Risk Effects of Damage Assessment Methods in a Fire Probabilistic Safety Assessment

Yong Hun Jung [a*], Kyungho Jin [a], and Dae Il Kang [a]
[a] *KAERI, 111 Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, 34057, Republic of Korea*
[*] *Corresponding author: jungyh@kaeri.re.kr*

***Keywords : probabilistic safety/risk assessment, fire scenario, fire analysis, fire risk, fire damage assessment**

1. Introduction

A fire probabilistic safety/risk assessment (PSA/PRA) evaluates the likelihood and potential consequences of fire events in a nuclear power plant (NPP) so that plant safety and integrity can be ensured and improved against fire events [1-2]. In a level-1 PSA the fire-induced risk is expressed as the Core Damage Frequency (CDF), whereas in a level-2 PSA it is expressed as the Large Early Release Frequency (LERF). Both risk metrics can be written in the following generic form:

$$CDF_F = \sum (\underline{FIF_i \times f(SF_i \,\&\, NSP_i)} \times CCDP_{F,i}) = \sum (\underline{FSF_i} \times CCDP_{F,i})$$

$$LERF_F = \sum (\underline{FIF_i \times f(SF_i \,\&\, NSP_i)} \times CLERP_{F,i}) = \sum (\underline{FSF_i} \times CLERP_{F,i})$$

Where

CDF_F	: Fire-induced Core Damage Frequency
$LERF_F$	: Fire-induced Large Early Release Frequency
FIF_i	: Fire Ignition Frequency
SF_i	: Fire Severity Factor
NSP_i	: Fire Non-Suppression Probability
FSF_i	: Fire Scenario Frequency
$CCDP_{F,i}$	: Fire-induced Conditional CD Probability
$CLERP_{F,i}$	: Fire-induced Conditional LER Probability
i	: Fire Scenario

The previous study [1] proposed the semi-detailed method, which divides a single fire scenario into three sub-scenarios, and demonstrated that it provides a more realistic representation of fire risk. The present study builds on that framework by investigating how different damage assessment methods affect the calculated fire risk.

2. Methodology

2.1 Binning (BIN) Approach

The intensity of a fire is primarily characterized by its peak heat release rate (HRR). Because the peak HRR is uncertain, it is represented by a probability distribution (commonly a gamma distribution) [2-5]. The peak HRR directly influences two key quantities in a fire PSA: Time-to-damage, Fire Non-Suppression Probability (NSP) and Fire Severity Factor (SF). The Binning Approach (BIN) (NUREG/CR-6850 Vol. 2, Appendix E) [2] discretizes the HRR probability distribution into a set of bins. Each bin j is defined by a width (the probability of the bin) and a representative peak HRR value. For every bin the following steps are performed:

(1) Calculate the time to damage for the representative HRR using the fire scenario conditions (e.g., distance to the target, plume model).
(2) Construct a discretized probability distribution of damage times by assigning the bin width wj to the corresponding damage time.
(3) Evaluate NSP for each damage time using the detection and suppression system characteristics.
(4) The resulting probability weighted NSP is then used in the fire scenario frequency calculation.

An alternative, less computationally intensive method is to adopt the P98 (98th percentile) timing profile of the HRR distribution. The P98 approach assumes that the fire grows at the rate corresponding to the 98th percentile of the HRR distribution. While this approach eliminates the need for binning, it can over-estimate fire growth and therefore risk.

2.2 Damage Threshold (DT) Method

The Damage Threshold (DT) method has been the standard technique for fire damage assessment since NUREG/CR-6850 [2]. It is a single threshold, conservative approach: a target is considered damaged when the instantaneous temperature (or heat flux) at the target exceeds a predefined damage threshold that reflects the material's thermal limit. The method relies on experimental data that identify the temperature or heat flux limits for various cable types and other fire exposed components. Because the DT method ignores the duration of exposure, it tends to be more conservative than methods that account for cumulative heating.

2.3 Damage Integral (DI) Method (Heat Soak Method)

The Damage Integral (DI) method (NUREG-2178 Vol. 2, Appendix A) [4], often called the heat soak method, extends the DT approach by incorporating the time integral of heat exposure. Damage is evaluated by the damage integral. The DI method therefore captures the cumulative effect of heating, providing a more realistic assessment while retaining a level of conservatism appropriate for safety analyses.

3. Example Analysis

3.1 Conditions and Assumptions

An example analysis was performed to compare three combinations of damage assessment methods: (1) using the P98 approach, (2) the BIN approach with the DT method, and (3) the BIN approach with the DI method.

The same conditions and assumptions are used for all cases, as summarized below:

- Ignition Source (IS): Electrical Enclosures (Bin 15), Switchgear & Load Centers w/ TS/QTP/SIS Cables [3]
- Heat Release Rate (HRR) Distribution: Gamma ($\alpha = 0.32$ & $\beta = 79$) [3]
- HRR Timing Profile: Interruptible Fires (IF) (Split Fraction 0.723) / Growing Fires (GF) (Split Fraction 0.277) [6]
- First Target (TG1): Thermoset (TS) Cable Tray located above the IS
- Temperature Damage Criteria [℃]: 330 [2]
- Vertical Distance from Fire Base to TG1 [ft]: 1 / 3 / 5
- Damage Mechanism and Model: Vertical Damage (Temperature Exposure) using the Modified Heskestad's Plume Centerline Temperature Correlation [7]
- Time to First Detection [min.]: 0 [6]
- Time to Delayed Detection (Eventually Detected) [min.]: 15 [6]
- Automatic Detection System - Unreliability, Unavailability, and Ineffectiveness: 5.00E-02, 1.00E-02, 5.80E-01 [6] (analyzed both w/ and w/o crediting this system)
- Failure Probability of Plant Personnel Present: 2.31E-01 [6]
- Failure Probability for MCR Indication: 1.00E-02 [6]
- Human Error Probability for MCR Response to MCR Indication: 1.00E-03 [6]
- Automatic Suppression System - Unreliability, Unavailability, and Ineffectiveness: 5.00E-02, 1.00E-02, 0.00E+00 [6] (analyzed both w/ and w/o crediting this system)
- Manual Suppression Rate [1/min.]: 1.49E-01 for Interruptible Fires / 1.00E-01 for Growing Fires [6]
- Fire Ignition Frequency (FIF): FIF(Bin 15) = 3.57E-05
- Conditional Core Damage Probability (CCDP): CCDP(FDS0) = 2.00E-07/ CCDP(FDS1) = 5.00E-05 / CCDP(FDS2) = 3.00E-03

All other parameters are taken as the default or medium values from the cited references.

3.2 Summary of Results

Table results of this example analysis are summarized in Tables I-VI. The results demonstrate that (1) the P98 approach generally yields the most conservative (i.e., highest) fire-induced CDF, (2) the BIN+DT approach reduces the CDF estimate, and (3) the BIN+DI (heat soak) method lowers the CDF further.

The use of the BIN approach delays the time to damage because it explicitly addresses the HRR uncertainty and utilizes timing profiles of lower peak HRR values. The use of the DI method delays the time to damage because it accounts for the cumulative heating of the target. These, in turn, increase the available time for suppression, and eventually, decrease the NSP. The use of the DI method also decreases the SF by increasing a damaging HRR, as it requires certain time of exposure above the threshold. These differences become more pronounced as the vertical distance between the ignition source and the target increases. Notably, the use of the P98 approach does not always result in the highest CDF; this is because the fire diameter during the fire growth period is reduced during the fire modeling process for the BIN+DT and BIN+DI methods.

4. Conclusions

The study confirms that damage assessment methodology significantly influences fire risk results. Using a bounding HRR profile (P98) generally produces the most conservative risk estimates. Applying the BIN approach with the traditional DT method yields a less conservative but more realistic risk estimate because the probability distribution of the peak HRR is explicitly represented. The DI (heat soak) method combined with the BIN approach provides the most realistic assessment; it captures both the intensity and the duration of heat exposure, leading to the lowest fire-induced risk among the three alternatives.

The choice of method should balance analytical effort and conservatism. For preliminary screening studies the P98 approach may be acceptable, whereas detailed analyses should employ the BIN+DI (heat soak) methodology. Consequently, fire PSA analysists should carefully select the damage assessment method that best matches the intended level of conservatism and the available computational resources.

Acknowledgements

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).

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Table I: Results of Example Fire Scenario Analysis:
TG1, TS Cable Tray at a Distance of 1 ft above IG, Switchgear or Load Center, No Crediting Fire Protection Systems.

		FIF	**SF**	**NSP(t_1)**	**NSP(t_2)**
(1) P98	GF (0.277)	9.89E-06	0.64	8.68E-01	5.83E-01
	IF (0.723)	2.58E-05	0.64	2.33E-01	1.30E-01
(2) BIN + DT	GF (0.277)	9.89E-06	0.64	6.86E-01	4.61E-01
	IF (0.723)	2.58E-05	0.64	1.95E-01	1.08E-01
(3) BIN + DI	GF (0.277)	9.89E-06	0.62	6.12E-01	4.11E-01
	IF (0.723)	2.58E-05	0.61	1.78E-01	9.86E-02
	FSF (FDS0)	**FSF (FDS1)**	**FSF (FDS2)**	**CDF**	**Ratio**
(1) P98	2.64E-05	3.52E-06	5.83E-06	**1.77E-08**	**100%**
(2) BIN + DT	2.81E-05	2.86E-06	4.70E-06	**1.43E-08**	**81%**
(3) BIN + DI	2.92E-05	2.47E-06	4.07E-06	**1.23E-08**	**70%**

Table II: Results of Example Fire Scenario Analysis:
TG1, TS Cable Tray at a Distance of 3 ft above IG, Switchgear or Load Center, No Crediting Fire Protection Systems.

		FIF	**SF**	**NSP(t_1)**	**NSP(t_2)**
(1) P98	GF (0.277)	9.89E-06	0.21	5.72E-01	3.48E-01
	IF (0.723)	2.58E-05	0.21	1.63E-01	9.05E-02
(2) BIN + DT	GF (0.277)	9.89E-06	0.21	4.56E-01	3.07E-01
	IF (0.723)	2.58E-05	0.21	1.36E-01	7.56E-02
(3) BIN + DI	GF (0.277)	9.89E-06	0.18	3.62E-01	2.43E-01
	IF (0.723)	2.58E-05	0.17	1.10E-01	6.09E-02
	FSF (FDS0)	**FSF (FDS1)**	**FSF (FDS2)**	**CDF**	**Ratio**
(1) P98	3.36E-05	7.83E-07	1.29E-06	**3.91E-09**	**100%**
(2) BIN + DT	3.40E-05	6.41E-07	1.05E-06	**3.18E-09**	**81%**
(3) BIN + DI	3.46E-05	4.27E-07	7.00E-07	**2.13E-09**	**54%**

Table III: Results of Example Fire Scenario Analysis:
TG1, TS Cable Tray at a Distance of 5 ft above IG, Switchgear or Load Center, No Crediting Fire Protection Systems.

		FIF	**SF**	**NSP(t_1)**	**NSP(t_2)**
(1) P98	GF (0.277)	9.89E-06	0.04	3.48E-01	2.34E-01
	IF (0.723)	2.58E-05	0.04	1.06E-01	5.86E-02
(2) BIN + DT	GF (0.277)	9.89E-06	0.04	3.52E-01	2.37E-01
	IF (0.723)	2.58E-05	0.04	1.09E-01	6.02E-02
(3) BIN + DI	GF (0.277)	9.89E-06	0.03	1.73E-01	1.16E-01
	IF (0.723)	2.58E-05	0.02	4.47E-02	2.46E-02
	FSF (FDS0)	**FSF (FDS1)**	**FSF (FDS2)**	**CDF**	**Ratio**
(1) P98	3.55E-05	9.43E-08	1.53E-07	**4.71E-10**	**100%**
(2) BIN + DT	3.54E-05	9.62E-08	1.56E-07	**4.79E-10**	**102%**
(3) BIN + DI	3.56E-05	2.73E-08	4.71E-08	**1.50E-10**	**32%**

IF: Interruptible Fires (Split Fraction 0.723); GF: Growing Fires (Split Fraction 0.277) [6].
Combination (1) P98: using the P98 approach;
Combination (2) BIN + DT: using the BIN approach with the DT method;
Combination (3) BIN + DI: using the BIN approach with the DI method.
FDS0: Damage to the ignition source only (DTS0);
FDS1: Damage to the DTS0 and the first target item (DTS1);
FDS2: Damage to the DTS0, DTS1 and all other targets within the fire compartment (DTS2) [1].

Table IV: Results of Example Fire Scenario Analysis:
TG1, TS Cable Tray at a Distance of 1 ft above IG, Switchgear or Load Center, Crediting Fire Protection Systems.

		FIF	**SF**	**NSP(t_1)**	**NSP(t_2)**
(1) P98	GF (0.277)	9.89E-06	0.64	5.45E-02	3.50E-02
	IF (0.723)	2.58E-05	0.64	1.55E-02	7.78E-03
(2) BIN + DT	GF (0.277)	9.89E-06	0.64	4.35E-02	2.91E-02
	IF (0.723)	2.58E-05	0.64	1.32E-02	6.92E-03
(3) BIN + DI	GF (0.277)	9.89E-06	0.62	3.91E-02	2.54E-02
	IF (0.723)	2.58E-05	0.61	1.21E-02	6.17E-03
	FSF (FDS0)	**FSF (FDS1)**	**FSF (FDS2)**	**CDF**	**Ratio**
(1) P98	3.51E-05	2.54E-07	3.50E-07	**1.07E-09**	**100%**
(2) BIN + DT	3.52E-05	1.94E-07	2.99E-07	**9.13E-10**	**85%**
(3) BIN + DI	3.53E-05	1.78E-07	2.53E-07	**7.74E-10**	**72%**

Table V: Results of Example Fire Scenario Analysis:
TG1, TS Cable Tray at a Distance of 3 ft above IG, Switchgear or Load Center, Crediting Fire Protection Systems.

		FIF	**SF**	**NSP(t_1)**	**NSP(t_2)**
(1) P98	GF (0.277)	9.89E-06	0.21	3.44E-02	2.31E-02
	IF (0.723)	2.58E-05	0.21	9.80E-03	5.35E-03
(2) BIN + DT	GF (0.277)	9.89E-06	0.21	2.74E-02	1.84E-02
	IF (0.723)	2.58E-05	0.21	8.21E-03	4.47E-03
(3) BIN + DI	GF (0.277)	9.89E-06	0.18	2.17E-02	1.46E-02
	IF (0.723)	2.58E-05	0.17	6.60E-03	3.61E-03
	FSF (FDS0)	**FSF (FDS1)**	**FSF (FDS2)**	**CDF**	**Ratio**
(1) P98	3.56E-05	4.76E-08	7.70E-08	**2.40E-10**	**100%**
(2) BIN + DT	3.56E-05	3.89E-08	6.25E-08	**1.96E-10**	**82%**
(3) BIN + DI	3.56E-05	2.59E-08	4.17E-08	**1.34E-10**	**56%**

Table VI: Results of Example Fire Scenario Analysis:
TG1, TS Cable Tray at a Distance of 5 ft above IG, Switchgear or Load Center, Crediting Fire Protection Systems.

		FIF	**SF**	**NSP(t_1)**	**NSP(t_2)**
(1) P98	GF (0.277)	9.89E-06	0.04	3.48E-01	2.34E-01
	IF (0.723)	2.58E-05	0.04	1.06E-01	5.86E-02
(2) BIN + DT	GF (0.277)	9.89E-06	0.04	3.52E-01	2.37E-01
	IF (0.723)	2.58E-05	0.04	1.09E-01	6.02E-02
(3) BIN + DI	GF (0.277)	9.89E-06	0.03	1.73E-01	1.16E-01
	IF (0.723)	2.58E-05	0.02	4.47E-02	2.46E-02
	FSF (FDS0)	**FSF (FDS1)**	**FSF (FDS2)**	**CDF**	**Ratio**
(1) P98	3.57E-05	5.63E-09	9.13E-09	**3.48E-11**	**100%**
(2) BIN + DT	3.57E-05	5.84E-09	9.30E-09	**3.53E-11**	**101%**
(3) BIN + DI	3.57E-05	1.62E-09	2.80E-09	**1.56E-11**	**45%**

IF: Interruptible Fires (Split Fraction 0.723); GF: Growing Fires (Split Fraction 0.277) [6].
Combination (1) P98: using the P98 approach;
Combination (2) BIN + DT: using the BIN approach with the DT method;
Combination (3) BIN + DI: using the BIN approach with the DI method.
FDS0: Damage to the ignition source only (DTS0);
FDS1: Damage to the DTS0 and the first target item (DTS1);
FDS2: Damage to the DTS0, DTS1 and all other targets within the fire compartment (DTS2) [1].