Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 22-23, 2025

Development of Quantitative Analysis Technology for Fire-Induced Multiple Spurious Operation Scenarios and Its Application to Domestic Nuclear Power Plant

Dae Il Kang*, Sun Yeong Choi and Yong Hun Jung
KAERI, 111 Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, 34057, Republic of Korea
**Corresponding author: dikang@kaeri.re.kr*

Keywords : fire, multiple spurious operations, NEI 00-01, MAAP, Operator Action

1. Introduction

EGM 09-002 [1] defines multiple spurious operations (MSO) as multiple fire induced circuit faults causing an undesired operation of one or more systems or components. In a fire probabilistic safety assessment (PSA), MSO analysis is conducted to evaluate their impact on equipment and systems, enabling proper modeling and quantification within the fire PSA framework. All fire scenarios affecting equipment or system functionality must be considered in fire PSA. The MSO analysis process begins with determining whether the general MSO scenarios outlined in NEI 00-01 are applicable to the target nuclear power plant (NPP).

In this study, the applicability of NEI 00-01 [2] MSO scenarios to a domestic reference NPP was reviewed, and a methodology for MSO scenario determination was developed. Additionally, thermal-hydraulic analyses were conducted using the Modular Accident Analysis Program (MAAP) code [3] to establish a basis for analyzing and modeling secondary-side breaks caused by MSOs. A quantitative analysis of key MSO scenarios was also performed.

2. Methods and Results

2.1. Review of NEI 00-01 MSO Scenario Applicability and Development of MSO Scenario Determination Method

With input from system analysis experts, PSA specialists, and deterministic MSO analysts, 47 out of 66 MSO scenarios (63 NEI 00-01 scenarios + 3 plant-specific scenarios) were identified as applicable to the reference plant and categorized as follows:

- Pre: 14 scenarios (from NEI 00-01 list) previously considered in domestic fire PSA studies.
- New: 22 scenarios (from NEI 00-01 list, 20 cases) newly identified for fire PSA consideration.
- Other: 8 scenarios (from NEI 00-01 list, 7 cases) related to signal issues or specific equipment malfunctions, included in the "New" category for modeling.
- Different: 3 plant-specific MSO scenarios not covered in NEI 00-01.

The developed MSO scenario determination methodology includes the following considerations:

- Power off: According to NUREG/CR-7150 Vol.1 [4], the probability of circuit energization due to spurious operation when AC or DC power is off is very low. Thus, NEI 00-01 MSO scenarios are not considered in such cases.
- Valve Operations: MSO scenarios depend on the normal operating status of valves and their required status in PSA. If a valve is normally closed and must remain closed, a spurious opening is considered. Conversely, if it should remain open, a spurious closure is evaluated.
- Piping Size: Per NUREG/CR-4850 Vol.1 [5], leaks from pipes smaller than one-third of the main pipe diameter are excluded from PSA, as their impact is negligible given the safety margins in NPP
- Design Features: If an orifice prevents pump runout, spurious pump runout scenarios are excluded. Similarly, check valves prevent reverse flow paths, mitigating certain MSO scenarios.

2.2. MAAP Analysis

When modeling the fault tree for initiating events caused by fire-induced opening of the atmospheric dump valve (ADV), the primary concern is determining the time required to close the ADV before the initiating event is classified as a secondary-side break (LSSB) event rather than a loss of condenser vacuum (LOCV) event. Even if the ADV opens due to an MSO, it eventually closes due to its fail-safe position design. However, there is a possiblility that the fail-safe design will fail. NUREG/CR-7150 Vol.2 [6] provides spurious operation duration conditional probability data over time. The plant's behavior in response to an open ADV also depends on whether auxiliary feedwater is supplied.

Table I presents the MAAP analysis results for fire-induced ADV openings and spurious operation duration probabilities. When two ADVs open (Cases 1-4), the reactor trips in 38.6 seconds. If no feedwater is supplied to any steam generator (SG) (Case 3), the SG depletion time is 424 seconds. When four ADVs open (Cases 5-6), the reactor trips in 34.2 seconds. If no feedwater is supplied (Case 5), the SG depletion time is 663 seconds. If feedwater is supplied before SG depletion, secondary-side cooling via the open ADV remains possible (Cases 1, 2, 4, 6).

Based on the difference between the SG depletion time (424sec) and reactor trip time(38.6sec), the spurious operation duration probability due to ADV opening was estimated to be 2.51E-2.

2.3. Important MSO Scenario Modeling and Quantitative Analysis

Six fire-induced MSO scenarios were selected for quantitative analysis:

- Fire-induced RCP Seal LOCA MSO scenario (NEI 00-01 general MSO scenarios 1/4)
- Fire-induced Steam Dump MSO scenario (NEI 00-01 general MSO scenarios 23/24 and 5/6)
- Fire-induced Loss of Emergency Power MSO scenario (NEI 00-01 general MSO scenarios 46/49)

The fire-induced RCP seal LOCA MSO scenario (Scenario 4 from NEI 00-01) involves seal LOCA occurring without an RCP trip. This scenario considers RCP trip failure and spurious restart of a stopped RCP. Three types of operator actions, as shown in Fig.1, were modeled:

- Manual trip failure in the main control room
- Manual trip failure outside the main control room
- Manual trip failure outside the main control room in case of NON-1E 125V DC loss

NEI 00-01 includes various fire-induced steam dump scenarios. However, based on the MSO scenario determination methodology and MAAP thermal-hydraulic analysis, only ADV opening and turbine bypass valve (TBV) opening were selected as secondary-side break-inducing MSO scenarios. The TBV opening secondary-side break scenario assumes the main steam isolation valve (MSIV) does not fail to close. Since spurious ADV or TBV opening, or MSIV failure to close, can revert to a fail-safe position due to overcurrent, the failure-to-sustain event was modeled using an AND gate.

Fire-Induced Loss of Emergency Power MSO Fault Trees are modeled as follows:

- NEI 00-01 Scenario 46: A single-event scenario where a non-safety bus, isolated during emergency diesel generator (EDG) operation, connects to a safety bus, causing EDG failure.
- NEI 00-01 Scenario 47: Two scenarios involving breaker malfunctions that connect both onsite and offsite power sources to the EDG:
    - Trip of the station auxiliary transformer * Running of startup transformer * EDG malfunction
    - Running of station auxiliary transformer * Trip of startup transformer * EDG malfunction

Among all analyzed MSO scenarios, the NEI 00-01 Scenario 4 (RCP seal LOCA) was identified as the most critical. This study confirmed that while MSO scenarios do not have a major impact on the overall fire PSA results, they cannot be ignored.

3. Concluding Remarks

This study systematically reviewed the applicability of NEI 00-01 MSO scenarios to a domestic reference NPP and developed a structured methodology for MSO scenario determination. Among 66 MSO scenarios, 47 were deemed relevant and classified into Pre, New, Other, and Different categories. Thermal-hydraulic analyses using the MAAP code provided insights into secondary-side breaks caused by fire-induced spurious operations. The estimated spurious operation duration probability due to ADV opening was 2.51E-2, offering quantitative insight into such events. Six key MSO scenarios underwent detailed quantitative analysis, with particular emphasis on the fire-induced RCP seal LOCA scenario, which emerged as the most critical due to its potential impact on plant safety.

Overall, this study highlights the necessity of incorporating MSO scenario analysis into fire PSA to better understand fire-induced circuit faults and their implications for NPP safety. The developed methodology and quantitative approach provide a robust framework for future fire PSA studies, ensuring a more comprehensive evaluation of fire-induced spurious operations in NPPs.

Acknowledgments

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government (Ministry of Science and ICT) (RS-2022-00144204).

REFERENCES

[1] EGM 09-002, Enforcement Guidance Memorandum—Enforcement Discretion for Fire Induced Circuit Faults, May 14, 2009. ADAMS Accession No. ML090300446.
[2] NEI, Guidance for Post Fire Safe Shutdown Circuit Analysis, NEI 00-01, Revision 3, Nuclear Energy Institute, 2011.
[3] EPRI, MAAP Version 5.06, Modular Accident Analysis, Electric Power Research Institute, 2021.
[4] Subudhi, M. et al., Joint Assessment of Cable Damage and Quantification of Effects from Fire (JACQUE-FIRE), Voulume 1: Phenomena Identification and Ranking Table (PIRT) Exercise for NPPFire-Induced Electrical Circuit Failure, NUREG/CR-7150, USNRC, 2014.
[5] Mary T. Drouin. et al., Analysis of Core Damage Frequency from Internal Events: Methodology Guidelines Volume 1, NUREG/CR-4550, USNRC, 1987.
[6] Subudhi, M. et al., Joint Assessment of Cable Damage and Quantification of Effects from Fire (JACQUE-FIRE), Voulume 2: Expert Elicitation Exercise, NUREG/CR-7150, USNRC, 2014.

Table I: MAAP Analysis Results of Fire-Induced ADV Opening and Spurious Operation Duration Probability

<Thermalhydraulic Analysis Results for Spurious Opening of ADVs>

Cases		Rx Trip, Main FW Off MSIV closed	Train A SG dryout	Train B SG dryout	Train A AFW injected	Train B AFW injected	PSV First Open	Core Uncovered
Case 1	2 ADV, 0.0 sec	38.6 sec (*)	No	No	38.6 sec	38.6 sec	No	No
Case 2	2 ADV, 0.0 sec	38.6 sec (*)	No	No	38.6 sec	No	No	No
Case 3	2 ADV, 0.0 sec	38.6 sec (*)	424 sec	3266 sec	No	No	3319 sec	5658 sec
Case 4	2 ADV, 0.0 sec	38.6 sec (*)	424 sec	3266 sec	3319 sec	No	3319 sec	No
Case 5	4 ADV, 0.0 sec	34.2 sec (*)	663 sec	681 sec	No	No	3786 sec	5666 sec
Case 6	4 ADV, 0.0 sec	34.2 sec (*)	No	721 sec	34.2 sec	No	No	No
Case 7	1 ADV, 0.0 sec	13695 sec (**)	14296 sec	17046 sec	No (***)	No (***)	17121 sec	19482 sec
Case 8	MSLB, 0.0 sec	1.46 sec (*)	133 sec	3026 sec	No	No	3101 sec	5387 sec

(*) Reactor trip due to low SG pressure (6.13 MPa, 889 psia)
(**) Reactor trip due to low pressurizer pressure (12.58 MPa, 1824 psia)
(***) Main feed water injected until reactor trip

<Spurious Operation Duration Conditional Probability>

AC Pr{T>t} CCDF	Time	DC Pr{T>t} CCDF
Mean	(minutes)	Mean
1	0	1
5.12E-01	1	5.12E-01
2.74E-01	2	2.74E-01
1.49E-01	3	1.49E-01
8.17E-02	4	8.17E-02
4.51E-02	5	4.51E-02
2.51E-02	6	2.51E-02
1.40E-02	7	2.20E-02
7.85E-03	8	2.20E-02
7.10E-03	9	2.20E-02

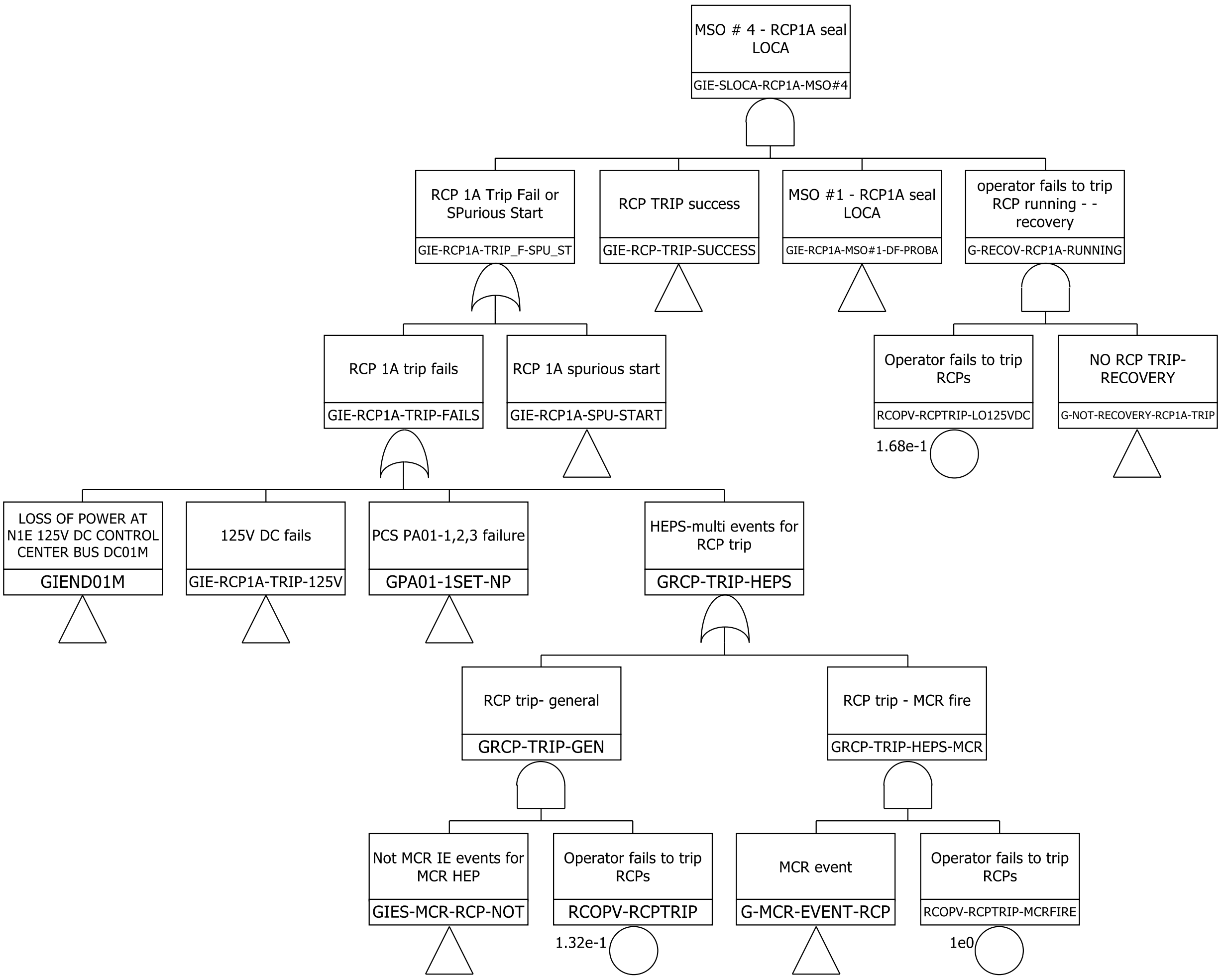

Fig.1. Fault Tree of Operator Actions for RCP Trip