DETAILED CIRCUIT ANALYSIS FOR FIRE PROBABILISTIC RISK ASSESSMENT

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ABSTRACT

As part of the Fire Probabilistic Risk Assessment (Fire PRA) detailed circuit analyses were performed for the event of a fire occurring on equipment declared as Safe Shutdown Equipment List (SSEL). Fire PRA methods have been used in the Individual Plant Examinations of External Event (IPEEE) program to facilitate a nuclear power plant examination for vulnerabilities. According to NUREG 6850 these studies address the full breadth of Fire PRA technical issues for power operations and include consideration of large early release frequency.
The complete circuits analysis is according to NUREG/CR-6850 represented by three tasks:

- Task 3: Cable selection (selection Fire PRA cables to dedicated SSEL equipment, which failure can affect their operation),
- Task 9: Detailed circuit analysis of SSEL equipment,
- Task 10: Circuit failure mode likelihood analysis.

First phase of circuit analysis was approach of selecting Fire PRA cables. In all of the cases, it was advantageous to perform all of Task 9 (detailed circuit failure analysis) cables within Task 3. The degree to which Task 3 and Task 9 are combined is highly dependent on plant-specific documentation.
Second phase of analysis was to conduct a more detailed analysis of circuit operation and functionality to determine equipment responses to specific cable failure modes. These relationships were then used to further refine the original cable selection by screening out cables that cannot prevent a component from completing its credited function.
Second phase contains the following key elements:

- Determine the component response to postulated conductor/cable failure modes,
- Screen out cables that do not impact the ability of a component to complete its credited function.

Third phase was presenting Task 10, which is estimating the probability of hot short cable failure modes of interest, which in turn can be correlated to specific component failure modes. Within that phase we estimate specific cable failure modes associated with fire-induced cable damage. Intention

was to provide a probabilistic assessment of the likelihood that a cable will experience one or more specific failure modes (e.g., short-to-ground, intra-cable conductor-to-conductor short, inter-cable conductor-to-conductor short, etc.).

Keywords: *Fire PSA, cable selection, circuit analysis*

1 INTRODUCTION

NUREG/CR-6850 [1] provides under its Task 2 (Fire PRA Components Selection) a procedure for creating the Fire PRA Component List. This list serves as the basis for the components to be modeled in the Fire PRA, and it is the key source of information for which corresponding cables need to be identified and located for the Fire PRA. As such, the Fire PRA Component List, Fire PRA Model, and corresponding cable identification are iterated upon to ensure an appropriate correspondence among these three items. The product of this task is a list of the equipment to be included in the Fire PRA and for which corresponding cables need to be identified and located for the nuclear power plant under analysis.

Detailed circuit analysis is to be performed on the cables identified. It is defined by three steps in NUREG6850 and EPRI-1011989 requirements which are performed within three dedicated Tasks discussed below.

Task 3 of the NUREG/CR-6850 Fire PRA methodology establishes the structured process for identifying all cables and circuits associated with the Fire PRA components selected in Task 2. This task represents the first phase of the Fire PRA electrical analysis and provides the foundation for understanding how fire-induced circuit failures may impact plant safety functions. The primary objective of Task 3 is to determine, for each Fire PRA component, all associated circuits and their routing throughout the plant.

Because of the strong interdependence between circuit selection and detailed failure analysis, NUREG/CR-6850 recognizes that plants may benefit from performing portions of Task 9 concurrently with Task 3. Task 9 of the NUREG/CR-6850 Fire PRA methodology represents the second major phase of the electrical analysis process and focuses on performing a detailed circuit failure analysis for all Fire PRA circuits identified in Task 3. This task expands upon the preliminary cable and circuit identification by examining how fire-induced effects can cause failures, spurious operations, or loss of function in plant electrical circuits. It builds the technical foundation needed to understand how fire damage can propagate through electrical systems and potentially challenge safety-related components.

Following the identification of Fire PRA cables in Task 3 and the detailed circuit failure evaluated in Task 9, Task 10 focuses on determining how likely specific circuit failure modes are to occur when exposed to fire-induced conditions. This includes quantifying the probabilities of open circuits, short circuits, spurious operations, and other failure behaviours that may impact safety-related systems. Task 10 is tightly integrated with both preceding electrical tasks. Its effectiveness depends directly on the quality of the circuit identification work performed in Task 3 and the detailed circuit behaviour insights from Task 9.

Practical experience has shown that performing Tasks 9 and 10 in a coordinated manner can significantly improve model robustness and ensure that detailed failure likelihood evaluations are focused on the circuits most relevant to overall fire risk.

Approach of Detailed circuit analysis followed robustness so in our case, one final package for dedicated functional status of SSC equipment has been provided considering all three tasks as part of one Final report.

2 DETAILED CIRCUIT ANALYSIS APROACH

Starting from the Fire PRA Component List developed under Task 2, the dedicated drawings had to be collected for each item from the list. Detailed Circuit Analysis is based on the collection of relevant drawings from NEK DCM database [2], considering dedicated cables, that are connected to components. Applicable drawings contain all considered cabling to be marked-up. As for the next step, additional drawings with functionality were needed to be collected from NEK DCM as well.
Based on the above, important series of drawings that form the basis for a detailed circuit analysis can be summarized as:

- Elementary diagrams;
- Cable routing diagrams;
- Cables block diagrams;
- Flow or Fluid diagrams
- Other vendor three-line equipment diagrams drawings.

Subsections following below describe the main steps in the detailed circuit analysis.

2.1 Task 3: Cable Selection

The primary objective of Task 3 was to determine, for each Fire PRA component, all associated circuits and their routing throughout the plant. This includes identifying cable locations within fire compartments so that potential fire impacts can be accurately assessed. The relationships established in Task 3 are essential for determining which components may be affected by fires in specific plant areas, and they form the basis for later tasks such as detailed circuit failure analysis (Task 9) and circuit failure mode likelihood analysis (Task 10).

Because of the strong interdependence between circuit selection and detailed failure analysis, NUREG/CR-6850 recognizes that plants may benefit from performing portions of Task 9 concurrently with Task 3.

Overall, Task 3 plays a critical role in ensuring that the Fire PRA accurately reflects electrical dependencies. By establishing a comprehensive and traceable Fire PRA Cable List, the task enables reliable identification of fire-vulnerable circuits and supports the broader risk-informed, performance-based framework outlined in the NUREG/CR-6850 methodology.

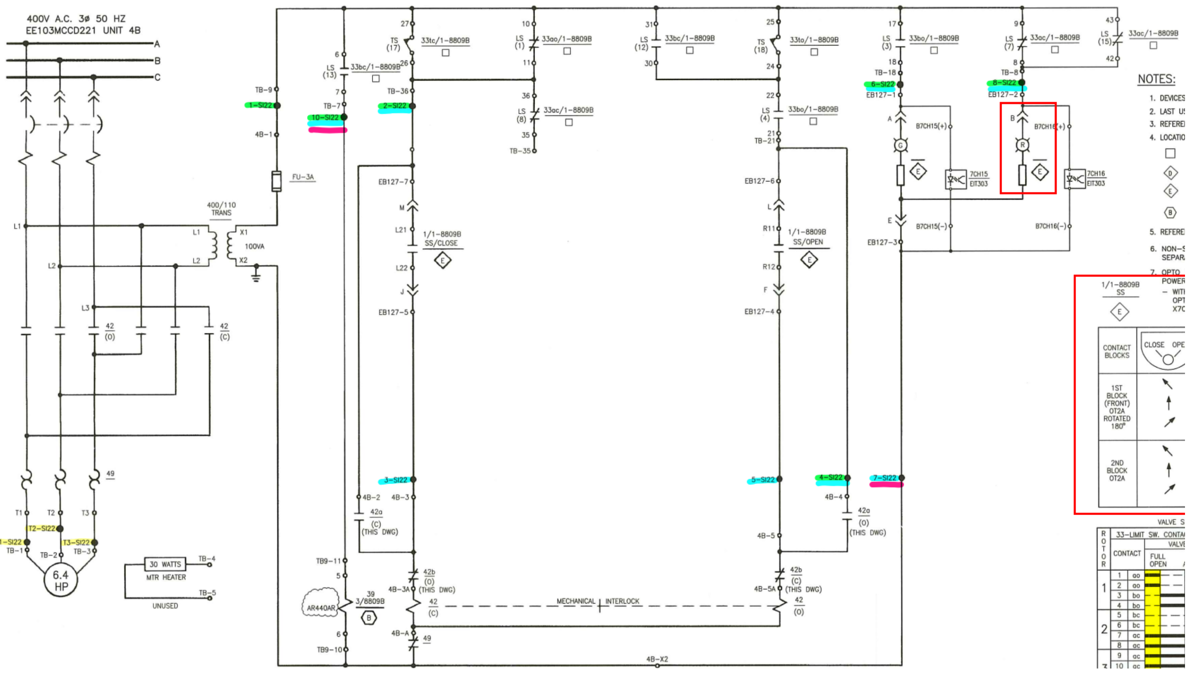

Figure 1: Example of Cable Selection on Elementary diagram

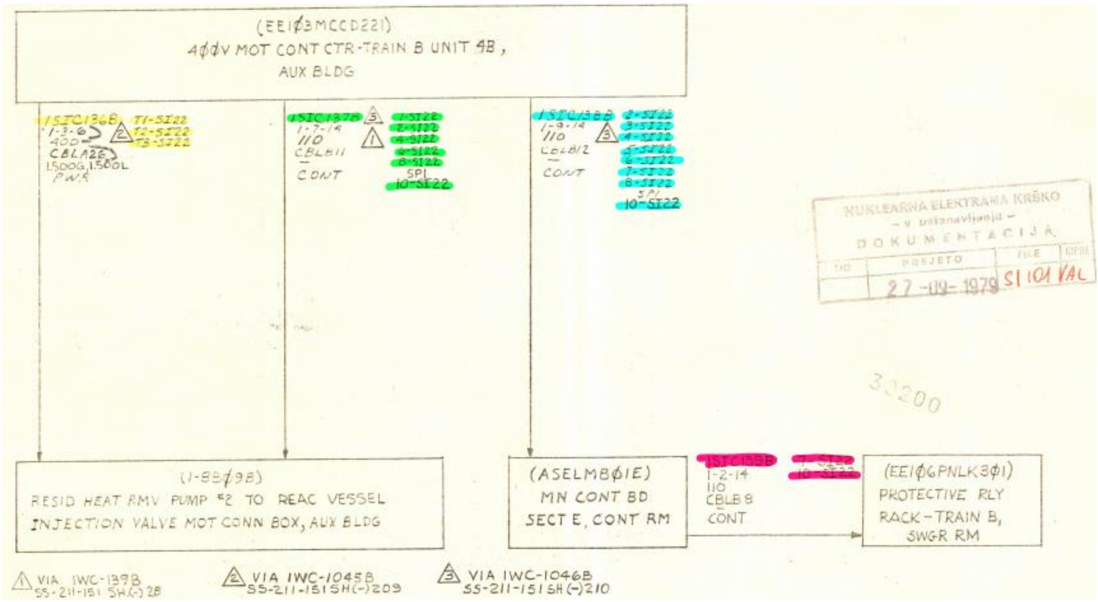

Figure 2: Example of Cable Selection on Cable Block diagram

Figure 1 and Figure 2 show examples of plant diagram used. As illustrated by the examples above, drawings taken from the plant with associated circuits are marked accordingly with affected cables that can cause limited operation or do a failure to associated equipment during fire.

2.2 Task 9: Detailed Circuit Failure Analysis

In the NUREG/CR-6850 framework, detailed circuit failure analysis is closely linked with both cable selection (Task 3) and circuit failure mode likelihood analysis (Task 10). The methodology emphasizes that certain aspects of Task 9 may be performed concurrently with Task 3, as the depth of analysis needed. This integrated approach helps to ensure early identification of critical failure mechanisms and allows the Fire PRA model to evolve efficiently.

Experience from practical Fire PRA applications shows that performing Task 9 too late in the project can delay model development and reduce opportunities for risk-informing subsequent tasks. Lessons learned from past implementations indicate that starting with model development earlier in project progression, even if with simplified assumptions, can provide valuable insights into where detailed circuit analysis efforts have to be focused.

Task 9 plays a crucial role in the overall Fire PRA by identifying how fire-induced thermal, smoke, or electrical impacts may lead to realistic circuit failure behaviours. These circuit-level insights directly support the construction of fault trees for fire-induced failures and ultimately improve the accuracy and credibility of fire risk quantification.

Task 9 is built directly on the cable and circuit identification performed in Task 3. Its purpose is to determine how each identified cable, or circuit behaves under fire exposure. This includes understanding the mechanisms of failure, the electrical and functional consequences, and how these failures should be represented in PRA logic structures. NUREG/CR-6850 notes that Task 9 may be conducted partially in parallel with Task 3 to improve efficiency, as the availability of circuit details and design information often overlaps.

The purpose of Task 9 is to establish a technically sound basis for modelling the effects of fire damage on electrical circuits by performing a detailed failure assessment for all Fire PRA circuits. These include open circuits, short circuits, grounding faults, inter-conductor faults, and spurious actuation of equipment.

An analyst determines how the circuit failure affects the associated component, including:

- Loss of function,
- Unintended operation,
- Erroneous signals, and

- Impacts on redundant trains.

During the analysis, considered were insulation damages which reflect on short or open circuit, grounding cable wire during exposure to smoke or fire, and interconnections between damaged cable wires which can be caused during insulation degradation.
Functional consequences for each circuit are evaluated, including:
- Assessment of component behavior during each failure mode;
- Identifying loss of required safety function or chance of spurious actuation;
- Evaluation of cascading effects on system logic.

This includes evaluating whether failures lead to component mispositioning, incorrect control signals, or relay actuation. Figure 3 and Figure 4 shows an example of mapping of circuit segments to component failure modes.

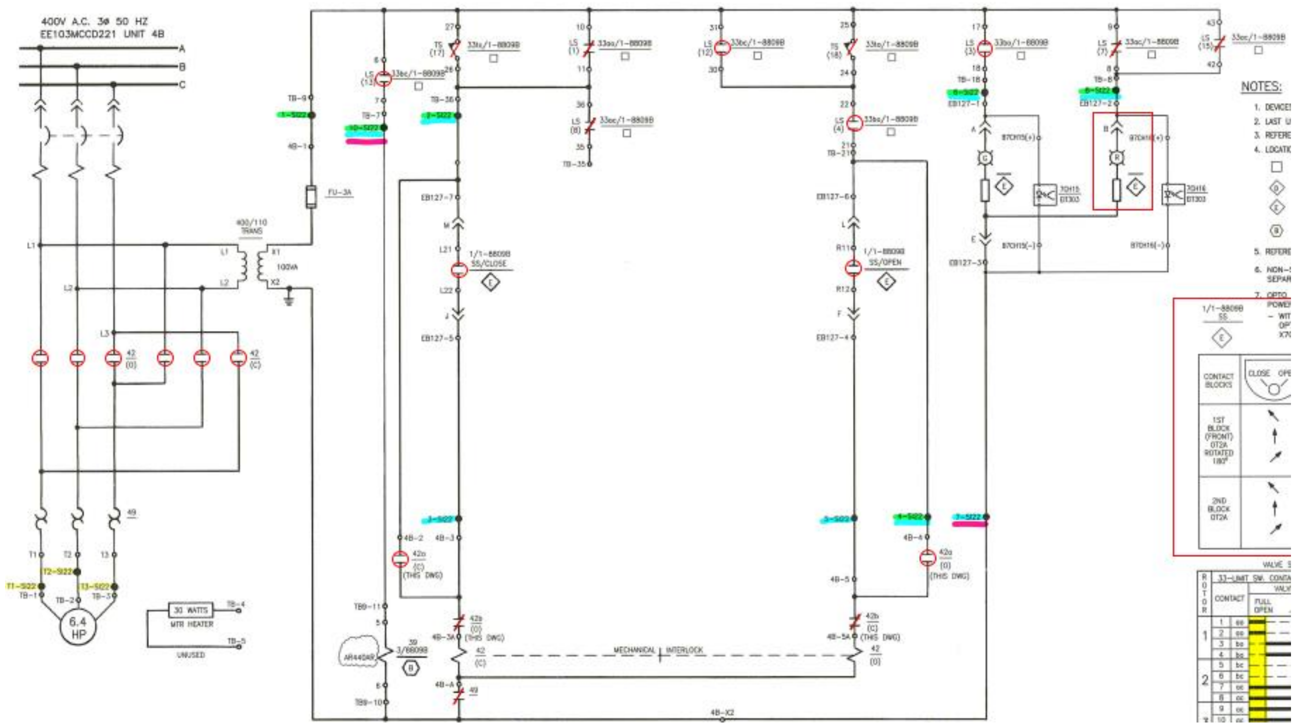

Figure 3: Example of Failure Mode Mapping Based on Task-3 Cable Designation

Results of Task 9 feed directly into:
- Fault-tree structures for fire-induced failures;
- Identification of PRA basic events;
- Inputs needed for probabilistic evaluations in Task 10 and Task 14 (Fire Risk Quantification), as defined by NUREG/CR-6850.

Task 10 evaluates the probabilities of each circuit failure mode identified in Task 9. These failure modes include shorts, ground faults, and various spurious operations. The task translates qualitative circuit behavior into quantitative PRA inputs, which directly support Tasks 14 (risk quantification) and 11 (detailed fire modelling) of the NUREG/CR-6850 methodology.

The purpose of Task 9 and 10 is to determine how likely each fire-induced circuit failure mode is to occur, based on physical principles, operating experience, fire modelling insights, and conservative engineering judgment.
The following general circuit failure modes and their effects on circuit behaviour / component response shall be considered in the circuit analysis evaluation:
- Engineering predicted cable Failure Modes:
    - Shorts-to-Ground

- Hot Shorts
  - Open Circuits
  - Line-to-Ground, Line-to-Line, and 3-phase faults (3-phase systems)
- Engineering predicted effects on Circuit/Component
  - Spurious Operation
  - Loss of Motive Power
  - Loss of Control Power
  - Loss of Control
  - Erroneous or Failed Indication

Based on equipment failure consequences for dedicated cables in Task-3, component assessment in Task-9 defines fault consequences on traceable cable connections, as indicated by Figure 4.

Figure 4: Example of Marked Fault Consequences on Traceable Cable Connections

Within dedicated cables that can affect equipment operability due to cable fault, marked were those at which specified failure can cause:

- LOP: loss of equipment power;
- LCP: loss of control power;
- LOC: loss of equipment control;
- LOCP: loss of overcurrent protection;
- HS: Hot short;
- LOI: loss of indication;
- LIS: loss of instrument signal;
- LOA: loss of annunciation;
- EA: erroneous annunciation.

Next step represents identification of interlocks and other important “off-scheme” circuits that affect component operation and / or define the boundary of the circuit analysis.

Cable failure criteria are not, however, the only consideration in conducting and documenting the circuit analysis for each component. To ensure comprehensive and consistent treatment during the circuit analysis process, the interlocks required to support the Function State shall be identified and dispositioned such that fire-induced damage to the interlock circuit is accounted for in the analysis.

General guidelines for interlock analysis include:

- Internal circuit contacts do not require specific disposition. For example, it is not necessary to discuss the operation of seal-in contacts.
- In dispositioning auxiliary contacts, the analyst shall decide whether the off-scheme cables will be included with the existing analysis or whether an “Equipment Dependency” will be created.

All interlock contacts originating from a source external to the circuit under analysis have been dispositioned by the circuit analysis and presented on equipment Detailed Circuit Analysis final report. Figure 5 shows an example of the analysis of required interlocks.

FDM **Electrical Analysis Report**

Function Code **11T2-B:Available:Non-Spurious** **CONTINUED**

Interlocks

Contact Set	Component	Description	Required	Cables Included	Equipment Dependency	Function State	Comments
XR101XFR002-XFR2A (X2-X5)	XR101XFR002-XFR2A	T2 Current Meas Xfmr-Phase A (21 kV)	☑	☑	☐		Unit Xfmr T2 current measurement to Unit Xfmr Prot Relay 11T2-B.
XR101XFR002-XFR2B (X2-X5)	XR101XFR002-XFR2B	T2 Current Meas Xfmr-Phase B (21 kV)	☑	☑	☐		Unit Xfmr T2 current measurement to Unit Xfmr Prot Relay 11T2-B.
XR101XFR002-XFR2C (X2-X5)	XR101XFR002-XFR2C	T2 Current Meas Xfmr-Phase C (21 kV)	☑	☑	☐		Unit Xfmr T2 current measurement to Unit Xfmr Prot Relay 11T2-B.
SWGM2/1-CTR1	SWGM2/1-CTR1	Current Meas Xfmr-Phase A at M2-T2 Brkr	☑	☑	☐		Brkr M2-T2 - Bus M2 current measurement to Unit Xfmr Prot Relay 11T2-B.
SWGM2/1-CTR2	SWGM2/1-CTR2	Current Meas Xfmr-Phase B at M2-T2 Brkr	☑	☑	☐		Brkr M2-T2 - Bus M2 current measurement to Unit Xfmr Prot Relay 11T2-B.

Figure 5: Example of Required Interlock Analysis

2.3 Task 10: Circuit Failure Mode and Likelihood Analysis

For Task 10 the base data from the Detailed Circuit Analysis and plant cable data are utilized to assign probabilities from lookup tables in NUREG/CR-7150 Volume 2 [3] for cables damaged in fire scenarios in the Fire PSA. Cable data that can have an impact on the probability assigned are:

- Cable insulation type (thermosetting or thermoplastic material)
- Cable shielding (unshielded, shielded, armored)
- Cable function (motive power, control, instrumentation)
- Number of conductors in the cable
- Voltage type (AC or DC) along with grounding (grounded or ungrounded)
- Control circuit design (single break or double break control scheme)

Different lookup tables are utilized for different circuits analyzed during the Detailed Circuit Analysis:

- Motor Operated Valves
- Solenoid Operated Valves
- Medium Voltage Circuit Breakers

Figure 6 shows a sample results of the Task 10 analysis that is then loaded as failure probabilities in the Fire PSA model.

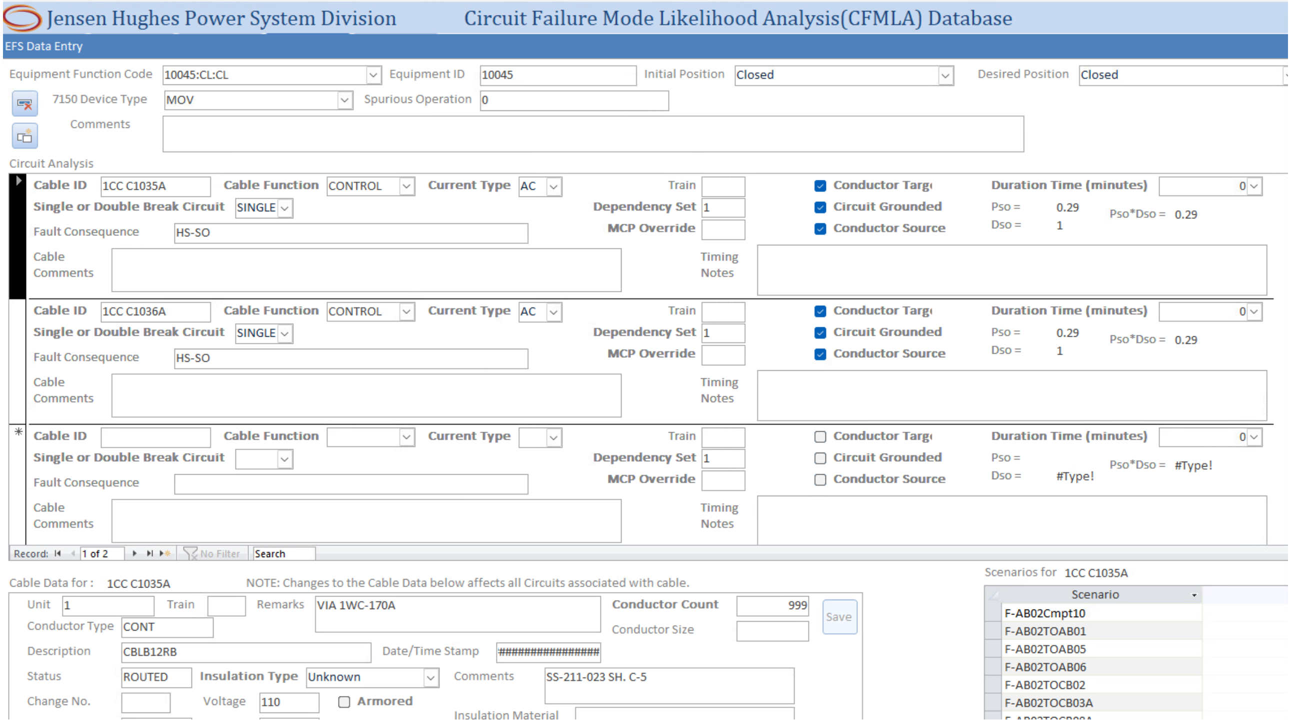

Figure 6: Example of Task 10 Calculated Probabilities

2.4 Work Sequences

For detailed circuit analysis, appropriate workflow had been established in order to provide appropriate results. To achieve best quality at work, workflow requested additional review for each of the equipment Detailed Circuit Analysis package.

Workflow steps to achieve high quality had been defined with best engineering approach for analyses which follows NUREG/CR-6850 and EPRI 1011989 work are as follows:

- Assembly all dedicated documents for single component;
- Providing cable selection for single component (Task-3);
- Designated functional states of equipment damage (Task-9);
- Providing interlock stat of functions (Task-9);
- Calculating circuit failure mode probabilités;
- Originating final report;
- Peer- reviewing the originated final review;
- If no comments, providing the final package.

When the peer review finds non-conformance during the review process, the originator must provide additional information and corrections if needed.

When second originated final report has been provided, a peer review must be repeated and verify the implemented changes.

Figure 7 shows an example of a final review form.

FDM **Electrical Analysis Report**

Function Code **1/RHAPRH03-R:Available:Available**

Equipment ID	Description	Component Type	System		Compartment
1/RHAPRH03-R	Alternate RH Pump Control Light	INL	RH	Residual Heat Removal System	

Initial Position: Available — Unit: 1 — ☑ Assembly ☐ SSD ☐ NPO ☐ Always Fail ☑ Comment Resolution

Desired Position: Available — ☑ CA ☑ Originate ☑ Fire PRA ☐ MSO ☑ Verification ☑ Final

Comments

References

Reference ID	Sheet	Rev	Type	Description
1188e12ar08	/	08	Flow	RH FLUID SYSTEM DIAGRAM
B-208-119s11	11	0	EWD	ELECTRICAL-ELEMENTARY DIAGRAM, RESIDUAL HEAT REMOVAL SYSTEM, ARHR PMP RHAPRH03 EE104SWGLD32 UNIT 2C
B-802-119s1	1	0	FLD	I & C (RH) SYSTEM FUNCTIONAL DIAGRAM - RESIDUAL HEAT REMOVAL SYSTEM - ALTERNATE RESIDUAL HEAT REMOVAL PUMP RHAPRH03
D-206-019	/	2	Single Line	ELECTRICAL - ONE LINE & RELAY DIAGRAM - ENGINEERED SAFETY FEATURES 400V BUS LD32
SS-211-044sE-52	E-52	E	Block	ELECTRICAL BLOCK DIAGRAMS - SYSTEM DC - DC POWER SUPPLY SYSTEM AND DISTRIBUTION
SS-211-119sL-4	L-4	A	Block	ELECTRICAL BLOCK DIAGRAMS - SYSTEM - RH - RESIDUAL HEAT REMOVAL SYSTEM

Power Supplies

Power Supply ID	Required	Breaker/ Fuse	Description
DC101PNLY501	☑	5	125V DC Main Switchboard for DG3

FDM **Electrical Analysis Report**

Function Code **1/RHAPRH03-R:Available:Available** **CONTINUED**

Cables

Cable	Function	Comment / Fault Consequence	CA Required	Multiple Hot Short	Intra-Cable Hot Short	Inter-Cable Hot Short	Grounded	AC or DC	Single or Double Break Design
1DC E1077Y	POWER	LCP-FTRA	☑	☐	☐	☐	☐		
1RH L1007Y	CONTROL	LOC-FTRA	☑	☐	☐	☐	☐		
1RH L1008Y	CONTROL	LOC-FTRA	☑	☐	☐	☐	☐		
1RH L1009Y	CONTROL	NR-Fault cannot cause SP/ST of pump	☐	☐	☐	☐	☐		
1RH L1010Y	CONTROL	LOC-FTRA	☑	☐	☐	☐	☐		

Interlocks

Revision

Revision	Originator	Originator Date	Checker	Checker Date	Comments
0	M. ZUPANČIČ	5. 11. 2025	U. ŠKOFLEK	5. 11. 2025	

Figure 7: Example of Final Review Form for Detailed Circuit Analysis

The report is provided within dedicated database software, [4].

3 CONCLUSIONS

Detailed Circuit Analysis (DCA), commonly associated with Task-3, Task-9 and Task-10 as combined, is one of the most technically demanding steps in fire probabilistic risk assessment developed in accordance to NUREG/CR-6850 Fire PRA methodology. Its purpose is to determine how fire-induced electrical effects can damage cables and circuits, potentially causing loss of function, spurious operations, or other unsafe system behaviors that influence plant safety.

Detailed circuit analysis assessment presents realistic electrical failure mechanisms caused by fire, such as:

- Conductor-to-conductor shorts;
- Conductor-to-ground faults;
- Open circuits due to insulation failure;

- Spurious actuations (e.g., unexpected pump starts, unintended valve movement, false instrument signals);
- Assume interlocks in operations within the failure.

As the fire can cause false signals or unintended actuation of components, the analysis need also to address:
- Probability of spurious operations,
- Cable susceptibility to thermal damage,
- Effects of bridging faults and conductor exposure.

Integrating Task 3 (Cable Selection), Task 9 (Detailed Circuit Failure Analysis), and Task 10 (Fire-Induced Circuit Failure Mode Likelihood Assessment) into a single consolidated analysis provides a more coherent, technically robust, and efficient workflow for Fire PRA. Although NUREG/CR-6850 structures these as separate tasks, in practice they are deeply interdependent. Bringing them together produces a more accurate and review-friendly result. A unified report becomes the single source of truth for all circuit-related fire vulnerability information.

This integrated approach aligns much better with how Fire PRA is actually performed in practice and avoids the fragmentation and inefficiencies that arise when these tasks are documented in isolation.

REFERENCES

[1] NUREG/CR-6850, EPRI 1011989 Fire PRA Methodology for Nuclear Power Facilities

[2] Nuklearna elektrarna Krško, DCM drawings database (elementary, block diagrams, flow and fluid diagrams, etc.)

[3] NUREG/CR-7150 Volume 2, Joint Assessment of Cable Damage and Quantification of Effects from Fire

[4] Jensen Hughes TECH-SCA-02, Rev.2 Cable Selection and Circuit Analysis