A Semi-Detailed Method for Fire Scenario Analysis in Fire PSA

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1. Introduction

A fire scenario is the basic unit of analysis in a fire probabilistic safety/risk assessment (PSA/PRA) and is defined as a set of elements that describes the progression of a fire event [1]. These elements typically include: the fire compartment (the physical analysis unit); the fire ignition source (e.g., an electrical cabinet or pump); damage targets (e.g., power and I&C cables); secondary combustibles (e.g., non-credited cables); and available fire detection and suppression features.

A typical fire event progresses through several stages [1]: ignition from a specific source; fire growth and release of heat, smoke, and soot; heat transfer to nearby targets and/or other combustibles, potentially causing fire propagation; and finally, either automatic or manual fire detection and suppression before targets are damaged, or the failure of these measures, resulting in damage to critical targets (components or cables).

The goal of fire scenario analysis is to estimate the frequency of a given fire scenario (FSF), which is defined as the frequency of an ignition source damaging a predefined set of targets before fire protection features can successfully intervene [2]. These frequencies are then combined with the conditional core damage probability (CCDP) or conditional large early release probability (CLERP) to determine each scenario's contribution to the plant's overall fire-induced core damage frequency (CDF) or large early release frequency (LERF). The total plant fire-induced CDF or LERF is calculated by summing the contributions from all fire scenarios, as shown in the following equations:

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

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

Fire scenarios can be defined and analyzed at various levels of detail. While more detailed analysis can yield a more realistic assessment of fire risk, it also significantly increases the analytical burden. The ideal approach, therefore, is to find a level of detail that meaningfully reduces conservatism without demanding an excessive level of effort. This study proposes a "semi-detailed method" for fire scenario analysis and applies it to example scenarios to evaluate its potential for risk reduction.

2. Methodology and Example Analysis

2.1 The Semi-Detailed Method (SDM)

In many fire PSAs, fire scenarios are defined and analyzed using a full/whole room burnup (FRB/WRB) assumption. Under this assumption, any fire inside a compartment is presumed to cause widespread damage to all target items present. In other words, each ignition source has only the single worst target set. This is a simple approach, as it does not require detailed information on the engineering characteristics of ignition sources, targets, or fire protection features. However, it is also highly conservative because it inevitably sets the fire severity factor (SF) and non-suppression probability (NSP) to 1.0, thereby allocating the entire fire ignition frequency (FIF) to the worst-case CCDP or CLERP.

To reduce this conservatism, our proposed semi-detailed method (SDM) divides a single FRB scenario into three distinct sub-scenarios, each with a progressively larger damage target set (DTS):

- Damage Target Set 0 (DTS0): The ignition source itself.
- Damage Target Set 1 (DTS1): Includes DTS0 plus the first target item (TG1), defined as the nearest and most vulnerable target or combustible.
- Damage Target Set 2 (DTS2): Includes DTS1 plus all other targets within the fire compartment.

From these target sets, we define three mutually exclusive fire scenarios with a fire damage state (FDS):

- Fire Damage State 0 (FDS0): Only DTS0 is damaged. This occurs if the fire is not severe enough to damage TG1, or if it is severe but is suppressed before damaging TG1 at time t_1.
- Fire Damage State 1 (FDS1): DTS1 is damaged, but DTS2 is not. This occurs if the fire is severe enough and is not suppressed by time t_1, but is suppressed before damaging the rest of the targets (DTS2) at time t_2.

- Fire Damage State 2 (FDS2): DTS2 is damaged. This occurs if the fire is not suppressed before damaging the wider set of targets at time t_2.

A key advantage of this method is that the specific locations of items in DTS2 are not required for the analysis. An analyst is only asked to identify what and where the TG1 is, which requires a relatively small amount of additional effort compared to a fully detailed analysis.

The corresponding fire scenario frequencies (FSF) are calculated as follows:

$$FSF(FDS0) = FIF \times [1 - (SF_1 \times NSP(t_1))]$$

This represents the total ignition frequency minus the frequency of fires that are both severe enough to damage TG1 (SF1) and are not suppressed in time ($NSP(t_1)$).

$$FSF(FDS1) = FIF \times [SF_1 \times (NSP(t_1) - NSP(t_2))]$$

This represents fires that are severe enough and not suppressed by t_1, but are suppressed between t_1 and t_2.

$$FSF(FDS2) = FIF \times [SF_1 \times NSP(t_2)]$$

This represents fires that are severe enough and are not suppressed even by time t_2.

The CDF for each scenario is then calculated as:

$$CDF(FDS_i) = FSF(FDS_i) \times CCDP(FDS_i).$$

2.2 Example Analysis Conditions and Assumptions

An example analysis was performed to compare the FRB and SDM approaches using the following conditions and assumptions:

- Fire Scenario Analysis Methods:
  [FRB] Full Room Burnup Assumption /
  [SDM] Semi-Detailed Method
- 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 (Split Fraction 0.723) /
  Growing Fires (Split Fraction 0.277) [4]
- First Target (TG1):
  Thermoset (TS) Cable Tray located above the IS
- Temperature Damage Criteria [°C]: 330 [1]
- 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 [5]
- Damage Assessment Method:
  Damage Integral (Heat Soak) Method (DI) [6]
- Time to First Detection [min.]: 0 [4]
- Time to Delayed Detection (Eventually Detected) [min.]: 15 [4]
- Automatic Detection System -
  Unreliability, Unavailability, and Ineffectiveness:
  5.00E-02, 1.00E-02, 5.80E-01 [4]
  (analyzed both w/ and w/o crediting this system)
- Failure Probability of Plant Personnel Present: 2.31E-01 [4]
- Failure Probability for MCR Indication: 1.00E-02 [4]
- Human Error Probability for MCR Response
  to MCR Indication: 1.00E-03 [4]
- Automatic Suppression System -
  Unreliability, Unavailability, and Ineffectiveness:
  5.00E-02, 1.00E-02, 0.00E+00 [4]
  (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 [4]
- 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
- Other Conditions and Assumptions:
  Default or Medium values as provided by the references

2.3 Summary of Results

The results of this example analysis (summarized in Tables I-VI) show that using the SDM instead of the FRB assumption reduces the scenario CDF by approximately one to four orders of magnitude.

This risk reduction is driven by two aspects. First, as the vertical distance between the IS and the TG1 increases, a higher heat release rate (HRR) is required for damage, which decreases the SF. Second, a greater distance also increases the time-to-damage for a given HRR. This provides more time for fire protection systems to act, which in turn lowers the NSP, especially when automatic or manual fire protection systems are credited.

4. Conclusions

This study proposed and demonstrated a semi-detailed method for fire scenario analysis in a fire PSA. The example analysis shows that this method can significantly reduce the calculated fire risk—by one to four orders of magnitude—compared to the highly conservative full room burnup assumption.

By moving beyond the simplistic FRB approach, the semi-detailed method provides a more realistic representation of fire risk. It allows analysts to gain more useful insights into defense-in-depth strategies by quantifying their benefits with only a small increase in analytical effort. The adoption of this method is expected to yield more practical and meaningful results in fire PSA.

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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)**
Growing Fire	(0.277)	9.89E-06	0.62	6.12E-01	4.11E-01
Interruptible Fire	(0.723)	2.58E-05	0.61	1.78E-01	9.86E-02
	FSF	**CCDP**	**CDF**	**Ratio to SDM**	**Ratio to FRB**
SDM(FDS0)	2.92E-05	2.00E-07	5.83E-12	4.72E-04	5.44E-05
SDM(FDS1)	2.47E-06	5.00E-05	1.24E-10	1.00E-02	1.16E-03
SDM(FDS2)	4.07E-06	**3.00E-03**	1.22E-08	9.90E-01	1.14E-01
SDM	3.57E-05	3.46E-04	**1.23E-08**	**1.00E+00**	**1.15E-01**
FRB	3.57E-05	**3.00E-03**	**1.07E-07**	**8.67E+00**	**1.00E+00**

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)**
Growing Fire	(0.277)	9.89E-06	0.18	3.62E-01	2.43E-01
Interruptible Fire	(0.723)	2.58E-05	0.17	1.10E-01	6.09E-02
	FSF	**CCDP**	**CDF**	**Ratio to SDM**	**Ratio to FRB**
SDM(FDS0)	3.46E-05	2.00E-07	6.91E-12	3.25E-03	6.46E-05
SDM(FDS1)	4.27E-07	5.00E-05	2.14E-11	1.00E-02	2.00E-04
SDM(FDS2)	7.00E-07	**3.00E-03**	2.10E-09	9.87E-01	1.96E-02
SDM	3.57E-05	5.96E-05	**2.13E-09**	**1.00E+00**	**1.99E-02**
FRB	3.57E-05	**3.00E-03**	**1.07E-07**	**5.03E+01**	**1.00E+00**

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)**
Growing Fire	(0.277)	9.89E-06	0.03	1.73E-01	1.16E-01
Interruptible Fire	(0.723)	2.58E-05	0.02	4.47E-02	2.46E-02
	FSF	**CCDP**	**CDF**	**Ratio to SDM**	**Ratio to FRB**
SDM(FDS0)	3.56E-05	2.00E-07	7.13E-12	4.75E-02	6.65E-05
SDM(FDS1)	2.73E-08	5.00E-05	1.36E-12	9.10E-03	1.27E-05
SDM(FDS2)	4.71E-08	**3.00E-03**	1.41E-10	9.43E-01	1.32E-03
SDM	3.57E-05	4.20E-06	**1.50E-10**	**1.00E+00**	**1.40E-03**
FRB	3.57E-05	**3.00E-03**	**1.07E-07**	**7.14E+02**	**1.00E+00**

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)**
Growing Fire	(0.277)	9.89E-06	0.62	3.91E-02	2.54E-02
Interruptible Fire	(0.723)	2.58E-05	0.61	1.21E-02	6.17E-03
	FSF	**CCDP**	**CDF**	**Ratio to SDM**	**Ratio to FRB**
SDM(FDS0)	3.53E-05	2.00E-07	7.05E-12	9.11E-03	6.59E-05
SDM(FDS1)	1.78E-07	5.00E-05	8.90E-12	1.15E-02	8.31E-05
SDM(FDS2)	2.53E-07	**3.00E-03**	7.58E-10	9.79E-01	7.08E-03
SDM	3.57E-05	2.17E-05	**7.74E-10**	**1.00E+00**	**7.23E-03**
FRB	3.57E-05	**3.00E-03**	**1.07E-07**	**1.38E+02**	**1.00E+00**

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)**
Growing Fire	(0.277)	9.89E-06	0.18	2.17E-02	1.46E-02
Interruptible Fire	(0.723)	2.58E-05	0.17	6.60E-03	3.61E-03
	FSF	**CCDP**	**CDF**	**Ratio to SDM**	**Ratio to FRB**
SDM(FDS0)	3.56E-05	2.00E-07	7.13E-12	5.33E-02	6.65E-05
SDM(FDS1)	2.59E-08	5.00E-05	1.29E-12	9.68E-03	1.21E-05
SDM(FDS2)	4.17E-08	**3.00E-03**	1.25E-10	9.37E-01	1.17E-03
SDM	3.57E-05	3.74E-06	**1.34E-10**	**1.00E+00**	**1.25E-03**
FRB	3.57E-05	**3.00E-03**	**1.07E-07**	**8.01E+02**	**1.00E+00**

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)**
Growing Fire	(0.277)	9.89E-06	0.03	1.03E-02	6.91E-03
Interruptible Fire	(0.723)	2.58E-05	0.02	2.64E-03	1.46E-03
	FSF	**CCDP**	**CDF**	**Ratio to SDM**	**Ratio to FRB**
SDM(FDS0)	3.57E-05	2.00E-07	7.14E-12	4.57E-01	6.67E-05
SDM(FDS1)	1.62E-09	5.00E-05	8.11E-14	5.19E-03	7.57E-07
SDM(FDS2)	2.80E-09	**3.00E-03**	8.41E-12	5.38E-01	7.86E-05
SDM	3.57E-05	4.38E-07	**1.56E-11**	**1.00E+00**	**1.46E-04**
FRB	3.57E-05	**3.00E-03**	**1.07E-07**	**6.85E+03**	**1.00E+00**