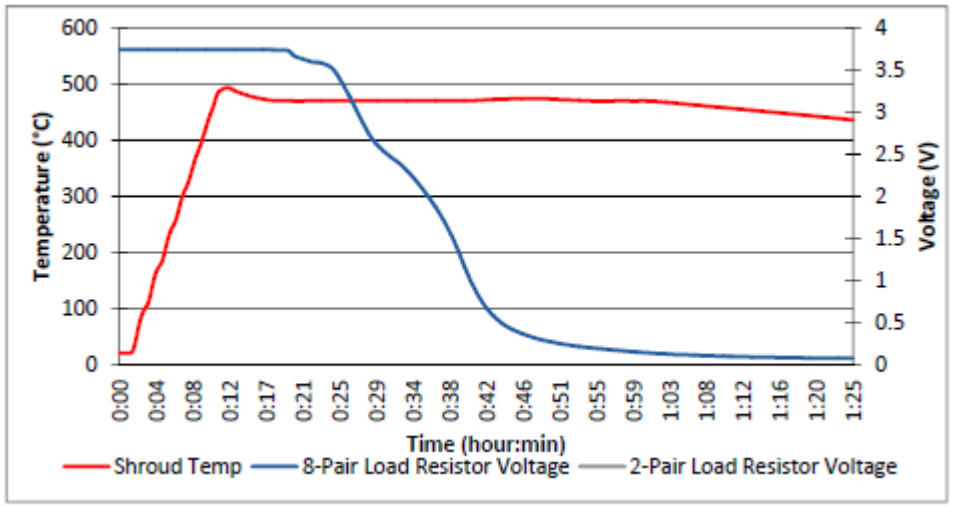
EPRI ELECTRIC POWER RESEARCH INSTITUTE

HEAF Testing

INSTRUMENT CIRCUIT TESTING



- Recommendation from JACQUE-FIRE 1 & 2
- Limited testing done to investigate failure mode and complement testing from 2001
- Scoping tests performed by SNL
  - 39 tests
  - Finding: under certain configurations slow signal leakage time occurs



Failure mode was observed in several TS cable and in one TP cable tested.

Regression analysis indicated that conductor count and specific insulation material had influence on leakage time.

INSTRUMENTATION CIRCUIT TESTING

Circuits Tested

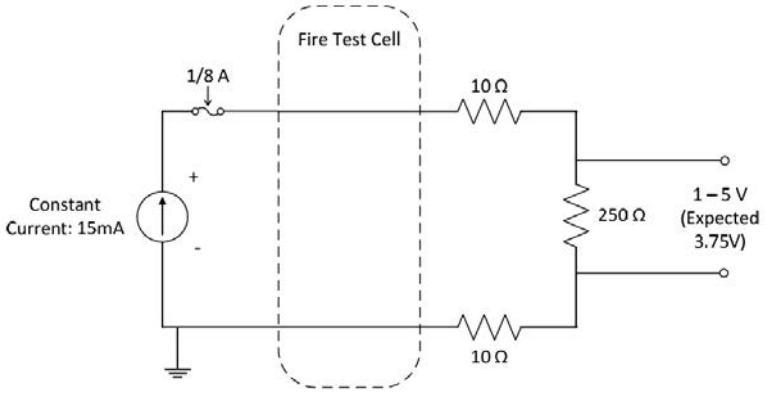


Figure 3-1: 4–20 mA Instrumentation circuit for fire test, grounded

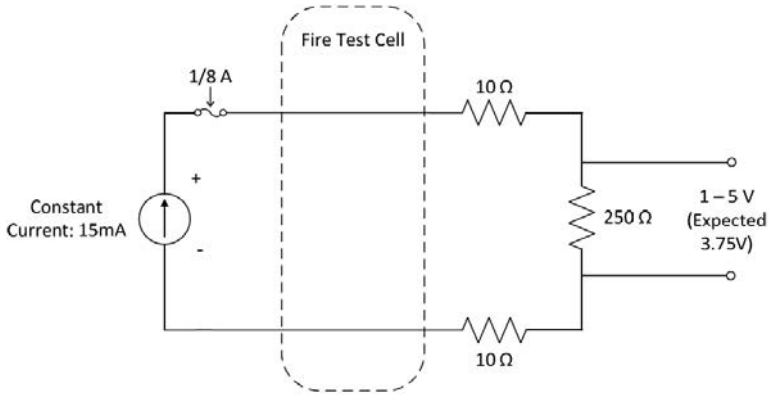


Figure 3-2: 4–20 mA Instrumentation circuit for fire test, ungrounded

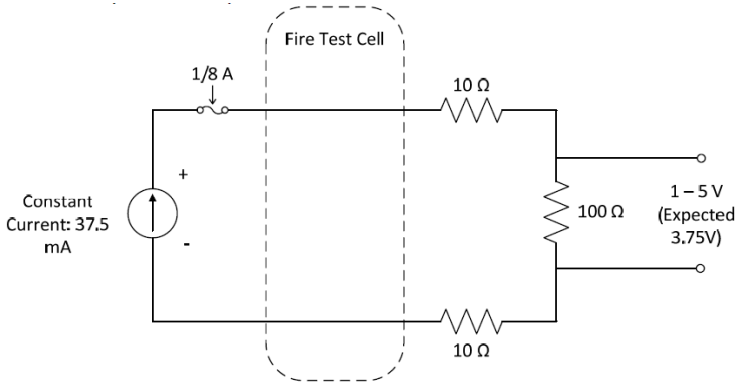


Figure 3-3: 10–50 mA Instrumentation circuit for fire test

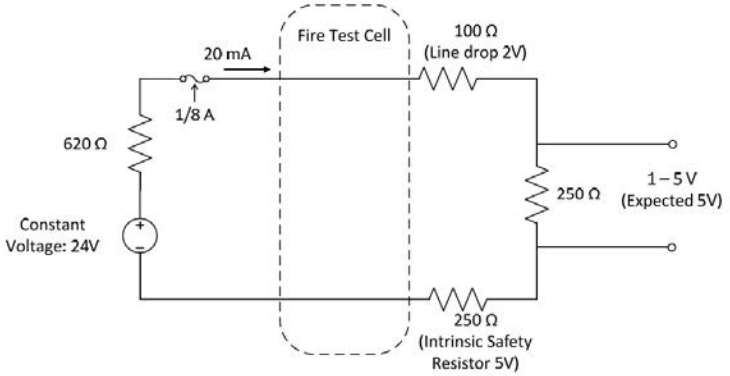


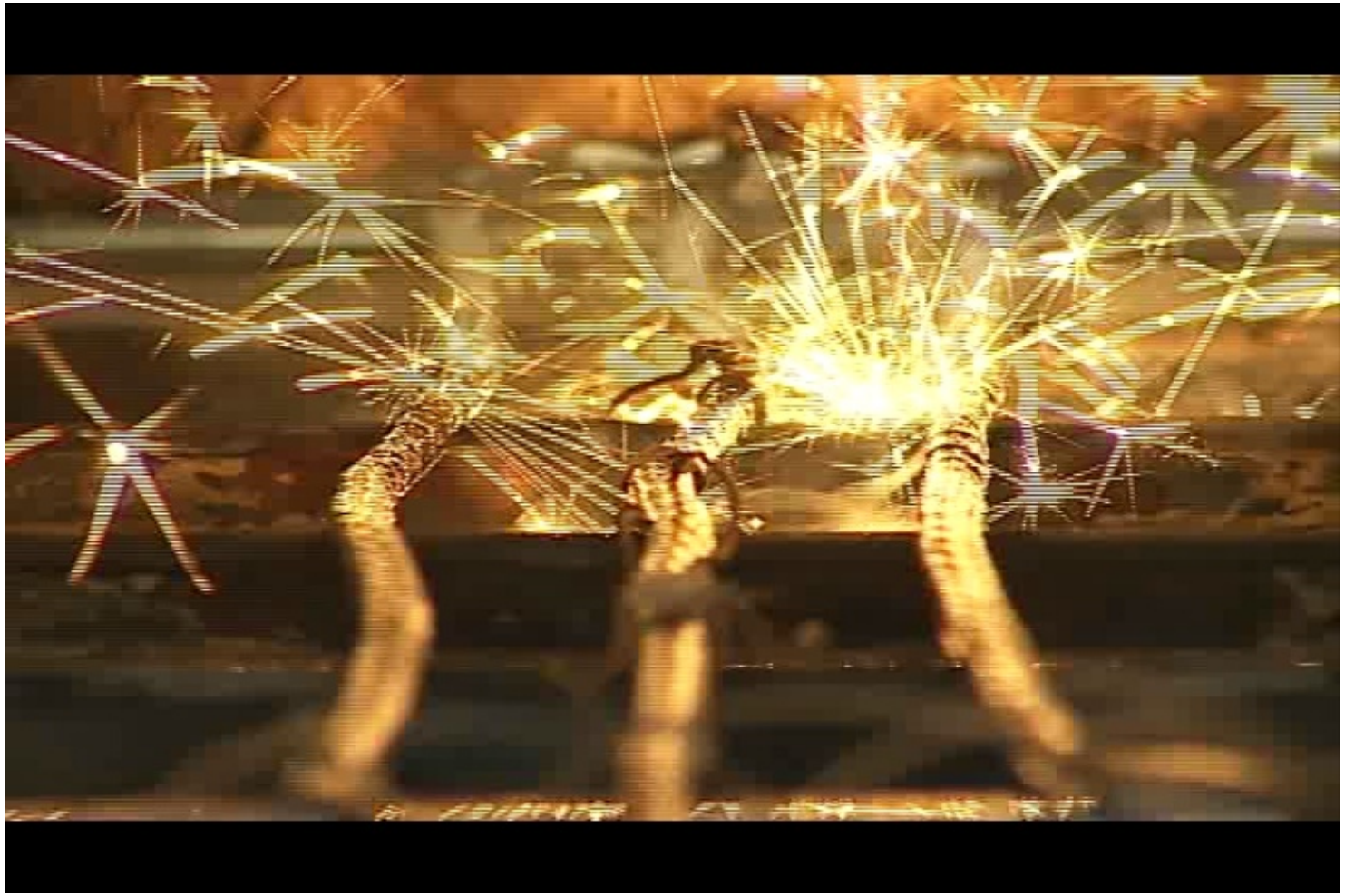
Figure 3-4: 1–5 VDC Instrumentation circuit for fire test

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

EPRI ELECTRIC POWER RESEARCH INSTITUTE

CIRCUIT FAILURE RESEARCH

DC Test Video and Pictures



CIRCUIT FAILURE RESEARCH

U.S.NRC UNITED STATES NUCLEAR REGULATORY COMMISSION *Protecting People and the Environment*

EPRI ELECTRIC POWER RESEARCH INSTITUTE