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Post-Fire Safe Shutdown Analysis Method for Fire Area of Nuclear Power Plant applying Fault Tree Analysis

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1. Introduction

A fire hazard analysis (FHA) of a nuclear power plant (NPP) means quantitative or qualitative risk analysis to review the risk of a hypothetical fire in each fire area and evaluate the appropriateness of fire prevention and protection measures to ensure safe-shutdown capability for reactor, and to demonstrate minimizing a possibility of radioactive material leakage out to the environment in the event of fire in the NPP.

The FHA includes various analyses and estimations of fire protection, such as a designation of fire protection compartments, fire load calculation, evaluation of the suitability of fire protection equipment, routing analysis of cables related to safe-shutdown, multiple spurious operations (MSO) analysis, and evaluation of fire protection plans and procedures. It requires a significant amount of time and manpower to review the various analyses and evaluations contained in the FHA report, as well as the vast amount of data, to derive meaningful regulatory issues. Since it is realistically difficult to review fire analysis results for all fire areas in NPP, which consists of over 200 fire areas in the same depth, there has been a demand for the development of computerized tools to improve analysis techniques for fire protection safety issues and support regulatory activities.

Until now, software from overseas has been used for post-fire safe-shutdown analysis (SSA), or existing probabilistic safety assessment (PSA) software has been used for fault tree analysis (FTA), and there has been no dedicated software for the post-fire SSA. Therefore, we proposed a method for performing the post-fire SSA for each fire area in NPP, applying FTA, and have developed a computer program to implement this methodology conceptually. We aim to establish a work process for performing post-fire SSA by applying the methodology based on the latest domestic and international codes and standards for fire protection and regulatory requirements, and to develop a dedicated computer program suitable for post-fire SSA based on this process for practical use.

2. Post-Fire Safe-Shutdown Analysis Method applying Fault Tree Analysis

The post-fire SSA has been performed by isolation assessment and interference effect assessment for components and cables related to safe-shutdown. The interference effect assessment is an analysis of the effects on safe-shutdown when a cable is affected by fire. The cable failure modes that must be considered in fire analysis are divided into three types: a hot short, a short-to-ground, or an open circuit. Associated circuit analysis considered in the interference effect assessment includes common power supply, common enclosure, spurious operation, and multi-high impedance faults.

A new approach was required to evaluate the causes of safe-shutdown failures compared to existing post-fire SSA methods and to establish corrective measures based on this evaluation. Therefore, FTA was applied to the post-fire SSA for each fire area. Applying FTA to the post-fire SSA has the following two advantages:

- Confirmation of satisfying post-fire safe-shutdown by quantification of area specific fault tree (FT) reflected components and cables affected by fire by combining room-level cable routing data and fire compartment information
- Establishment of corresponding follow-up and apposite counter-measures, including improvements, by identifying a list of the components and cables affected by fire, 'basic event' (BE) in the FT, that is the root cause that triggers 'top event' (i.e., reactor safe-shutdown fail) by querying cut-sets of the FT

The overall workflow of the post-fire SSA presented in this paper is as shown in Figure 1 below.

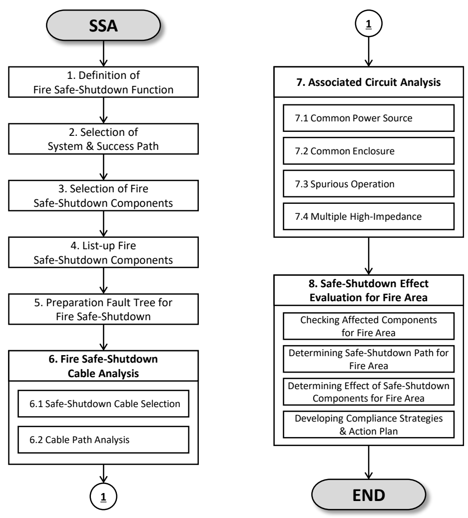

Fig. 1. Work flow of the post-fire safe-shutdown analysis

2.1 Preparation of Plant Common Fault Tree for Post-Fire Safe-Shutdown Analysis

According to the regulatory guidelines [1] and analysis methodology [2], [3] of the U.S. NRC, functions for safely shutting down the reactor, even fire occurs in any fire area during normal operation of NPP are defined first, and systems for safe-shutdown are selected. Then, safe-shutdown components (classified as required for hot shutdown or important to safe-shutdown) configured in each system, and required to perform their function are selected. A safe-shutdown components list is prepared including its type, id, description, (normal operation, required to hot shutdown, required to cold shutdown, power loss, malfunction for negative effect to safe-shutdown) status, and location for selected all safe-shutdown components (including multiple spurious operation (MSO) scenario review). The selected components are assigned to the corresponding system, success path, and function to prepare a safe-shutdown logic diagram in the form of a fault tree. At this stage, the FT is prepared in the components level, and expanded in the cable level after completion of cable identification and routing analysis. To summarize, it is as follows:

- The top event is set to ‘reactor safe-shutdown fail’
- The intermediate objects (gate) below the top event are set as failure of the previously selected function (ex., ‘safe-shutdown function A fail’)
- The sub-objects (gate) of the functions are set as unavailability of selected systems (ex., ‘safe-shutdown system A-1 unavailable’)
- The sub-objects (gate) of the system unavailability are set as abnormal operation of each component of the system (ex., ‘safe-shutdown component A-1-X fail or malfunction or spurious operation’)
- The basic event in most low-level consists of the function code of the safe-shutdown cables (connected and interlocked with the safe-shutdown components) affected by fire.

Figure 2 below is an example of a fault tree for the post-fire SSA created in the manner described above.

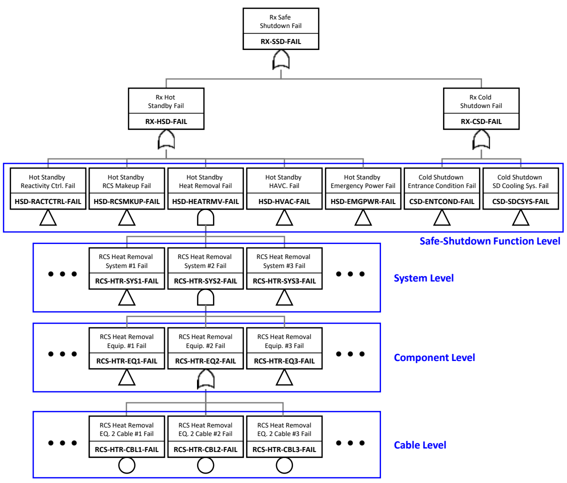

Fig. 2. Example of fault tree for the post-fire SSA

A Comparison of the FT for PSA and the FT for post-fire SSA is shown in Table I below [4]. A typical FT for (level 1) PSA is prepared by setting reactor core damage as the top event and reflecting various initiating events and system characteristics, and additionally including various requirements such as common cause failures, testing and maintenance, and human reliability. The FT for post-fire SSA is prepared by setting failure of reactor safe-shutdown as the top event, and composing the functions, systems, components, cables mentioned above, including the MSO scenario.

Table I: Comparison of fault tree in PSA and post-fire SSA

	FT in PSA	**FT in post-fire SSA**
Goal	Sys. Failure Probability or Core Damage Frequency (Level 1)	Rx Safe-Shutdown for Post-Fire
Applicable Target	System or Plant (Rx Core)	Safe-Shutdown when a Fire occurs in each Fire Area in NPP
Top Event	System Failure or Core Damage	Rx Safe-Shutdown Fail
Intermediate Event (Gate)	Safe Function / Sys. (Reactivity Ctrl., RCS Inventory Ctrl., RCS Pressure Ctrl., Core & RCS Heat Removal, Containment Integrity)	Safe-Shutdown Function / Sys. (Reactivity Ctrl., Rx Coolant Makeup, Rx (Decay) Heat Removal, Process Monitoring, Support Function
Basic Event	Safe Sys. Component (Assigned Failure Probability or Failure Rate)	Assigned equal value to B.E. for Fire-Affected Components & Cables in each Fire Area
Initial Event	Single Event among Internal Event (LOCA, Transient), External Event (Earthquake, Fire, Flooding)	Fire in each Fire Area (Single Fire; Fire in Single Area)
Quantification	Event Tree & Fault Tree Link, Sys. F.T. Integration	Quantification of Area Specific F.T. reflected Fire-Affected Components & Cables for each Fire Area
Analysis Result	Sys. Failure Probability or CDF ⇒ Probability (< 1.0)	Success or Fail of Rx Safe-Shutdown (Top = 0.0: OK, Top > 0.0: Fail)
Cut-Set	Minimal Cut-Set	All Cut-Set List

2.2 Generating Area Specific Fault Tree

To generate area specific FT, first, search for the components and cables affected by fire in each fire area, as shown in Figures 3 and 4 below. Search for cables affected by fire and components connected to them by comparing room-based cable routing data with the fire compartment for each fire area. Search for a list of all the cables installed or routed in a specific fire area.

Set all mean values of the BEs in the FT for post-fire SSA of target NPP to ‘0.0’ to prepare a ‘plant common FT’ as shown in Figure 5 below.

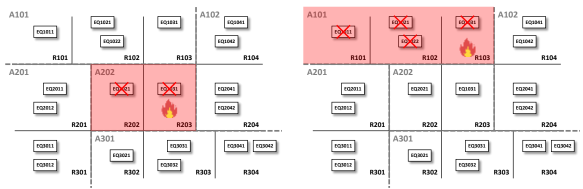

Fig. 3. Example of components affected by fire in fire area

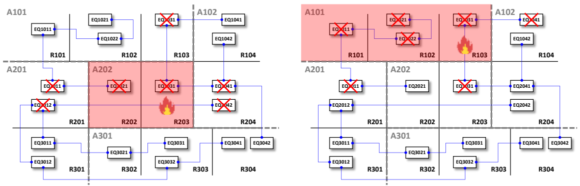

Fig. 4. Example of components affected by cables

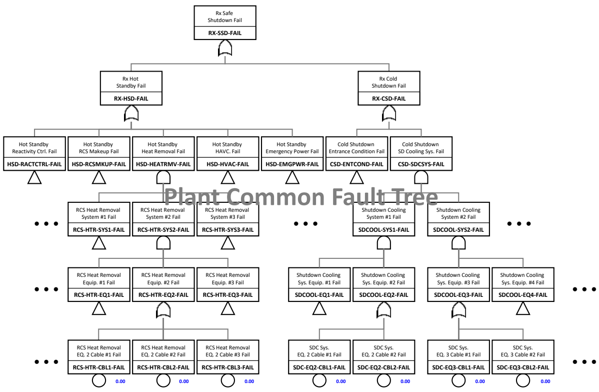

Fig. 5. Example of plant common FT for the post-fire SSA

The area specific FT are generated as shown in Figures 6 and 7 below by assigning (mean) values greater than 0.0 to all BEs in the FT corresponding to the fire-affected components and cables searched for each area. As a quantification result of the area specific FT generated in this way, it is possible to determine whether the safe-shutdown of the fire area is satisfied or not based on the top event value. (Top = 0.00 → safe-shutdown satisfied, Top > 0.00 → safe-shutdown failed)

In both case, the same quantification result (safe-shutdown satisfaction or failure) can be obtained: when the BE of the FT is prepared to the component level and a positive value is assigned to the BE corresponding to the components connected to the fire-affected cable; and when the BE corresponding to the fire-affected cable is prepared to the cable level and a positive value is assigned to the BE corresponding to the fire-affected cable.

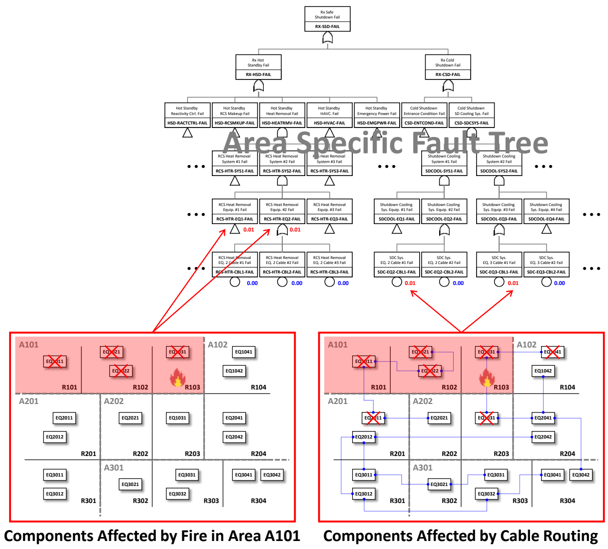

Fig. 6. Example 1 of area specific FT for the post-fire SSA

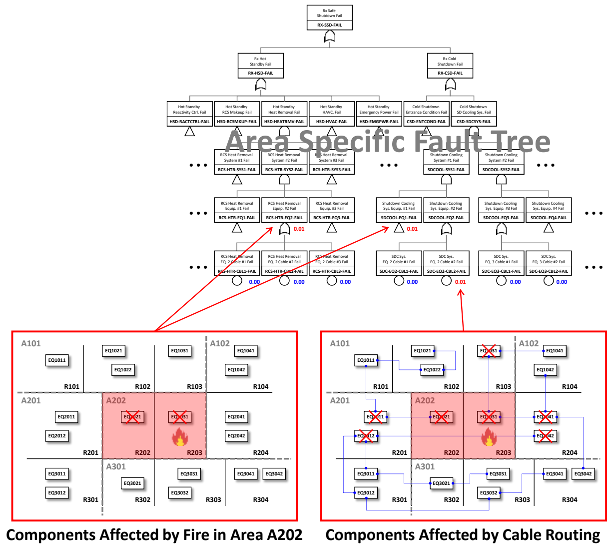

Fig. 7 Example 2 of area specific FT for the post-fire SSA

2.3 Quantifying Area Fault Tree

The quantification method for the area specific FT generated as above is shown in Figure 8 below. For each fire area, the FT reflecting the components and cables affected by fire is quantified by performing a Boolean operation on each type (AND, OR, etc.) of gate starting from the object just above the BE. The (mean) value of each gate in FT is calculated in order from left to right within the same level (depth) of the FT, and the logical operations are performed from the gate just above BE to the top event.

• Start from **Bottom** to **Top**; Boolean operation of each Gate

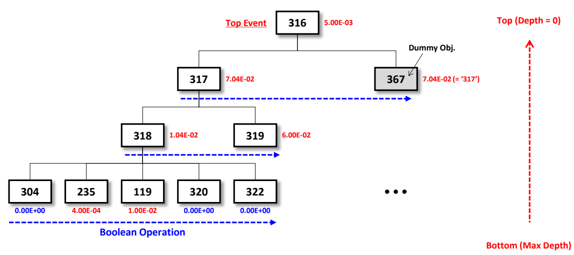

Fig. 8. Quantifying method of area specific FT

As shown in Figure 9 below, by querying the cut-set in the quantified FT, a list of components and cables that cause 'safe-shutdown fail' in the event of a fire in the fire area can be derived. By extracting the set of objects within the FT from the BE (components or cables affected by fire) for each fire area to the top event, all cut-sets within the FT that cause 'safe-shutdown fail' can be identified.

• Start from **Top** to **Bottom**; Object (Gate or Event) with positive mean value in level of quantified F.T.

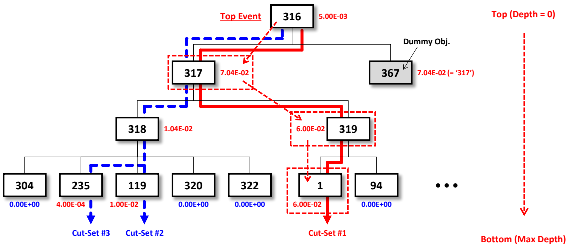

Fig. 9. Cut-set searching method for quantified FT

3. Development of a Computer Program Implemented Concept of the Post-Fire Safe-Shutdown Analysis Applying Fault Tree Analysis

To verify the 'post-fire SSA method applying FTA' described above, a computer program implementing this concept was developed, and the results of the post-fire SSA were compared with those of the existing FTA software using the same data and FT for a specific NPP.

3.1 Major Features and Work flow of the Computer Program

The computer program that conceptually implements the above methodology performs analysis according to the workflow shown in Figure 10 below. The process proceeds in the following order: loading FT data, generating FT structure, processing fire area data (ex., fire compartment, cable routing, etc.) and extracting function codes by area, and repeating by fire area (applying the corresponding BE in the FT; generating area specific FT → quantifying the FT → searching for cut-sets → summarizing & outputting the quantification results).

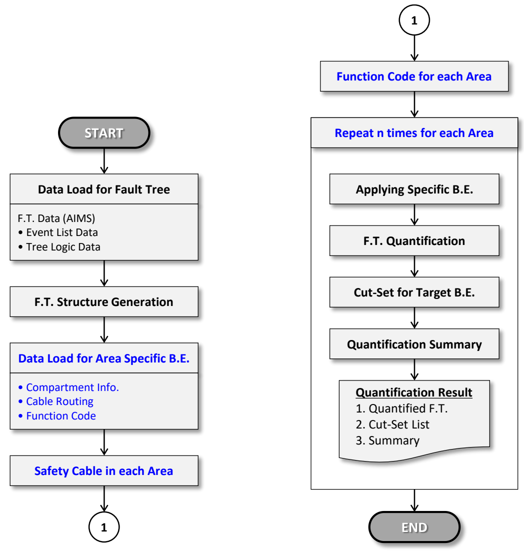

Fig. 10. Work flow of the computer program for post-fire SSA

3.2 Analysis Results Comparison with Existing FTA Software for PSA

Using the computer program, we performed analyses on specific NPP and fire areas. Figures 11 and 12 below show examples of quantified FTs and the resulting cut-sets from the FTA results, respectively.

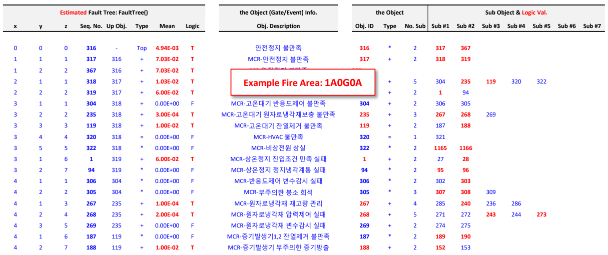

Fig. 11. Example of FT quantification result by the computer program for post-fire SSA

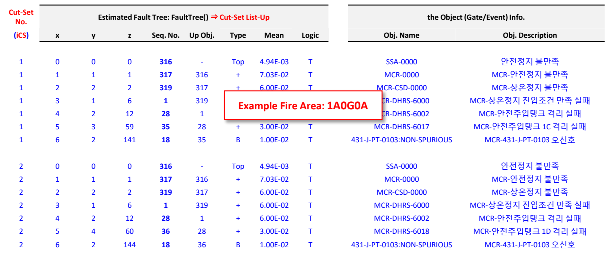

Fig. 12. Example of Cut-Set Searching Result of Quantified FT by the Computer Program for post-fire SSA

Table II below compares the mean values of top events with those of existing FTA software using the same data and FT for a specific NPP. In most fire areas, the results quantified by the computer program were slightly higher than the results quantified by the PSA software; however, this did not interfere with the judgment of whether safe-shutdown was satisfied or not, and the possibility of post-fire safe-shutdown determined by the quantified results was evaluated equally in all cases.

Table II: Comparison of FTA results of the post-fire SSA computer program and PSA software

No.	Area	DFire FTA		AIMS-PSA	
		Top	Result	Top	Result
1	**1C0G0**	**8.51E-02**	**Fail**	**6.22E-02**	**Fail**
2	**1A0G0A**	**4.00E-02**	**Fail**	**2.98E-02**	**Fail**
3	**1A0G0B**	**4.05E-02**	**Fail**	**3.02E-02**	**Fail**
4	1A0G1	0.00E+00	OK	0.00E+00	OK
5	1A0G2	0.00E+00	OK	0.00E+00	OK
29	**1A226A**	**4.10E-08**	**Fail**	**2.05E-05**	**Fail**
30	**1A226B**	**2.00E-08**	**Fail**	**1.03E-08**	**Fail**
39	**1A325A**	**2.21E-04**	**Fail**	**2.20E-04**	**Fail**
40	**1A325B**	**1.12E-05**	**Fail**	**1.10E-05**	**Fail**
41	1A402B	0.00E+00	OK	0.00E+00	OK
42	**1A421A**	**4.45E-02**	**Fail**	**3.37E-02**	**Fail**
43	**1A421B**	**4.04E-02**	**Fail**	**3.02E-02**	**Fail**
48	**1A424A**	**1.00E-08**	**Fail**	**1.00E-08**	**Fail**
49	**1A424B**	**1.00E-08**	**Fail**	**1.00E-08**	**Fail**
50	**1A532A**	**2.34E-02**	**Fail**	**2.31E-02**	**Fail**
51	**1A532B**	**2.34E-02**	**Fail**	**2.32E-02**	**Fail**
52	**1A5G1**	**1.43E-01**	**Fail**	Error	N/A
53	1A622A	0.00E+00	OK	0.00E+00	OK
54	**1A622B**	**1.00E-08**	**Fail**	**1.00E-08**	**Fail**
55	**1F0G0**	**1.00E-04**	**Fail**	**2.00E-04**	**Fail**
56	1F0G1	0.00E+00	OK	0.00E+00	OK
57	**1F0G2**	**1.00E-04**	**Fail**	**1.00E-04**	**Fail**

4. Conclusions

We proposed a post-fire SSA method based on FT generation and quantification of components and cables affected by fire in a fire area of a NPP. We also implemented a computer program for post-fire SSA applying this method. This FTA method and computer program able to be used for comparison and review with existing post-fire SSA results. Furthermore, it can be utilized in conjunction with existing analysis methods and software for future post-fire SSA of NPP.

By comparing the results with those analyzed using existing software, we have secured a computerized tool that able to verify independently. If this is applied in practice, it is expected to reduce the manpower required for fire analysis, and minimize human errors, thereby improving work efficiency and the quality of results.

REFERENCES

[1] U.S. NRC Reg. Guide 1.189 Rev. 5, Fire Protection for Nuclear Power Plant
[2] NEI 00-01, rev. 4, Guidance for Post Fire Safe Shutdown Circuit Analysis
[3] BTP CMEB 9.5-1, Fire Protection Program, rev. 4
[4] Myung-Soo Kim, Mi-Gyeong Kim, "A Review on Characteristics of PSA Fault Trees and Post-fire Safe Shutdown Logic Models", Korea Energy Society 2024 Autumn Conference
[5] Mun-Soo Kim, Mi-Gyeong Kim, Beom-Gyu Kim, "Selection of Safety Shutdown Components for Nuclear Power Plant Fire Hazard Analysis", Korean Institute of Fire Science & Engineering 2018 Spring Conference
[6] In-Hwan Kim, Heok-Soon Lim, Yeon-Kyoung Bae, "Study of Post-fire Safe-Shutdown Analysis of a CANDU Main Control Room Based on NEI 00-01 Methodology", Fire Science & Engineering, Vol. 30, No. 4, p.20-26, 2016
[7] Hyuk-Soon Lim, In-Hwan Kim, Moon-Hak Jee, "Safety Shutdown Evaluation on Main Control Room Fire of CANDU NPP", Korean Institute of Fire Science & Engineering 2015 Autumn Meeting
[8] In-Hwan Kim, Yun-Jung Kim, Mun-Hee Park, "Study on the Post-Fire Safe-Shutdown Analysis for CANDU NPPs", KNS 2015 Autumn Meeting
[9] Hyun-Tae Yim, Jun-Hyun Park, "Post Fire Safe Shutdown Analysis Using a Fault Tree Logic Model", KNS 2005 Autumn Meeting
[10] Chang-Gi Jeong, Bok-Yeong Lee, Ki-Oak Kim, Chan-Ho Park, Byung-Ho Ahn, "Assessment of Fire Safe-Shutdown Capability of NPP", Fire Protection Technology No. 31, 20-32, 2001
[11] Hyun-Tae Yim, Dong-Hwan Ha, Jun-Hyun Park, "Selection of Safe Shutdown Components for a Fire Hazard Analysis", KNS 2001 Spring Meeting
[12] Jun-Hyun Park, Il-Seok Jung, Seung-Yeol Hong, Seung-Bok Kang, Dong-Hak Ko, "Evaluation of Post-fire Safe Shutdown Capability for Operating Nuclear Power Plants", KNS 2001 Spring Meeting

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