Review and Application of the Recent Modeling Approach for Liquid Fuel Fire Scenarios in Nuclear Power Plants

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1. Introduction

A fire event probabilistic safety assessment (PSA) is performed on a fire scenario basis. In other words, fire-induced risk, primarily represented as core damage frequency (CDF) for the level-1 PSA and large early release frequency (LERF) for the level-2 PSA, is assessed for each unique fire scenario. A fire scenario in a fire PSA is generally modeled as a progression of damage states of targets such as equipment and cables over time that is initiated by a postulated fire involving an ignition source. A fire modeling analysis in a fire PSA is a tool used to determine the damage states of targets and the associated time, which are essential data for quantifying final fire-induced risk, i.e., the CDF and LERF. [1].

Most ignition sources in nuclear power plants are solid fuels. Solid fuels require formulation of gaseous decomposition compounds, generally leaving behind char, called pyrolysis, before ignition. Some of these ignition sources, such as pumps, generators, and transformers, contain liquid fuels as energy sources or lubricants. Unlike with solid fuels, liquid fuels directly evaporate and form gaseous fuels. Generally, liquid fuels have lower flash points and are easier to ignite than solid fuels. Horizontal flame spread rates on liquid fuels range from 1.0 to 100 cm/s, which are similar to upward flame spread rates and one to three order(s) of magnitude higher than lateral flame spread rates on thick solid fuels.

The objective of this paper is to analyze how much the use of a recent modeling approach for the risk-significant liquid fuel fire scenarios affects the results of fire modeling compared to the use of a previous approach.

2. Review of the Recent Modeling Approach

2.1. Liquid fuel spill fires

There are four major classifications of liquid fuel fire scenarios based on the identification of confined or unconfined spill and fixed quantity or continuously-fed conditions. The continuously-fed condition is beyond the scope of this paper.

Liquid fuel spill fires are characterized by the type (properties) of the liquid fuel spilled, the amount (volume) of liquid fuel that can be spilled, and the size (area) of the spill. The heat release rate (HRR) profiles are determined based on these characteristics (NUREG/CR-6850 [1], Section 11.5.1.3).

2.2. Amount of the liquid fuel spill

In general, two different scenarios of liquid fuel spill fires can be considered by the spill volume, called large fires and small fires. After identifying the volume of liquid fuel that could be spilled, one can assume a spill volume of 100% and assign a severity factor of 0.02 for the large fires, while assuming a spill volume of 10% and assigning a severity factor of 0.98 for the small fires (NUREG/CR-6850 [1], Appendix E, Section E.3).

A revised approach (NUREG/CR-6850 Supplement 1 [2], Section 9, FAQ-08-0044) has been developed specifically for main feedwater pump (MFW) oil spill fires to avoid overestimations of their risk. For such fires, three different scenarios can be considered by the spill volume, called very large fires, large fires, and small fires. For these scenarios, one can assume a spill volume of 100%, 10%, or ~ 0% and assign a severity factor of 0.0034, 0.0306, or 0.966, respectively. The small fires represent scenarios involving small oil leaks and resulting fires that only damage the MFW pump.

2.3. Size of the liquid fuel spill

If the properties of the liquid fuel are known and the volume of liquid fuel that can be spilled is determined, the next step is to determine the spill area or depth. Liquid fuel spills can be confined (i.e., captured in a pan or diked area) or unconfined. Because the spill area depends on whether the spill is confined or unconfined, that should be identified first.

The spill area of confined liquid fuel spill fires can be easily determined from the confined area (i.e., a pan or diked area). For unconfined liquid fuel spill fires, on the other hand, the determination of the spill area is relatively complicated because it is generally affected by the initial momentum of the fluid, the fluid surface tension, and the surface characteristics onto which the liquid fuel is spilled.

The practical and conservative approach for determining the spill area of confined liquid fuel spill fires is using the following empirical model developed by Gottuk and White [3] and recommended by NUREG/CR-6850 [1], Appendix G, Section G.4. (Note that the spill areas per unit volume in the original NUREG/CR-6850 are incorrect, and have been corrected in its errata sheet [4].):

$$\delta = 0.7 \cdots\cdots\cdots\cdots\cdots\cdots \text{(when } V \leq 95\text{)}$$
$$\delta = 2.8 \cdots\cdots\cdots\cdots\cdots\cdots \text{(when } V > 95\text{)}$$

where,
δ = spill depth (mm)
V = spill volume (ℓ).

The problem with this model is that there exists a discontinuity in the spill area estimates at 95 L (25 gallons), which leads to inconsistencies in the HRR estimates. To cope with this issue, the following empirical model is suggested in the recent document of the U.S. NRC for use in the fire protection significance determination process [5], revised in May 2018:

$$\delta = 2.0 \cdots\cdots\cdots\cdots \text{(when } V < 43)$$
$$\delta = 0.52\, ln(V_f) + 0.04 \cdots \text{(when } V \geq 43).$$

Although this model was developed using only the JP-4 fuel data, it provides conservative estimates of spill depth and area for unconfined liquid hydrocarbon fuel spill fires based on the data collected by Gottuk and White [6]. Note that a spill depth of 2 mm is assumed for spill volumes of 43 L or less. This is based on the experimental observation that flames do not spread away from the initial ignition points on liquid fuel spills that are 2 mm or less deep.

2.4. Heat release rate profiles of the liquid fuel spill fires

If the size of the spill and properties of the liquid fuel are known, the HRR can be calculated using the Babrauskas' correlation for the burning rate of pool fires as follows (NUREG-1805 [7] Eq. 3-8):

$$\dot{Q} = \dot{m}''_{max} \Delta h_{c,eff} A\left(1 - e^{-k\beta D}\right)$$

where,
$\dot{Q}$ = heat release rate (kW)
$\dot{m}''_{max}$ = max. mass loss rate per unit area (kg/m^2·s)
$\Delta h_{c,eff}$ = effective heat of combustion (kJ/kg)
A = spill area (m^2)
$k\beta$ = absorption coefficient (m^{-1})
D = spill diameter (m).

Note that, for a non-circular spill area, an equivalent effective diameter, calculated as follows, is used:

$$t_b = \frac{\delta}{v} = \frac{V}{Av}$$

where,
t_b = burning duration (s)
v = regression rate (m/s).

For a fixed spill volume, the burning duration of the liquid fuel spill fire is calculated using the fundamental equation as below (NUREG-1805 [7] Eq. 3-3):

$$D_{eff} = \sqrt{\frac{4A}{\pi}}$$

As the liquid fuel spill combusts, its depth and volume reduce but its area stays the same over the burning duration. The regression rate, defined as a volumetric loss of liquid fuel per unit surface area of the spill per unit time, is calculated using the following equation (NUREG-1805 [7] Eq. 3-4):

$$v = \frac{\dot{m}''_{max}}{\rho}$$

where,
ρ = liquid fuel density (kg/m^3).

The HRR of liquid fuel fires is assumed to reach peak value instantaneously at ignition, and stay at the peak value until all the liquid fuel is consumed. The assumption of a constant HRR at a peak over the whole period is reasonable based on the fact that real liquid fuel fires feature rapid growth to the peak intensity (NUREG/CR-6850 [1], Appendix G, Section G.4).

3. Application of the Recent Modeling Approach

3.1. Size and heat release rate profiles of the reference unconfined liquid fuel spill fire scenarios

The HRR profile, which describes fire intensity as a function of time, is the most important element characterizing the fire scenario itself and significantly affecting the results of fire modeling [8] such as the properties of the fire plume, ceiling jet, and hot gas layer (HGL); target response to heat and smoke; and thus, habitability conditions in a fire compartment as well. The size of the spill is a major factor for determining the HRR profiles and the results of unconfined liquid fuel spill fires. In this study, the effects of the changes in the modeling approach on the HRR profiles were analyzed.

Fig. 1 and 2 show the depth and area of the unconfined liquid fuel spills calculated using the previous and recent approaches, respectively. Moreover, Fig. 3 and 4 show the peak HRR and fire duration of the unconfined spill fires with lube and mineral oils, as estimated based on the previous and recent approaches, respectively. The results indicate that the use of the recent approach leads to significant increases in the spill depth and fire duration, as well as to significant decreases in the spill area and peak HRR. In particular, such effects are enhanced near the spill volume of 95 L at which the previous approach shows discontinuity and inconsistency.

One of the most risk significant fire scenarios of the reference plant is oil fires in the essential service water (ESW) pump rooms. According to the design data, the volume of ESW pump lube oil that can be spilled on the floor was determined to be 80 L (100%) for the large fires and 8 L (10%) for the small fires, depending on the probabilities of occurrence (0.98 and 0.02).

Fig. 5 and 6 show the HRR profiles of two representative scenarios for unconfined ESW pump lube oil spill fires estimated using the previous and recent approaches. The results indicate that the peak HRR declines from 19.2 to 5.75 MW by 13.5 MW, 70% (based on the spill volume of 8 L) as the modeling approach changes. The results also indicate that changes in the modeling approach delay the fire duration from 13.6 to

39.0 s by 25.3 s, 1.86 times (based on the spill volume of 8 L).

Note that the unconfined 80 L of the ESW pump lube oil spill modeled using the previous approach is too thin and wide so that it cannot reflect the reality of the scenarios. The spill depth of 0.7 mm is much thinner than the empirical lower limit of the spill depth (i.e., 2 mm), which allows flames to spread away from the initial ignition points on the spills. (This issue also applies to the 8 L model based on the previous approach.) In addition to that, the spill area of 114 m^2 is far more extensive than the bare floor area of the ESW pump room of the reference plant. If the real spill is as thin as 0.7 mm, then the spill area is bounded by walls, which means that the spill is no longer unconfined.

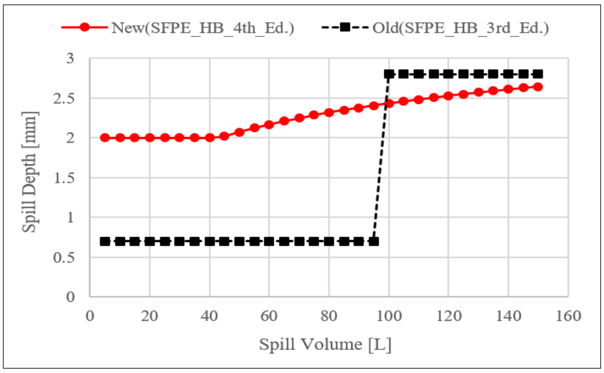

Fig. 1. Depth of Unconfined Liquid Spills

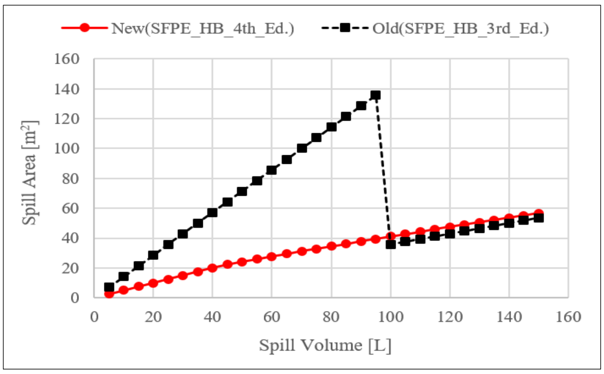

Fig. 2. Area of Unconfined Liquid Spills

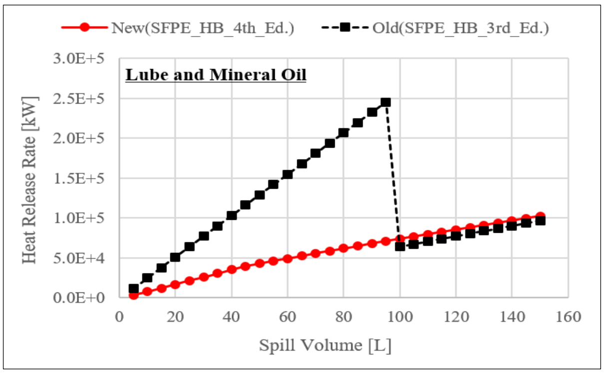

Fig. 3. Peak Heat Release Rate of Unconfined Liquid Spill Fires: Lube and Mineral Oil

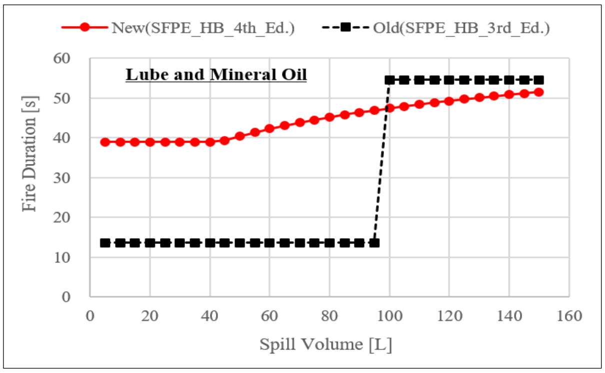

Fig. 4. Fire Duration of Unconfined Liquid Spill Fires: Lube and Mineral Oil

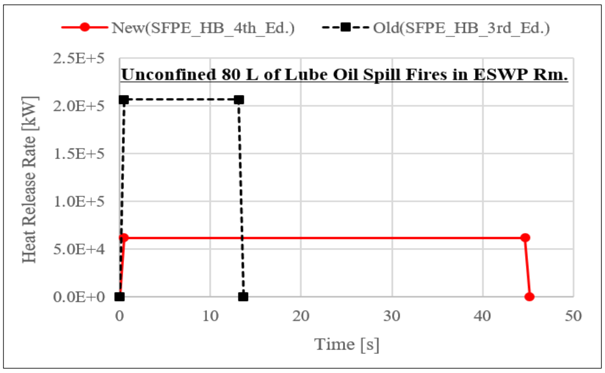

Fig. 5. Heat Release Rate Profile of Reference Large Fire Scenarios: Unconfined 80 L Lube Oil Spill Fires in the ESWP Room

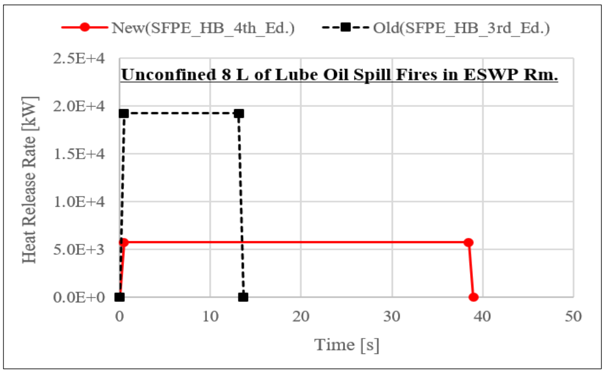

Fig. 6. Heat Release Rate Profile of Reference Small Fire Scenarios: Unconfined 8 L Lube Oil Spill Fires in the ESWP Room

3.2. Zone of influences of the reference unconfined liquid fuel spill fire scenarios

Like HRR profiles, the vertical and radial zone of influence (ZOI) values are important elements in fire modeling. They are used to screen ignition sources that cannot cause damage to components or cables in the fire area and that are not capable of causing fire to spread to secondary combustibles, and to identify the damaged target set for a specified scenario. The vertical and radial ZOI values are mainly determined by the peak HRR of the ignition source; so the size of the spill is a major factor determining the ZOI values and the results of unconfined liquid fuel spill fires. Also analyzed in this study were the effects of changes in the modeling approach on the vertical and radial ZOI values.

Table I presents effects on the vertical and radial ZOI values. Two Fire Dynamics Tools (FDTs) from the NUREG-1805 Supplement 1, Vol. 2 [9] were used to estimate the vertical and radial ZOI values summarized in Table I. The plume centerline temperature and the vertical ZOI were calculated using the spreadsheet: "09_Plume_Temperature_Calculations_Sup1.xls". The radiant heat flux from the fire to a target and the radial ZOI were calculated using the spreadsheet: "05.1_Heat_Flux_Calculations_Wind_Free_Su1.xls". Note that the following assumptions were made for the calculation: ambient temperature is 25 ℃; convective and radiative fractions are 0.7 and 0.3; fire elevation is 0 m (i.e., spill fires are placed on the floor); damage and ignition criteria for TS, TP, and SE targets are 330 ℃, 11 kW/m^2; 205 ℃, 6 kW/m^2; and 65 ℃, 3 kW/m^2.

Table I shows that, as a result of the changes in the modeling approach, the vertical ZOI was reduced from 11.6 to 7.24 m by 4.34 m, 37%, and the radial ZOI was also shrunk from 6.46 to 3.53 m by 2.9 m, 45% (based on the thermoset target).

Table I: Vertical and Radial Zone of Influence of Reference Small Fire Scenarios: Unconfined 8 L Lube Oil Spill Fires in the ESWP Room

Approach / Reference	Vertical ZOIs for (TS) (TP) & Radial ZOIs for (TS) / (TP) / (SE) [m]
Old / [1], [3]	(11.6) / (15.7) & (6.46) / (8.75) / (12.4)
New / [5], [6]	(7.24) / (9.80) & (3.53) / (4.78) / (6.76)

Notes: TS = Thermoset target, TP = thermoplastic target, SE = sensitive electronic target

4. Concluding Remarks

This study first reviewed the recent modeling approach for liquid fuel fire scenarios. Comparative analysis of the reference scenarios was conducted to investigate the effects of using the recent modeling approach.

Through comparative analysis of the reference scenarios, we found that use of the recent approach leads to significant increases in the spill depth and fire duration, as well as to significant decreases in the spill area and peak HRR. The results of comparative analysis of the reference scenarios also indicate that the vertical and radial ZOI values are significantly decreased by use of the recent approach.

Further detailed analyses using fire modeling tools such as CFAST (Consolidated model of Fire And Smoke Transport) [10] and Fire Dynamics Simulator (FDS) [11] are required to examine the detailed effects of the recent approach for a more realistic evaluation of liquid fuel fire scenarios.

Acknowledgements

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