

A Method for Analyzing Multiple Spurious Operations in Nuclear Power Plant Fires Using Fault Tree Analysis

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1. Introduction

Today, the world faces energy security challenges and surging electricity demand, driven by geopolitical conflicts, carbon neutrality commitments, and the rapid growth of high-tech industries such as AI. In response, nuclear power is re-emerging as a key solution capable of providing a stable, low-carbon energy supply, leading many nations to expand or resume nuclear energy programs.

Although continuous efforts have enhanced the safety of nuclear power plants (NPPs), a major source of national power, a fire at Browns Ferry Unit 1 in the United States in 1975 was a serious accident that required fundamental changes to the nuclear fire protection program. As demonstrated in the Browns Ferry, when a fire occurs at a NPP, cables in the fire-affected area are damaged. This causes failures in the electrical circuits of active equipment (power supply, control logic, instrumentation signals, etc.), resulting in Multiple Spurious Operations (MSO), where one or more active devices operate in unintended directions and lose their functionality.

The U.S. Nuclear Regulatory Commission (NRC) required the implementation of the MSO analysis and corrective measures based on the results of the investigation into the Browns Ferry's fire incident in General Design Criterion (GDC) 3 of Appendix A of 10CFR Part 50, and the Nuclear Energy Institute (NEI) presented the Generic MSO List (May 2009). The U.S. NRC, through EGM 09-002 (May 2009) and regulatory guide RG-1.189 Rev. 2 (Oct. 2009), identified areas of dissatisfaction with the MSO and required NPP operators to implement action plans for them. [1], [2], [3]

In Korea, Nuclear Safety and Security Commission (NSSC) Notice No. 2015-11 (Technical Standards for Fire Hazard Analysis) was comprehensively revised to include the MSO analysis, and regulatory guide KINS/RG-N10.06 was issued to require an estimation of MSO in the event of a fire. Furthermore, the NSSC Notice No. 2018-9 (Article 12 General Matters for Fire Safety Shutdown Analysis) was revised to specify "circuit analysis including MSO analysis," and MSO analysis in accordance with NEI 00-01 (Rev. 4) is required during the licensing of continued operation of NPPs. [4], [5]

Aligned with these latest domestic and international regulatory guidelines and technical standards, this study

applies fault tree analysis (FTA) method to the MSO analysis caused by NPP fires. [1] - [6]

2. Multiple Spurious Operation Analysis Method using Fault Tree Analysis

Generally, post-fire safe shutdown analysis (SSA) of NPP, including the MSO analysis, has performed according to the procedures shown in Figures 1 and 2 below. [7]

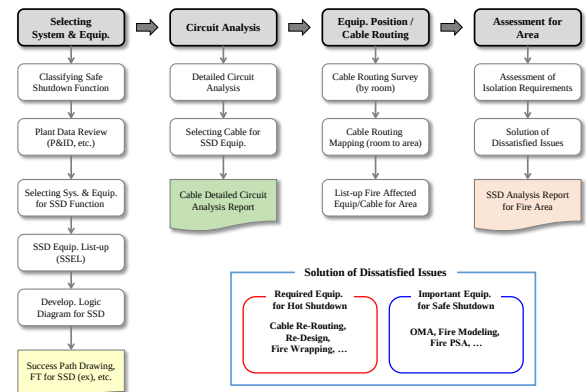


Fig. 1. General process of the post-fire safe shutdown analysis

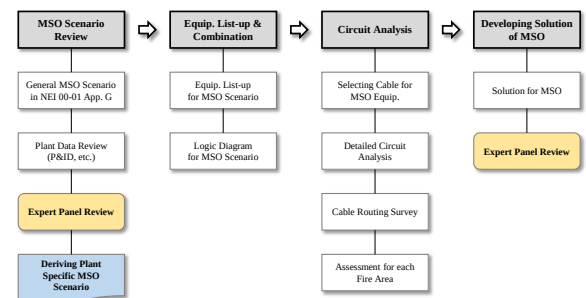


Fig. 2. Process of the multiple spurious operation analysis

Existing MSO analysis has conducted by evaluation of isolation requirements for each fire area by related components and cables based on the specific scenarios. Although NPPs are designed so that different divisions of equipment for the same function do not coexist in specific fire areas, if the installation paths of cables connected to the components are traced and extended to fire areas, areas where cables connected to the equipment in different divisions overlap are identified, resulting in the failure to satisfy isolation requirements. While the existing analysis method based on isolation requirements

evaluation is intuitive and straightforward, it has a limitation in that it cannot reflect that MSOs can occur due to combinations of components in the same or different divisions, and non-safety components affecting safety-grade components. A new approach was required to evaluate the MSO scenarios for the target NPP and the MSO occurrences in each fire area, identify their causes, and establish corrective measures; therefore, the fault tree analysis (FTA) method has applied to the MSO analysis. Using the FTA method to the MSO analysis has the following advantages:

- Confirming MSO occurrences in a specific fire area by Boolean operation of area-specific fault trees (FTs) reflecting fire-affected components and cables by integrating room-level cable routing data and fire compartment information for each MSO scenario.
- Establishing targeted countermeasures, including follow-up actions and system improvements, by querying the top events of the FT for each scenario and identifying the root-cause basic events (BE) (fire-affected components and cables).
- Facilitating easy citation and reference of analysis results for each MSO scenario and fire area in the post-fire SSA.

2.1 Selection of MSO Scenarios for Target NPP

Appendix G of NEI 00-01 Rev. 4 presents a list of general MSO scenarios. By reviewing the category and system of target NPP, applicable unique MSO scenarios were selected.

The table below classifies the list of general MSO scenarios presented in NEI 00-01 by relevant system and safe shutdown functions.

Table I: General MSO scenario list in NEI 00-01 rev.4

MSO List	Plant System	Classification
MSO #1 ~ #5	RCS	RCS Inventory Ctrl. / RCS Integrity
MSO #6 ~ #14	CVCS	
MSO #15, #16	CS	
MSO #17	SI	
MSO #18, #19	RCS	
MSO #20	RC Gas Vent	
MSO #21	CVCS	
MSO #22	Primary Sampling	Decay Heat Removal
MSO #23 ~ 27	MS, Turbine & Aux.	
MSO #28 ~ #33	Aux. Feed	
MSO #34	Steam Blowdown	
MSO #35	Secondary Sampling	RCS Pressure Ctrl.
MSO #36 ~ #37	RCS	
MSO #38	CVCS	Support Functions
MSO #40 ~ #45	CCW, CSW	
MSO #46 ~ #49	Emergency Power	
MSO #50 ~ #53	General	
MSO #54	Loss of HVAC	Other Scenarios
MSO #55	Valve Failure	
MSO #56	Others	

Among the general MSO scenario list, applicability to the target NPP was reviewed considering design characteristics, and the success path was identified to derive the equipment combination accordingly. The example below applies MSO Scenario 1 (Loss of RCP

Seal Cooling) to the Korean Standard Nuclear Power Plant (KSNP), illustrates the success path of the scenario, and identifies the list of related components and their logical combinations.

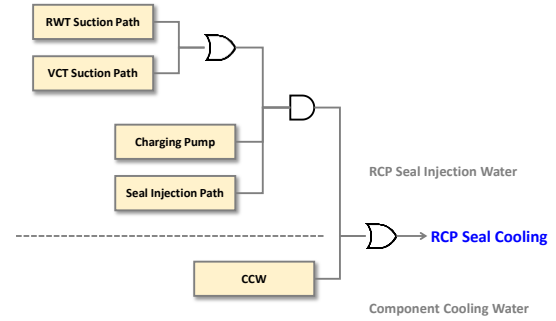


Fig. 3. Success path example of MSO scenario #1

Table II: Example of application MSO scenario (MSO #1)

MSO-01	Loss of RCP Seal Cooling
Safe Shutdown Function	RCS Inventory Ctrl.
Logical Combination	[(1) AND (2)] OR (3) OR (4)] AND (5) (1) RWT Suction Path Isolation (2) VCT Suction Path Isolation (3) All Charging Pumps Stop (4) Seal Injection Path Isolation (5) CCW Isolation

2.2 Preparing Fault Tree for Selected MSO Scenario

For all related components derived for each selected MSO scenario, an MSO component list including type, component number, name, states (e.g., normal operation, required, power loss), and location was compiled, and an FT was constructed using the logical combinations in which MSOs occur. [8] ~ [10]

When preparing the FT, modeling is performed down to the component level and specifying the failure (malfunction or spurious operation) mode in which the component causes MSO. Since the cables involved vary depending on the failure mode, the failure mode of the component must be considered to select the appropriate cables for analysis. [11]

A summary of the FT construction process is as follows:

- Set the top event of the FT for each scenario to 'MSO-00 Occurrence' (create the FT for each selected MSO scenario)
- Intermediate gates are prepared using logical combinations of the components derived earlier
- The lowest BE consists of components that may spuriously operate (or malfunction) due to fire and the failure mode in which those components cause MSO

Figure 4 below is an example of the FT for MSO Scenario 1 constructed as described above.

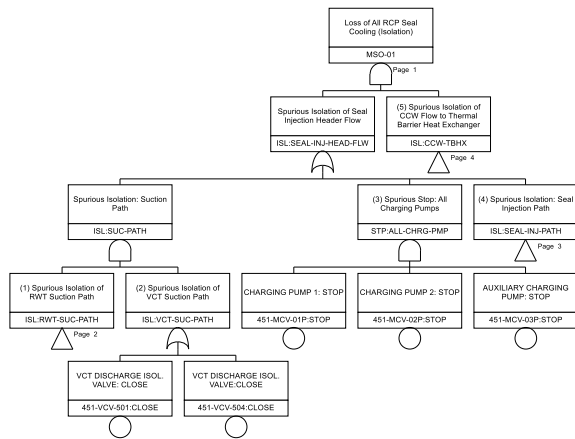


Fig. 4. Example of fault tree for MSO scenario #1

When comparing differences between FTs for probabilistic safety assessment (PSA) and MSO analysis, generally, the FT for (level 1) PSA sets core damage (frequency) as the top event and is constructed by reflecting various initiating events, the design characteristics of the target NPP, and the system, while additionally including various requirements such as common cause failures, testing and maintenance, and human reliability. In contrast, the FT for MSO analysis sets the occurrence of a specific MSO as the top event and is composed of logical combinations of the aforementioned components, as well as individual components and their failure (spurious operation or malfunction) modes causing MSO. [12]

2.3 Cable and Routing Analysis relating MSO

First, the power, control, and instrumentation cables required for the operation of the MSO-related components selected for each scenario are identified. Next, the safe shutdown impacts resulting from the spurious operations of these MSO-related components, as well as the interlock circuits that induce such spurious operations, are evaluated. The MSO cables for each component are then selected by verifying the motive power requirements and the power source from the upstream bus. Finally, a compartment-level cable routing analysis is performed by comparing routing data from the cable database with raceway drawings, which is subsequently cross-referenced with fire protection area data to determine the cable installation locations for each fire area.

2.4 Preparing Area Specific Fault Tree

To generate an area-specific FT for each fire area, fire-affected cables in each fire area have to be retrieved first, as shown in Figure 5 below. Using the results of the cable and routing analysis conducted earlier, the fire-affected cables for each fire area and their connected component lists are identified.

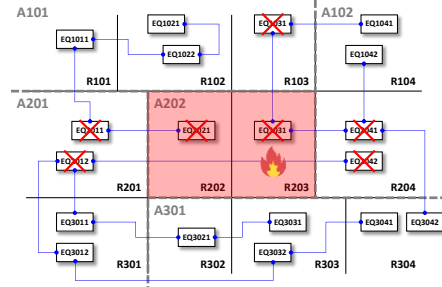


Fig. 5. Example of cables affected by fire

To prepare the 'scenario-common FT' as shown in Figure 6, all BEs in the FT previously developed for analyzing the target NPP's specific MSO scenario are set to 'false' ('F').

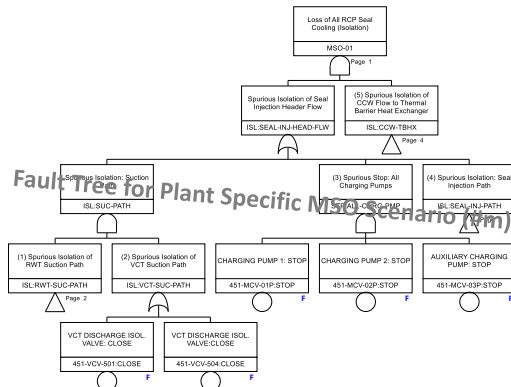


Fig. 6. Example of Common FT for MSO Scenario (#m)

To prepare the area-specific MSO FT as shown in Figure 7 below, 'true' (T) is assigned to BEs matching the function codes, components, and failure modes of the retrieved fire-affected cables for each fire area. Additionally, 'true' (T) is assigned to other BEs in the FT where the required position of the component aligns with its corresponding component and failure code."

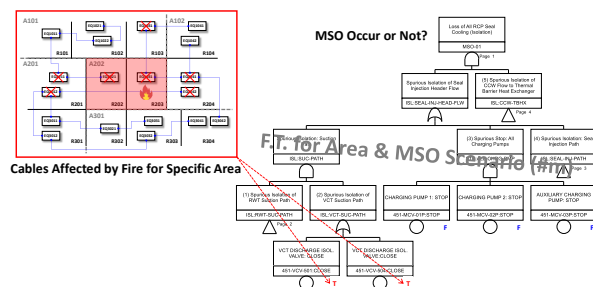


Fig. 7. Example of Area Specific FT for MSO Analysis

By performing a Boolean operation on the area-specific FT generated for MSO analysis, the occurrence of MSO in the corresponding fire area can be determined based on the resulting top event value. (Top event = 'T': MSO occurred, Top event = 'F': MSO did not occur)

2.5 Boolean Operation on MSO Fault Tree for Each Fire Area

To evaluate the area-specific MSO FT prepared above, the Boolean operation is performed according to the gate types (AND, OR, etc.) for each fire area, starting from the logic gates

immediately above the lowest level (BEs) where the function codes of the fire-affected cables are reflected. Boolean operations are executed from left to right within the same depth of the FT, progressing from the gates right above the BEs up to the top event.

By extracting cut-sets from the evaluated MSO FT, a list of components and cables that cause MSO in the event of a fire in the corresponding fire area can be derived. By extracting the logical combination of BEs within the FT ranging from the BEs (component and failure mode caused by fire-affected cables) assigned for each fire area up to the top event, all cut-sets of the FT that cause MSO can be identified. [13] ~ [15]

3. Application Example of the MSO Analysis Method using Fault Tree Analysis

To verify the 'MSO analysis method using FTA' described above, four MSO scenarios were applied to the target NPP, and the analysis results are shown in Table 3 below. Logical operations were repeated by using function codes corresponding to fire-affected cables for each fire area to the common FT for MSO scenarios.

The MSO scenarios applied as examples are as follows.

- MSO-01: Loss of All RCP Seal Cooling (Isolation)
- MSO-02: Loss of All RCP Seal Cooling (Diversion)
- MSO-03: Thermal Shock of RCP Seal
- MSO-04: Catastrophic RCP Seal Failure

For the MSOs of Scenarios #1, #2, and #4 to occur, the related components must spuriously operate in the same direction, and since Scenario #3 causes thermal shock when the RCP seal cooling is isolated and the sealing water is re-injected after heating, it can only occur in areas where the Scenario #1 or #2 occurred.

Table III: Example of MSO analysis results using the method

Fire Area	MSO #1	MSO #2	MSO #3	MSO #4
RCB	Occur	Occur	Occur	Occur
PAB General A	Occur	Occur	Occur	Occur
PAB General B	Occur	Occur	Occur	Occur
HPSI Pump Room A	OK	-	OK	OK
HPSI Pump Room B	OK	-	OK	OK
Battery Room A	OK	-	OK	OK
Battery Room B	OK	-	OK	OK
AFW Pump Room A	OK	Occur	Occur	OK
AFW Pump Room B	OK	OK	OK	OK
CC Pump Room A	OK	Occur	Occur	OK
CC Pump Room B	OK	OK	OK	OK
Cable Spreading A	Occur	Occur	Occur	Occur
Cable Spreading B	Occur	Occur	Occur	Occur
Remote Shutdown A	OK	Occur	Occur	OK
Remote Shutdown B	OK	OK	OK	OK
Elec. Equip. Room A	Occur	Occur	Occur	Occur
Elec. Equip. Room B	Occur	Occur	Occur	Occur
Computer Room	OK	Occur	Occur	OK
Control Room	Occur	Occur	Occur	Occur
SAB General Area	Occur	Occur	Occur	Occur

As previously expected, Scenario #3 is confirmed to occur only in the areas where Scenario #1 or #2 occurred.

4. Conclusions and Future Work

This paper presents an MSO analysis method that determines MSO occurrence in a corresponding fire area. This is achieved by generating common FTs for the selected MSO scenarios of the target NPP, deriving area-

specific FTs by reflecting fire-affected cables for each fire area, and performing logical operations on them. The proposed method was applied to several MSO scenarios of the target NPP. This method can be used in parallel with existing MSO analysis methods for comparison and verification. Comparing the results with those obtained from existing methods enables independent verification. Furthermore, its practical application is expected to improve work efficiency and the quality of analysis results by minimizing human error and required effort.

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