



Assessment of Pollutant Dispersion in Emergency Scenarios at an Oil Terminal: A Case Study Using the ALOHA Model

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Abstract

This study assesses pollutant dispersion and associated safety impacts resulting from kerosene leakage at oil terminal facilities located in Bangkok and Samut Prakan, Thailand, using the ALOHA (Areal Locations of Hazardous Atmospheres) software to simulate vapor dispersion and fire scenarios. The assessment focused on evaluating the hazard distances of the Flammable Area of Vapor Cloud, Toxic Threat Zone, and Thermal Radiation from Pool Fire under different meteorological conditions. A total of ten simulation scenarios were simulated, consisting of seven scenarios in Bangkok (Scenario 1.1–1.7) and three scenarios in Samut Prakan (Scenario 2.1–2.3).

The results suggest that the flammable vapor cloud area remained relatively constant across all scenarios, hazard distances of approximately 22 m in Bangkok and 23 m in Samut Prakan. This finding suggests that kerosene has a low evaporation rate, causing the flammable vapor cloud to remain confined near the leakage source within the bund wall area and to be minimally influenced by meteorological conditions.

For the Toxic Threat Zone, Samut Prakan exhibited significantly greater impact distances than Bangkok. The AEGL-1 distances ranged from 55–60 m and AEGL-2 distances ranged from 24–26 m in Samut Prakan, whereas Bangkok showed AEGL-1 distances of 33–37 m and AEGL-2 distances of 22–23 m. These differences may be explained by the larger fuel storage capacity, larger tank dimensions, and greater containment areas in Samut Prakan, which may have promoted higher evaporation and vapor accumulation in the atmosphere.

The assessment of Thermal Radiation from Pool Fire revealed substantially larger impact distances in Samut Prakan compared with Bangkok. Thermal radiation distances at 10 kW/m² were approximately 95–96 m in Samut Prakan and 63–64 m in Bangkok. At 5 kW/m², the distances were approximately 134–135 m in Samut Prakan and 90–91 m in Bangkok, while at 2 kW/m², the distances were approximately 208–210 m in Samut Prakan and 140–142 m in Bangkok. These results suggest that Thermal Radiation from Pool Fire may represent the most extensive hazard compared with the Flammable Area of Vapor Cloud and Toxic Threat Zone.

Overall, Samut Prakan exhibited greater hazard distances for all parameters than Bangkok, which may be associated with its larger storage tanks, greater fuel inventory, and larger containment areas, potentially resulting in larger fuel puddles and higher vapor generation. The findings also suggest that the dispersion behavior of kerosene in this study may resemble quasi-heavy gas behavior which may cause vapor clouds to accumulate near ground level and generate hazards primarily within the near-field region close to the leakage source. In contrast, the dominant hazard associated with the incident was Thermal Radiation from Pool Fire, which produced the widest impact area.

The results of this study can support safety and environmental management planning in industrial areas involving fuel storage and handling operations, contributing to improved emergency preparedness and more effective mitigation of risks associated with flammable liquid leakage incidents. However, this study did not include sensitivity analysis; therefore, the observed relationships between hazard distances and site characteristics should be interpreted with caution.

Keywords : Kerosene; ALOHA Model; Consequence Analysis; Toxic Threat Zone; Thermal Radiation; Oil Terminal

Introduction

Industrial accidents involving oil storage facilities have demonstrated that fuel leakage and fire incidents can generate hazardous vapor clouds, toxic gases, thermal radiation, and explosion hazards, potentially affecting workers and nearby communities, particularly in densely populated urban areas. Therefore, The assessment of hazard distances is therefore an important element of emergency response planning, including evacuation planning, area control, and operational decision-making. Consequence assessment is a fundamental component of quantitative risk analysis for hazardous material releases and is widely applied to support risk-informed decision making in industrial facilities [1].

Several studies investigated toxic gas dispersion and emergency response planning using ALOHA. Yoksahachat (2016) [2] reported that chlorine leakage could affect nearby communities within several kilometers under downwind conditions and emphasized the importance of preventive maintenance and shelter-in-place strategies. Tseng et al. (2012) [3] further demonstrated that wind speed and atmospheric stability significantly influenced toxic dispersion distances. In addition, studies involving flammable liquid leakage and pool fire scenarios suggested that leak size and fuel quantity strongly affect hazard distances and emergency response requirements (Permnam, 2021) [4].

Thermal radiation behavior associated with kerosene pool fires has also been extensively studied. Patel and Sohani (2015) [5] reported that kerosene pool fires could produce thermal radiation hazard distances exceeding 100 m under certain conditions. Parent et al. (2019) [6] demonstrated that soot radiation and pool diameter were dominant factors controlling thermal radiation intensity, while Mišić et al. (2018) [7] suggested that thermal radiation may represent one of the dominant hazards associated with kerosene leakage incidents, particularly in

densely populated urban areas. Furthermore, aviation fuel vapor clouds may exhibit near-field hazard characteristics and quasi-heavy gas behavior under low wind speed and stable atmospheric conditions, although ALOHA may have limitations in predicting near-field dispersion due to “near-field patchiness.”

However, most previous studies focused primarily on toxic industrial chemicals, liquefied gases, refinery products, or isolated fire scenarios [8, 9]. Limited studies have investigated aviation kerosene leakage in urban oil terminal facilities, particularly in Thailand, using a unified modeling approach that comparatively evaluates Toxic Threat Zone, Flammable Area of Vapor Cloud, and Thermal Radiation from Pool Fire under different meteorological conditions.

Therefore, this study applies the ALOHA model to assess hazard distances associated with aviation kerosene leakage scenarios in oil terminal facilities located in Bangkok and Samut Prakan, Thailand, in order to support emergency preparedness and industrial risk management.

Materials and Methods

Atmospheric dispersion models are used to estimate how pollutant concentrations vary over time and space after being released into the air. In this study, the ALOHA model was employed to simulate vapor dispersion and estimate the concentration levels and exposure durations under defined emergency scenarios. The model provides quantitative information regarding airborne concentration levels and potential exposure time; however, it does not calculate the probability of injury or health outcomes for exposed individuals.

Based on a review of relevant literature and technical guidelines, the assessment of pollutant dispersion under emergency conditions at oil terminal facilities was conducted through a structured modeling approach, as described in the following sections.

Goal and Scope of the Study

The case study oil terminals are located in Bangkok and Samut Prakan, Thailand, where kerosene is only stored in large aboveground storage tanks. and therefore multi-fuel interaction scenarios were not considered. The facilities are located in urbanized areas surrounded by residential and commercial land uses, indicating the potential for significant off-site consequences in the event of a major accident.

The goal of this study is defined as follows:

- 1) To assess hazard distances associated with toxic vapor dispersion resulting from aviation fuel leakage (Toxic Threat Zone).
- 2) To evaluate the flammable vapor cloud hazard distances associated with aviation fuel leakage (Flammable Area of Vapor Cloud).
- 3) To assess the thermal radiation hazard distances resulting from pool fire scenarios caused by aviation fuel leakage (Thermal Radiation from Pool Fire).

Research Instruments

The tools used in this study are as follows:

- 1) ALOHA (Areal Locations of Hazardous Atmospheres) software was employed to perform atmospheric dispersion modeling of hazardous chemical releases.
- 2) Google Earth software was used to visualize and overlay the dispersion

modeling results onto geographic maps in order to illustrate the spatial extent of affected areas.

Data Used in the Study

1. Meteorological Data

Meteorological data used in this study were based on five-year average observations (2020–2024) obtained from the Don Mueang Meteorological Station (Bangkok) and the Suvarnabhumi Airport Meteorological Station (Samut Prakan) [10], representing local atmospheric conditions at the respective oil terminal facilities. Key parameters considered in the simulations included wind speed, wind direction, measurement height, atmospheric stability, surface roughness, cloud cover, and relative humidity. These parameters were incorporated into the ALOHA model to characterize atmospheric dispersion conditions and evaluate their influence on the transport and hazard distances of released kerosene vapor under different seasonal meteorological conditions.

2. Chemical Data

The chemical substance analyzed in this study is kerosene, which represents the primary component of Kerosene fuel stored at the study sites. The physicochemical and hazard parameters used as input for the ALOHA model are summarized in **Table 1**.

Table 1 Physicochemical and Hazard Parameters of Kerosene Used in the Simulation

Parameter	Value
Chemical Name	Kerosene
Flashpoint	(Tagliabue Closed Cup ASTM D56) 38 °C (100 °F) (Min) [11, 12]
Autoignition	210 °C (410 °F) [11]
Combustion Products	Highly dependent on combustion conditions. A complex mixture of airborne solids, liquids, and gases including CO, CO ₂ , and unidentified organic compounds will evolve during combustion [11]
Molecular Weight	140.00 g/mol [13]
Acute Exposure Level Guidelines 1 (AELG-1) (60 min)	290 mg/m ³ [14, 15]
Acute Exposure Level Guidelines 2 (AELG-2) (60 min)	1100 mg/m ³ [14, 15]
Acute Exposure Level Guidelines 3 (AELG-3) (60 min)	N/A [14, 15]
Protective Action Criteria (PAC-1)	290 mg/(cu m) [16]
Protective Action Criteria (PAC-2)	1100 mg/(cu m) [16]
Protective Action Criteria (PAC-3)	4100 mg/(cu m) [16]
Lower Explosive Limit (LEL)	7000 ppm [11]
Upper Explosive Limit (UEL)	50000 ppm [11]
Ambient Boiling Point	160.0 °C [11]

Parameter	Value
Vapor Pressure at Ambient Temperature	8.09×10^{-5} atm [11]
Ambient Saturation Concentration	80.9 ppm (0.0081%) [17]
Heat Capacity (gas,const.press)	3400 J/(Kg@800°K, 101325 Pa) [17]
Heat Capacity (liq,const.press)	2100 J/(Kg@288.15°K, 101325 Pa) [17]
Heat of Combustion	42800000 J/kg [12]
IDLH	No data available

Note: AEGL-3 was unavailable (N/A) for kerosene in the ALOHA database. Therefore, Toxic Threat Zone assessments in this study were based only on AEGL-1 and AEGL-2 criteria. Although PAC-3 values were available from the Protective Action Criteria database, they were not used in the present analysis.

3. Scenario Definition for Dispersion Modeling

The leakage scenarios were defined for two oil terminal locations: Bangkok and Samut Prakan. The selected storage tank in Bangkok has a height of 15 m, a diameter of 24 m, and a fuel inventory of 5.85 million liters, corresponding to 90% of its maximum capacity. The selected storage tank in Samut Prakan has a height of 19.5 m, a diameter of 33 m, and a fuel inventory of 13.5 million liters, also corresponding to 90% of its maximum capacity. In both locations, the largest storage tank was selected to represent a conservative scenario. This selection was adapted from the principle used in the Thai Ministerial Regulation on Oil Depots B.E. 2556, Clause 48(5) [18] and National Fire Protection Association. 2024. NFPA 11 [19], which requires the quantity of foam concentrate to be calculated based on the tank requiring the maximum amount of foam solution.

For both study areas, the leakage scenario was assumed to occur from a 12-inch diameter opening, corresponding to the actual 12-inch fuel pipeline connected to the storage tank. Therefore, the 12-inch leak diameter represents a full-bore rupture scenario of the pipeline. The release height was defined at approximately 5% of the total tank height above the tank bottom because the pipeline in

both locations is installed at the lower section of the tank (5% above the tank bottom). This assumption reflects the actual engineering configuration of the storage tank pipeline system.

The assumed failure mechanism was severe structural damage to the pipeline caused by an earthquake or significant ground subsidence. Under such conditions, the flexible pipe section connected to the metallic piping may experience excessive tensile stress and tearing, resulting in fuel leakage from a vertical fixed-roof storage tank. Accordingly, the selected 12-inch leak diameter and 5% release height were intended to represent a realistic but conservative leakage scenario for emergency planning and hazard assessment.

To account for seasonal meteorological variability, five-year average meteorological data from 2020 to 2024 that was summarized in **Table 2** atmospheric data. Simulation scenarios for the Bangkok study site and Samut Prakan study site were used for all twelve months of the year that was summarized in **Table 3** and the condition in **Table 4**. The simulation scenarios were then categorized according to prevailing wind directions to evaluate hazard distances and potential risk areas under seasonal wind conditions.

Table 2 Atmospheric Data

Scenario	Parameter and Value						
	Wind Speed and Direction (average at 10 m height)	Ground Roughness	Cloud Cover	Air Temperature (average)	Stability Class	Inversion Height	Relative Humidity (average)
1.1	2.48 m/s from East	Urban or Forest	6 tenths	27 °C	C	No Inversion	62 %
1.2	2.8 m/s from South	Urban or Forest	6 tenths	29 °C	C	No Inversion	68 %
1.3	3.17 m/s from SSW	Urban or Forest	6 tenths	30 °C	C	No Inversion	72 %
1.4	3 m/s from West	Urban or Forest	6 tenths	29.5 °C	C	No Inversion	77 %
1.5	3.42 m/s from SW	Urban or Forest	6 tenths	29 °C	C	No Inversion	75 %

Scenario	Parameter and Value						
	Wind Speed and Direction (average at 10 m height)	Ground Roughness	Cloud Cover	Air Temperature (average)	Stability Class	Inversion Height	Relative Humidity (average)
1.6	2.47 m/s from North	Urban or Forest	6 tenths	26 °C	C	No Inversion	78 %
1.7	2.46 m/s from NE	Urban or Forest	6 tenths	27 °C	C	No Inversion	66 %
2.1	2.13 m/s from East	Open country	6 tenths	28 °C	C	No Inversion	72 %
2.2	2.9 m/s from South	Open country	7 tenths	29 °C	C	No Inversion	75 %
2.3	2.14 m/s from ENE	Open country	6 tenths	27 °C	C	No Inversion	66 %

Table 3 Simulation Scenarios for the Bangkok and Samut Prakan Study Site

Scenario No.	Release Condition	Wind Direction	Month(s)	Model Applied
1.1	Flammable fuel leakage without ignition	East	January	Toxic Vapor Cloud; Flammable Threat Zones
	Flammable fuel leakage with ignition			Thermal Radiation from Pool Fire
1.2	Flammable fuel leakage without ignition	South	February, March, April, May	Toxic Vapor Cloud; Flammable Threat Zones
	Flammable fuel leakage with ignition			Thermal Radiation from Pool Fire
1.3	Flammable fuel leakage without ignition	South–Southwest (SSW)	June	Toxic Vapor Cloud; Flammable Threat Zones
	Flammable fuel leakage with ignition			Thermal Radiation from Pool Fire
1.4	Flammable fuel leakage without ignition	West	July, September	Toxic Vapor Cloud; Flammable Threat Zones
	Flammable fuel leakage with ignition			Thermal Radiation from Pool Fire
1.5	Flammable fuel leakage without ignition	Southwest	August	Toxic Vapor Cloud; Flammable Threat Zones
	Flammable fuel leakage with ignition			Thermal Radiation from Pool Fire
1.6	Flammable fuel leakage without ignition	North	October	Toxic Vapor Cloud; Flammable Threat Zones
	Flammable fuel leakage with ignition			Thermal Radiation from Pool Fire
1.7	Flammable fuel leakage without ignition	Northeast	November, December	Toxic Vapor Cloud; Flammable Threat Zones
	Flammable fuel leakage with ignition			Thermal Radiation from Pool Fire
2.1	Flammable fuel leakage without ignition	East	October, November, January	Toxic Vapor Cloud; Flammable Threat Zones
	Flammable fuel leakage with ignition			Thermal Radiation from Pool Fire
2.2	Flammable fuel leakage without ignition	South	February, March, April, May, June, July, August, September	Toxic Vapor Cloud; Flammable Threat Zones
	Flammable fuel leakage with ignition			Thermal Radiation from Pool Fire
2.3	Flammable fuel leakage without ignition	Northeast	December	Toxic Vapor Cloud; Flammable Threat Zones
	Flammable fuel leakage with ignition			Thermal Radiation from Pool Fire

Table 4 The Release Rate for the Bangkok and Samut Prakan Study Site

Scenario	Parameter and Value			
	Max Average Sustained Release Rate (vapor release rate to atmosphere)	Total Amount Released (vapor)	Maximum Puddle Area	Note
1.1	11.8 Kg/min (averaged over ≥ 1 min)	708 kg	1,455.6 m ²	Chemical escaped as liquid and formed an evaporating puddle; puddle spread to 43 m diameter
1.2	12.6 kg/min (averaged over ≥ 1 min)	746 kg		
1.3	14.9 kg/min (averaged over ≥ 1 min)	878 kg		
1.4	13.8 kg/min (averaged over ≥ 1 min)	815 kg		
1.5	14.9 kg/min (averaged over ≥ 1 min)	880 kg		
1.6	9.36 kg/min (averaged over ≥ 1 min)	552 kg		
1.7	9.92 kg/min (averaged over ≥ 1 min)	585 kg		
2.1	10.1 kg/min (averaged over ≥ 1 min)	600 kg	1,645 m ²	Chemical escaped as liquid and formed an evaporating puddle; puddle spread to 46 m diameter
2.2	14.4 kg/min (averaged over ≥ 1 min)	851 kg		
2.3	9.6 kg/min (averaged over ≥ 1 min)	568 kg		

The effect of secondary containment was incorporated into the ALOHA simulations through the Maximum Puddle Area parameter. For each study site, the maximum puddle area was calculated based on the effective containment area enclosed by the surrounding bund wall. It was assumed that the released fuel remained within the secondary containment system and did not overflow beyond the bund boundary.

The calculated maximum puddle areas were 1,455.6 m² for the Bangkok site and 1,645 m² for the Samut Prakan site. These values were entered into ALOHA as user-defined Maximum Puddle Area inputs to constrain liquid pool expansion and to estimate subsequent evaporation rates, vapor dispersion, and thermal radiation impacts.

Results and Discussion

The Assessment Results

ALOHA simulation results for kerosene leakage scenarios at the Bangkok and Samut Prakan study sites are presented in **Tables 5 and 6**. Hazard distances estimates for the Flammable Area of Vapor Cloud, Toxic Threat Zone, and Thermal Radiation from Pool Fire were evaluated and compared under representative meteorological conditions.

The results showed that the flammable vapor cloud hazard distance was limited to approximately 22 m from the release point, indicating that the flammable threat zone remained largely confined within the containment dike surrounding the storage tank. The ALOHA model did not generate graphical

threat contours in the immediate vicinity of the release source, which may be associated with near-field dispersion limitations.

The maximum Toxic Threat Zone extended to approximately 34 m from the release point based on the Acute Exposure Guideline Levels (AEGs), indicating a relatively localized health impact area. In contrast, the Thermal Radiation from Pool Fire scenario produced the largest hazard distance, reaching approximately 142 m at a thermal radiation level of 2 kW/m². These results suggest that thermal radiation represents the most extensive hazard associated with the simulated kerosene leakage scenario.

The results showed that the maximum flammable vapor cloud hazard distance was approximately 23 m from the release point, indicating that the flammable threat zone remained largely confined within the containment dike surrounding the storage tank. The ALOHA model did not generate graphical threat contours in the immediate vicinity of the release source, which may be associated with near-field dispersion limitations.

The maximum Toxic Threat Zone extended up to 60 m from the release point based on the Acute Exposure Guideline Levels (AEGs), indicating a relatively localized health impact area. In contrast, the Thermal Radiation from Pool Fire scenario produced the largest hazard distance, reaching approximately 210 m from the source. These findings suggest that thermal radiation represents the most extensive hazard associated with the simulated kerosene leakage scenario.

Table 5 The assessment results at the Bangkok study site

Model Applied	Result						
	1.1 East Wind	1.2 South Wind	1.3 South South-west Wind	1.4 West Wind	1.5 South-west Wind	1.6 North Wind	1.7 North North-east Wind
Flammable Threat Zones (Estimates)	Red: 22 m (4200 ppm)	Red: 22 m (4200 ppm)	Red: 22 m (4200 ppm)	Red: 22 m (4200 ppm)	Red: 22 m (4200 ppm)	Red: 22 m (4200 ppm)	Red: 22 m (4200 ppm)
	Yellow: 22 m (700 ppm)	Yellow: 22 m (700 ppm)	Yellow: 22 m (700 ppm)	Yellow: 22 m (700 ppm)	Yellow: 22 m (700 ppm)	Yellow: 22 m (700 ppm)	Yellow: 22 m (700 ppm)
Toxic Vapor Cloud (Estimates)	AEGL-2: 22 m (1100 mg/m ³)	AEGL-2: 22 m (1100 mg/m ³)	AEGL-2: 22 m (1100 mg/m ³)	AEGL-2: 22 m (1100 mg/m ³)	AEGL-2: 22 m (1100 mg/m ³)	AEGL-2: 22 m (1100 mg/m ³)	AEGL-2: 22 m (1100 mg/m ³)
	AEGL-1: 34 m (290 mg/m ³)	AEGL-1: 36 m (290 mg/m ³)	AEGL-1: 37 m (290 mg/m ³)	AEGL-1: 36 m (290 mg/m ³)	AEGL-1: 36 m (290 mg/m ³)	AEGL-1: 33 m (290 mg/m ³)	AEGL-1: 34 m (290 mg/m ³)
Thermal Radiation from Pool Fire (Estimates)	Red: 64 m (10.0 kW/m ²)	Red: 63 m (10.0 kW/m ²)	Red: 63 m (10.0 kW/m ²)	Red: 63 m (10.0 kW/m ²)	Red: 63 m (10.0 kW/m ²)	Red: 64 m (10.0 kW/m ²)	Red: 64 m (10.0 kW/m ²)
	Orange: 91 m (5.0 kW/m ²)	Orange: 90 m (5.0 kW/m ²)	Orange: 90 m (5.0 kW/m ²)	Orange: 90 m (5.0 kW/m ²)	Orange: 90 m (5.0 kW/m ²)	Orange: 91 m (5.0 kW/m ²)	Orange: 91 m (5.0 kW/m ²)
	Yellow: 142 m (2.0 kW/m ²)	Yellow: 141 m (2.0 kW/m ²)	Yellow: 140 m (2.0 kW/m ²)	Yellow: 140 m (2.0 kW/m ²)	Yellow: 140 m (2.0 kW/m ²)	Yellow: 141 m (2.0 kW/m ²)	Yellow: 142 m (2.0 kW/m ²)

Table 6 The assessment results at the Samut Prakan study site

Model Applied	Result		
	2.1 East Wind	2.2 South Wind	2.3 East North-east Wind
Flammable Threat Zones (Estimates)	Red: 23 m (4200 ppm)	Red: 23 m (4200 ppm)	Red: 23 m (4200 ppm)
	Yellow: 23 m (700 ppm)	Yellow: 23 m (700 ppm)	Yellow: 23 m (700 ppm)
Toxic Vapor Cloud (Estimates)	AEGL-2: 25 m (1100 mg/m ³)	AEGL-2: 26 m (1100 mg/m ³)	AEGL-2: 24 m (1100 mg/m ³)
	AEGL-1: 58 m (290 mg/m ³)	AEGL-1: 60 m (290 mg/m ³)	AEGL-1: 55 m (290 mg/m ³)
Thermal Radiation from Pool Fire (Estimates)	Red: 96 m (10.0 kW/m ²)	Red: 95 m (10.0 kW/m ²)	Red: 96 m (10.0 kW/m ²)
	Orange: 135 m (5.0 kW/m ²)	Orange: 134 m (5.0 kW/m ²)	Orange: 135 m (5.0 kW/m ²)
	Yellow: 209 m (2.0 kW/m ²)	Yellow: 208 m (2.0 kW/m ²)	Yellow: 210 m (2.0 kW/m ²)

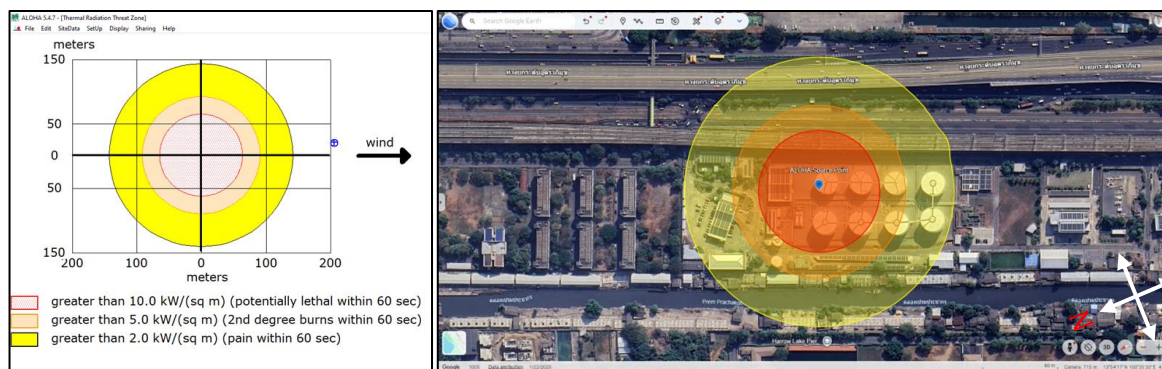


Figure 1 The maximum predicted thermal radiation impact distance in Bangkok study site.

The hazard zone (Threat Zone) assessment results for the kerosene leakage scenario generated using the ALOHA model and overlaid on Google Earth satellite imagery. The figure identifies the release source location (ALOHA Source Point) and the corresponding impact areas predicted by the model. The revised figure has been enhanced with higher resolution and includes a linear scale bar (80 m) and a north arrow referenced to True North to improve spatial interpretation and map readability.

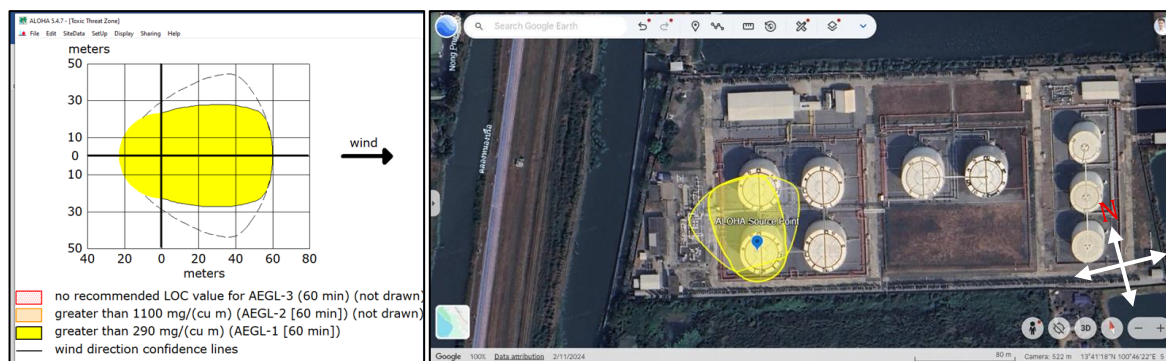


Figure 2 The maximum predicted Toxic Threat distance in Samut Prakan study site.

The hazard zone (Threat Zone) assessment results for the kerosene leakage scenario generated using the ALOHA model and overlaid on Google Earth satellite imagery. The figure identifies the release source location (ALOHA Source Point) and the corresponding impact areas predicted by the model. The revised figure has been enhanced with higher resolution and includes a linear scale bar (80 m) and a north arrow referenced to True North to improve spatial interpretation and map readability.

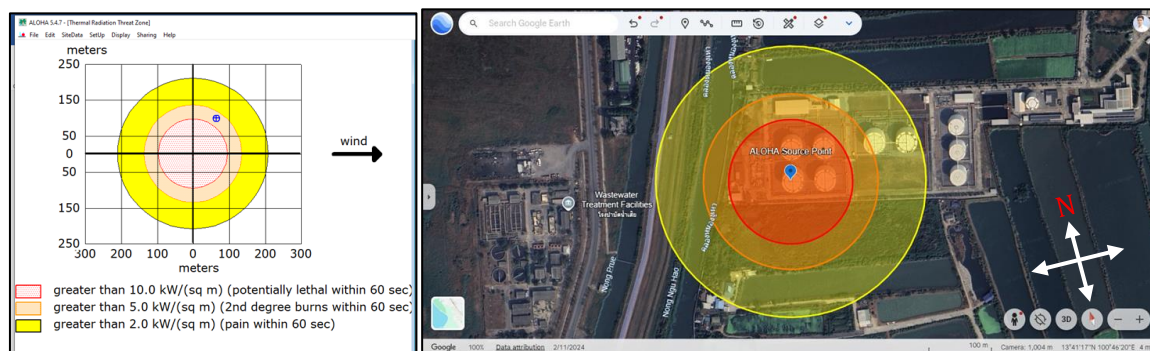


Figure 3 The maximum predicted thermal radiation impact distance in Samut Prakan study site.

The hazard zone (Threat Zone) assessment results for the kerosene leakage scenario generated using the ALOHA model and overlaid on Google Earth satellite imagery. The figure identifies the release source location (ALOHA Source Point) and the corresponding impact areas predicted by the model. The revised figure has been enhanced with higher resolution and includes a linear scale bar (100 m) and a north arrow referenced to True North to improve spatial interpretation and map readability.

Overall Assessment of the Flammable Area of Vapor Cloud for Scenarios 1.1–1.7

The results indicated that the Flammable Area of Vapor Cloud remained relatively constant across Scenarios 1.1–1.7, with a maximum hazard distance of approximately 22 m from the release point.

The relatively short flammable hazard distance may be attributed to the low vapor pressure and slow evaporation rate of kerosene. As a result, the quantity of vapor available to form a flammable mixture with air may have remained limited, which could have contributed to combustible vapor accumulation near the liquid surface and release location rather than dispersion over longer distances.

The results suggest that meteorological variations had limited influence on the flammable hazard distance within the investigated range of conditions. Although wind speed varied between 2.46 and 3.42 m/s, the Red Zone (60% LEL) and Yellow Zone (10% LEL) remained unchanged at approximately 22 m. This observation suggests that, within the investigated wind speed range, atmospheric transport was insufficient to significantly extend the flammable vapor cloud. Similarly, air temperature varied from 26 to 30°C without producing noticeable changes in hazard distance. Relative humidity also varied between 62% and 78% but showed no apparent influence on the flammable threat zone. This finding is consistent with the expectation that flammable vapor generation is governed primarily by fuel properties, such as vapor pressure, flash point, and evaporation rate, rather than by atmospheric humidity.

The overall distribution of flammable hazard distances for scenarios 1.1–1.7 is illustrated in the **Figure 4**.

Overall Assessment of the Toxic Threat Zone for Scenarios 1.1–1.7

The Toxic Threat Zone associated with kerosene leakage remained relatively limited across Scenarios 1.1–1.7. The maximum AEGL-1 hazard distance reached 37 m in Scenario 1.3 under south-southwesterly (SSW) wind conditions, whereas AEGL-2 remained approximately 22 m in all scenarios. Similar to the flammable vapor cloud results, ALOHA did not generate graphical threat contours near the release source because of limitations associated with near-field dispersion behavior.

Although meteorological conditions varied among the scenarios, AEGL hazard distances remained within a relatively narrow range. These findings suggest that atmospheric conditions may have influenced vapor dispersion to some extent; however, the relatively low evaporation rate and quasi-heavy gas characteristics of kerosene may have played a more important role in controlling toxic hazard distances. Slightly greater AEGL-1 distances were observed at higher temperatures, whereas no clear relationship was identified between relative humidity and hazard distance. It should also be recognized that atmospheric dispersion predictions are subject to uncertainties associated with source characterization, meteorological inputs, and inherent model assumptions, which may influence the accuracy of predicted hazard distances [20].

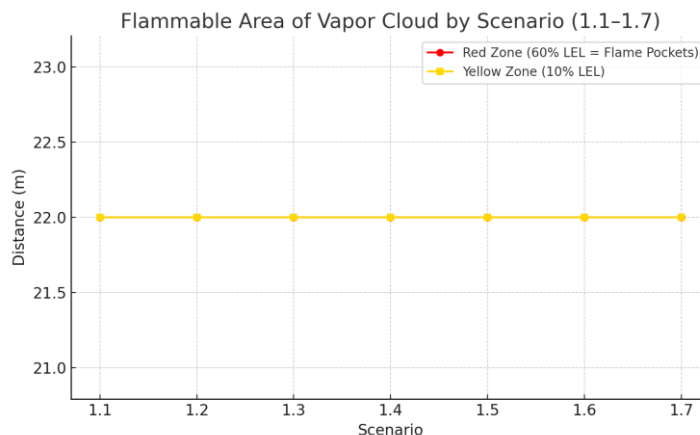


Figure 4 Comparison of Flammable Threat Zone Distances for Scenarios 1.1–1.7 at the Bangkok Study Site

The overall distribution of toxic hazard distances for scenarios 1.1–1.7 is illustrated in the **Figure 5**.

Overall Assessment of Thermal Radiation from Pool Fire for Scenarios 1.1–1.7

Thermal Radiation from Pool Fire produced the largest hazard distances among all evaluated scenarios. The maximum predicted hazard distances were approximately 64 m, 91 m, and 142 m for thermal radiation levels of 10, 5, and 2 kW/m², respectively. According to ALOHA hazard criteria, these radiation levels may result in severe injury, second-degree burns, or minor burn injuries following prolonged exposure.

The thermal radiation hazard distances remained relatively consistent across all scenarios, with Red Zone (10 kW/m²), Orange Zone (5 kW/m²), and Yellow Zone (2 kW/m²) distances ranging from 63–64 m, 90–91 m, and 140–142 m, respectively. This limited variation suggests that meteorological conditions had only a minor influence on thermal radiation hazard distances within the investigated range. Instead, thermal radiation hazards appeared to be governed primarily by pool fire characteristics, particularly pool diameter and heat release rate.

The overall distribution of thermal radiation distances for Scenarios 1.1–1.7 is illustrated in the **Figure 6**.

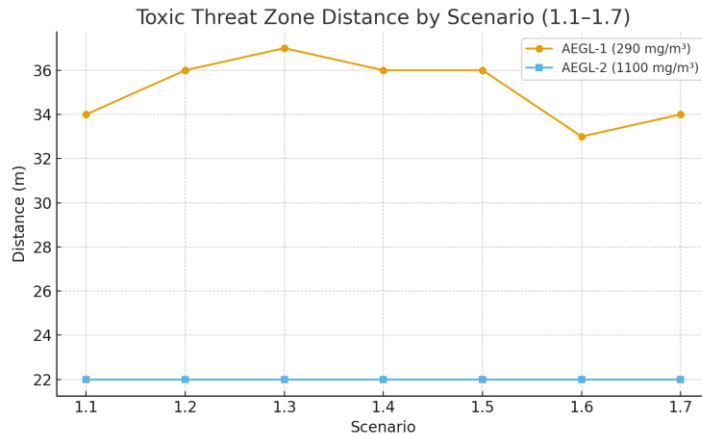


Figure 5 Comparison of Toxic Threat Zone Distances for Scenarios 1.1–1.7 at the Bangkok Study Site

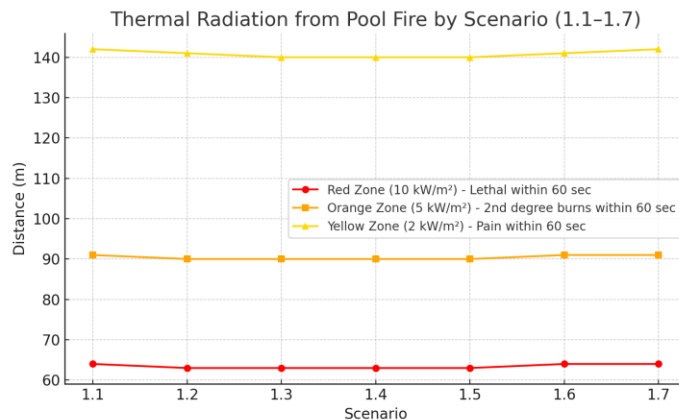


Figure 6 Comparison of Thermal Radiation Distances for Scenarios 1.1–1.7 at the Bangkok Study Site

Overall Assessment of the Flammable Area of Vapor Cloud for Scenarios 2.1–2.3

The simulation results showed that the Flammable Area of Vapor Cloud remained consistent across Scenarios 2.1–2.3, with a maximum hazard distance of approximately 23 m from the release source. The predicted flammable threat zone was confined within the containment dike surrounding the storage tank, indicating that combustible vapor accumulation remained localized near the release area.

Similar to the Bangkok scenarios, ALOHA did not generate graphical threat contours in the immediate vicinity of the release source because of limitations associated with near-field dispersion behavior. Therefore, the extent of the Flammable Area of Vapor Cloud was illustrated separately, as shown in Figure 10.

Despite variations in meteorological conditions, including wind speed (2.13–2.90 m/s), air temperature (27–29°C), and relative humidity (66–75%), no significant variation in flammable hazard distance was observed. Both the Red Zone (60% LEL) and Yellow Zone (10% LEL) remained at approximately 23 m across all scenarios. These findings suggest that, within the investigated range of meteorological conditions, flammable hazard distances were influenced more strongly by the physical properties of kerosene than by atmospheric variability. Consequently, the flammable vapor cloud remained restricted to the near-field region surrounding the storage tank.

The overall distribution of flammable hazard distances for Scenarios 2.1–2.3 is illustrated in the **Figure 7**.

Overall Assessment of the Toxic Threat Zone for Scenarios 2.1–2.3

The Toxic Threat Zone predicted for the Samut Prakan oil terminal extended farther than that observed in the Bangkok scenarios. The maximum AEGL-1 and AEGL-2 hazard distances were predicted in Scenario 2.2, reaching approximately 60 m and 26 m from the release source, respectively. Compared with the Flammable Area of Vapor Cloud, the Toxic Threat Zone exhibited greater sensitivity to meteorological variability, particularly for AEGL-1, which consistently extended farther than AEGL-2 due to its lower concentration threshold.

Although Scenario 2.2 was characterized by the highest wind speed, air temperature, and

relative humidity, the increase in hazard distance remained relatively small. These findings suggest that meteorological conditions may have influenced vapor transport and near-ground dispersion to some extent; however, the overall variation among scenarios was limited. Consequently, toxic hazard distances appear to be influenced not only by atmospheric conditions but also by kerosene evaporation behavior and vapor generation characteristics.

Acute inhalation toxicity and long-term environmental air quality impacts represent different assessment endpoints. Although kerosene is not considered highly toxic in terms of short-term inhalation exposure, it may still contribute to VOC emissions and photochemical ozone formation under atmospheric conditions.

The overall distribution of toxic hazard distances for Scenarios 2.1–2.3 is illustrated in the **Figure 8**.

Overall Assessment of Thermal Radiation from Pool Fire for Scenarios 2.1–2.3

Thermal Radiation from Pool Fire produced the largest impact distances among all evaluated hazards in the Samut Prakan scenarios. The maximum predicted hazard distances were approximately 96 m, 135 m, and 210 m for thermal radiation levels of 10, 5, and 2 kW/m², respectively. According to the ALOHA hazard criteria, these radiation levels may result in severe injury, second-degree burns, or minor burn injuries following short-term exposure.

Only minor differences were observed among Scenarios 2.1–2.3, with variations of approximately 1–2 m across all thermal radiation threat zones. Despite differences in meteorological conditions and release characteristics, the predicted thermal radiation distances remained highly consistent. This observation suggests that thermal radiation hazards were influenced more strongly by pool fire characteristics, such as burning area and fuel combustion properties, than by atmospheric variability. Compared with the Flammable Area of Vapor Cloud and Toxic Threat Zone, Thermal Radiation from Pool Fire generated the widest impact area, highlighting its significance as the dominant hazard associated with the simulated kerosene leakage scenarios.

The overall distribution of thermal radiation distances for Scenarios 2.1–2.3 is illustrated in the **Figure 9**.

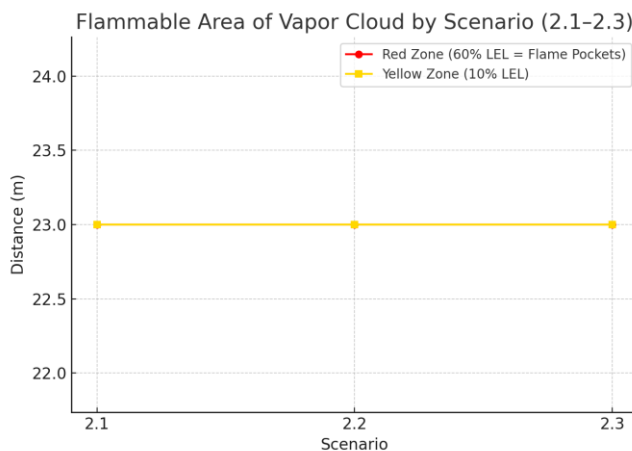


Figure 7 Comparison of Flammable Threat Zone Distances for Scenarios 2.1–2.3 at the Samut Prakan Study Site

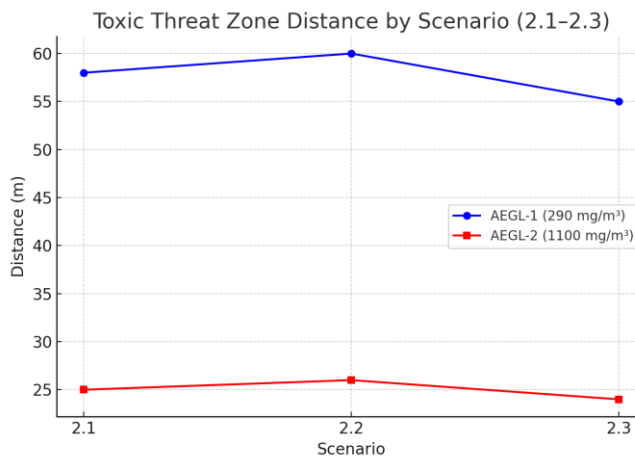


Figure 8 Comparison of Toxic Threat Zone Distances for Scenarios 2.1–2.3 at the Samut Prakan Study Site

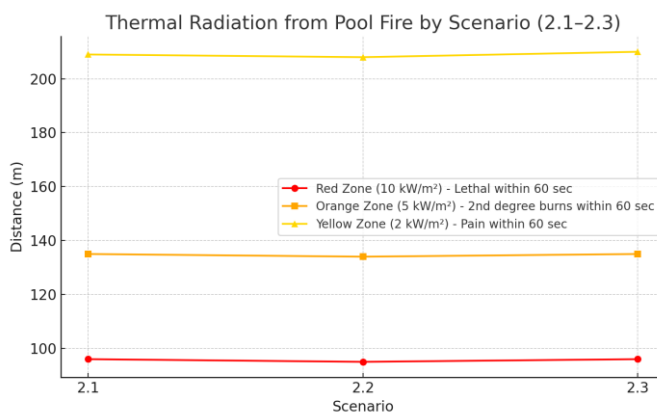


Figure 9 Comparison of Thermal Radiation Distances for Scenarios 2.1–2.3 at the Samut Prakan Study Site

Comparison of Hazard Impact Distances between Bangkok and Samut Prakan

A comparative analysis of kerosene leakage consequences was conducted between the Bangkok and Samut Prakan study sites. Hazard distances associated with the Flammable Area of Vapor Cloud, Toxic Threat Zone, and Thermal Radiation from Pool Fire were evaluated and compared. The results are summarized in **Table 7** and presented graphically in the figures below.

Comparison with Previous Studies

Although direct validation using field measurements was beyond the scope of this study, the simulation results were compared with findings reported in previous ALOHA-based assessments of aviation fuel releases [21]. The Risk Assessment and Hazard Analysis study conducted for Aviation Turbine Fuel

(ATF) storage facilities reported that aviation fuel vapor clouds generally exhibited near-field hazard characteristics and quasi-heavy gas behavior, with vapor accumulation occurring close to the release source, particularly under low wind speed conditions. Similar behavior was observed in the present study, where the Flammable Area of Vapor Cloud remained confined within the bunded area and exhibited limited hazard distances despite variations in meteorological conditions.

The ATF study also identified thermal radiation from pool fire scenarios as one of the most significant consequences associated with aviation fuel releases. This observation is consistent with the present findings, in which Thermal Radiation from Pool Fire produced substantially greater impact distances than both the Flammable Area of Vapor Cloud and the Toxic Threat Zone.

Table 7 Comparison of Hazard Impact Distances between Bangkok and Samut Prakan study sites

Parameter	Bangkok (m)	Samut Prakan (m)
Flammable Area of Vapor Cloud (Red Zone)	22.0	23.0
Toxic AEGL-1	35.0	58.0
Toxic AEGL-2	22.0	25.0
Thermal 10 kW/m ²	63.5	95.5
Thermal 5 kW/m ²	90.5	134.5
Thermal 2 kW/m ²	141.0	209.0

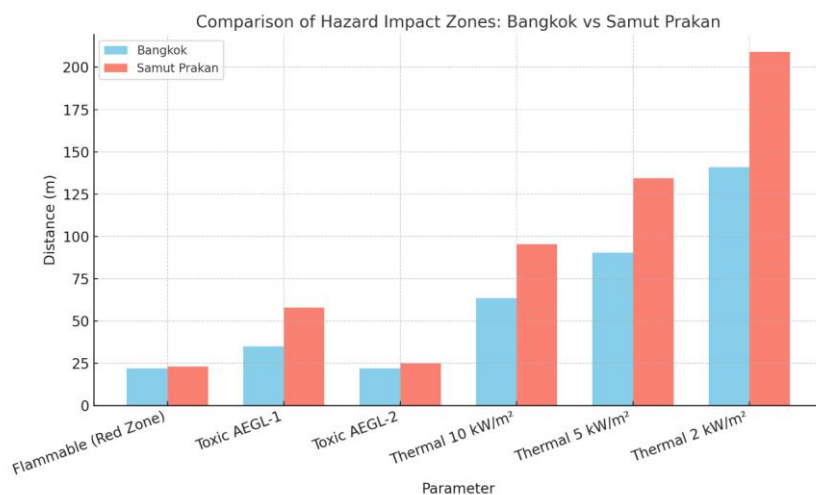


Figure 10 Comparison of Hazard Impact Distances between Bangkok and Samut Prakan Study Site

Similarly, Mišić et al. (2018) [7] evaluated thermal radiation hazards resulting from kerosene pool fires using both ALOHA and PHAST consequence modeling software. Their study demonstrated that thermal radiation distances increased with release rate, fuel quantity, and pool diameter, and identified Thermal Radiation from Pool Fire as the dominant hazard associated with kerosene release incidents. Comparable results were obtained in the present study, where thermal radiation represented the largest hazard zone among all evaluated consequences. While Mišić et al. focused on kerosene releases from railway tanker accidents, the present study examined leakage scenarios from fixed-roof storage tanks in oil terminal facilities. Nevertheless, both studies highlighted the importance of pool fire consequences in emergency planning for kerosene storage and handling operations.

Mišić et al. (2018) [7] further reported that ALOHA and PHAST produced comparable hazard distances despite differences in predicted

release rates, suggesting that ALOHA can provide reasonable preliminary estimates for consequence assessment and emergency response planning. Overall, the consistency between the present findings and previously published studies supports the applicability of ALOHA for preliminary hazard assessment of kerosene release scenarios and provides additional confidence in the observed hazard patterns.

Sensitivity Analysis of Meteorological Parameters

A sensitivity analysis was conducted to evaluate the influence of wind speed and atmospheric stability on the predicted hazard distances. Scenario 2.2 was selected as the base case because it produced the maximum Toxic Threat Zone among the original simulations. Wind speed and atmospheric stability class were varied independently while all other source, chemical, and site-specific parameters were kept constant. The results are summarized in **Table 8**.

Table 8 Sensitivity analysis of wind speed and atmospheric stability class on predicted hazard distances

Sensitivity Case	Variable Tested	Wind Speed (m/s)	Stability Class	Other Input Parameters	Flammable Area of Vapor Cloud (m)	AEGL-1 (m)	AEGL-2 (m)	Thermal Radiation 2 kW/m ² (m)
Base Case	Reference condition	2.90	C Slightly Unstable	Constant	23	60	26	208
W1	Wind speed sensitivity	1.50	C Slightly Unstable	Constant	18	161	62	208
W2	Wind speed sensitivity	4.00	C Slightly Unstable	Constant	23	58	25	208
S1	Stability sensitivity	2.90	A Very Unstable	Constant	23	24	23	208
S2	Stability sensitivity	2.90	D Neutral	Constant	27	88	36	208
S3	Stability sensitivity	2.90	F Stable	Constant	34	264	98	208

The results indicate that atmospheric stability had a substantially greater influence on hazard distances than wind speed. When wind speed was varied from 1.5 m/s (W1) to 4.0 m/s (W2), the Flammable Area of Vapor Cloud changed only slightly, ranging from 18–23 m. Similarly, Thermal Radiation from Pool Fire remained unchanged at approximately 208 m. Toxic hazard distances exhibited moderate sensitivity to wind speed, with AEGL-1 varying from 58 m to 161 m and AEGL-2 varying from 25 m to 62 m. The largest toxic hazard distances occurred under the lowest wind speed condition (1.5 m/s), indicating that reduced atmospheric dilution allowed vapor concentrations to remain above AEGL thresholds over longer distances.

In contrast, atmospheric stability produced much larger variations in the predicted hazard zones. Under highly unstable conditions (Class A), AEGL-1 and AEGL-2 distances decreased to 24 m and 23 m, respectively, whereas under stable conditions (Class F), they increased substantially to 264 m and 98 m. Flammable hazard distances also increased from 23 m under Class A conditions to 34 m under Class F conditions. These results indicate that atmospheric stability strongly influences vapor cloud dilution and dispersion behavior. Stable atmospheric conditions suppress vertical mixing and promote the accumulation of vapors

near ground level, resulting in significantly larger Toxic Threat Zones.

Thermal Radiation distances remained constant across all sensitivity cases, confirming that thermal radiation hazards are controlled primarily by pool fire characteristics, such as burning area and heat release rate, rather than by meteorological variability. Overall, the sensitivity analysis demonstrates that atmospheric stability is the dominant meteorological parameter affecting toxic vapor dispersion, while wind speed has a secondary influence and thermal radiation hazards remain largely insensitive to the meteorological conditions evaluated in this study [22].

Conclusions

This study evaluated the potential consequences of aviation fuel (kerosene) leakage at oil terminal facilities in Bangkok and Samut Prakan, Thailand, using the ALOHA dispersion model. Flammable vapor cloud, toxic exposure, and thermal radiation hazard zones were assessed to support emergency response planning and risk management. The main findings are summarized as follows:

Overall comparison of kerosene leakage simulation scenarios

Table 9 Summary Comparison of Kerosene Leakage Simulation Results

Comparison Category	Bangkok (Scenario 1.1–1.7)	Samut Prakan (Scenario 2.1–2.3)
Scenario	7 scenarios (multiple wind directions)	3 scenarios (dominant east–south wind patterns)
Flammable Area (Red/Yellow Zone)	22 m (constant across all scenarios)	23 m (constant across all scenarios)
Toxic Threat Zone (AEGL-1/AEGL-2)	AEGL-1: 33–37 m AEGL-2: 22 m	AEGL-1: 55–60 m AEGL-2: 24–26 m
Thermal Radiation (Pool Fire)	10 kW/m²: 63–64 m 5 kW/m²: 90–91 m 2 kW/m²: 140–142 m	10 kW/m²: 95–96 m 5 kW/m²: 134–135 m 2 kW/m²: 208–210 m
Overall Impact Severity	Shorter hazard distances	Longer hazard distances

A comparison of kerosene leakage consequences between the Bangkok and Samut Prakan oil terminals showed that the Samut Prakan site consistently produced greater hazard distances across all evaluated parameters, particularly for the Toxic Threat Zone and Thermal Radiation from Pool Fire.

The Flammable Area of Vapor Cloud remained limited and relatively similar at both

locations, with hazard distances of approximately 22 m in Bangkok and 23 m in Samut Prakan. The flammable threat zone was confined within the containment dike surrounding the storage tanks, indicating that flammable hazards were largely restricted to the near-field region.

For the Toxic Threat Zone, Samut Prakan exhibited greater AEGL-1 and AEGL-2 distances (58 m and 25 m, respectively) than Bangkok

(35 m and 22 m, respectively), indicating a larger potential impact area.

Thermal Radiation from Pool Fire produced the largest impact distances among all evaluated hazards. In Samut Prakan, hazard distances reached approximately 95.5 m, 134.5 m, and 209 m at thermal radiation levels of 10, 5, and 2 kW/m², respectively, compared with 63.5 m, 90.5 m, and 141 m in Bangkok. These findings suggest that thermal radiation hazards were influenced more strongly by physical fire characteristics, such as pool size and fuel quantity, than by meteorological variability. Thermal radiation intensity is primarily governed by pool diameter and heat release rate [23], which may explain the substantially larger hazard distances observed in the pool fire scenarios. The results are consistent with previous studies reporting that pool diameter and heat release rate are primary factors governing thermal radiation intensity and hazard distance.

Overall, the findings indicate that the principal hazard associated with kerosene leakage is not long-range flammable vapor cloud dispersion but rather thermal radiation from pool fire and the accumulation of vapors in the near-field region surrounding the release source. The observed dispersion characteristics also suggest quasi-heavy gas behavior, with vapor accumulation occurring predominantly near ground level rather than following conventional Gaussian-type dispersion patterns.

Influence of Kerosene Properties on Hazard Distance Assessment

The results suggest that the dispersion behavior of kerosene differs from that of both typical light gases and conventional dense gases due to its relatively low vapor pressure, low evaporation rate, and high boiling point. Consequently, kerosene vapor clouds remained largely confined to the vicinity of the release source, producing limited flammable hazard distances and localized vapor accumulation.

The observed dispersion characteristics may be described as a transitional dispersion regime exhibiting quasi-heavy gas behavior. In the near-field region, vapor accumulation appeared to be influenced primarily by fuel properties and limited evaporation, resulting in ground-level accumulation within the bunded area. These dispersion characteristics may resemble certain aspects of dense-gas dispersion, including restricted vertical mixing and localized vapor concentrations.

At greater distances from the release source, atmospheric transport processes became increasingly important, and dispersion patterns appeared to be influenced by meteorological factors such as wind speed, turbulence, temperature, and atmospheric stability. Under far-field conditions, the observed dispersion behavior showed characteristics consistent with Gaussian atmospheric diffusion processes [24]. Under these conditions, the dispersion behavior showed characteristics more consistent with Gaussian-type dispersion.

Overall, the findings suggest that kerosene vapor dispersion cannot be adequately described by a single dispersion mechanism. Instead, the observed behavior appears to represent a transitional dispersion regime in which near-field transport exhibits quasi-heavy gas characteristics, while far-field dispersion becomes increasingly influenced by atmospheric mixing processes.

Influence of Meteorological Conditions on Hazard Distances

Meteorological conditions influenced the predicted hazard distances to varying degrees depending on the hazard type. Among the parameters considered, wind speed and air temperature appeared to have a greater influence on the Toxic Threat Zone than on the Flammable Area of Vapor Cloud and Thermal Radiation from Pool Fire. In contrast, relative humidity showed only a limited effect on the predicted hazard distances.

The results suggest that toxic vapor dispersion was moderately sensitive to meteorological variability. Slight increases in Toxic Threat Zone distances were observed under conditions of higher wind speed and temperature, which may have enhanced vapor transport and evaporation. However, the magnitude of these changes remained relatively small, indicating that atmospheric conditions were not the sole factors controlling toxic hazard distances.

The Flammable Area of Vapor Cloud showed minimal variation across all scenarios despite changes in meteorological conditions. This behavior may be associated with the relatively low vapor pressure and slow evaporation rate of kerosene, which limited the formation of flammable vapor concentrations beyond the immediate vicinity of the release source. Consequently, the flammable hazard zone remained largely confined to the near-field region surrounding the storage tank.

Thermal Radiation from Pool Fire exhibited the least sensitivity to meteorological conditions. Hazard distances remained relatively consistent across all scenarios, suggesting that thermal radiation was influenced more strongly by pool fire characteristics, such as burning area, fuel quantity, and heat release rate, than by atmospheric variability. This observation is consistent with consequence analysis theory, which indicates that pool fire consequences are generally controlled by fuel inventory and burning area rather than meteorological variability [25].

Meteorological conditions influenced the Toxic Threat Zone more than the Flammable Area of Vapor Cloud and Thermal Radiation from Pool Fire. However, the overall effect remained limited compared with fuel properties and release characteristics. The sensitivity analysis demonstrated that atmospheric stability exerted a greater influence on toxic hazard distances than wind speed, while thermal radiation hazards remained largely unaffected by the meteorological conditions considered in this study.

Influence of Physical Site Characteristics

Physical site characteristics appeared to play an important role in determining the predicted hazard distances. The Samut Prakan facility contained larger storage tanks with greater fuel inventories than those at the Bangkok site, which may have contributed to larger release quantities and more extensive hazard zones. In addition, release size remained an important factor, as larger leak openings generally resulted in greater fuel discharge and increased potential for vapor generation.

The presence of containment structures, such as bund walls surrounding the storage tanks, also influenced the predicted consequences. These structures restricted the spread of leaked fuel and confined liquid accumulation within a defined area, thereby limiting the extent of vapor generation and dispersion. As a result, the Flammable Area of Vapor Cloud remained relatively consistent across all scenarios despite variations in meteorological conditions and release quantities.

The low evaporation rate of kerosene resulted in relatively limited vapor generation, causing flammable hazard distances to remain relatively short and, in some cases, graphical threat contours could not be displayed because

the hazard zone was confined to the immediate vicinity of the release source. These findings highlight the importance of both fuel properties and site-specific physical characteristics in determining the extent of hazard zones associated with kerosene leakage incidents.

In contrast, the Samut Prakan study site is located in a more open environment characterized by agricultural land and fewer surrounding structures. As a result, in the event of a fuel leakage incident, vapor dispersion may extend over a wider area compared with the Bangkok site.

These differences in surrounding terrain and land use conditions contribute to variations in dispersion behavior between the two study areas and should therefore be considered when evaluating hazard zones and emergency response planning.

Limitations and Recommendations

This study has several limitations that should be considered when interpreting the results. First, ALOHA is primarily intended for emergency response planning and short-term release scenarios. The model is less suitable for evaluating long-duration releases exceeding one hour and does not simulate the dispersion of combustion products such as smoke generated during fire incidents. In addition, ALOHA may not generate graphical threat contours for low-volatility substances with limited dispersion distances, as observed in some kerosene release scenarios.

Second, the simulations were based on long-term average meteorological data (2020–2024), which may not fully represent extreme weather conditions. Consequently, the predicted hazard distances should be interpreted as representative estimates rather than worst-case scenarios. Furthermore, ALOHA does not explicitly account for complex terrain, buildings, or other obstacles that may influence local airflow patterns and vapor dispersion. A sensitivity analysis was performed to evaluate the influence of wind speed and atmospheric stability on the predicted hazard distances. The results indicated that atmospheric stability exerted a greater influence on toxic hazard distances than wind speed; however, a formal uncertainty analysis was not performed.

Third, the present study focused on leakage scenarios involving fixed-roof storage tanks and did not consider other potential release

sources, such as pipelines, valves, pumps, or fuel transportation vehicles. In addition, escalation scenarios, including domino effects, BLEVE events, secondary fires, and simultaneous failures of storage tanks and secondary containment systems, were beyond the scope of this study. Such events could increase fuel spread area, pool fire dimensions, vapor generation, and associated hazard distances.

Another limitation is that direct model validation was not performed using field measurements, accident investigation records, or alternative consequence modeling software. Although the simulation results were qualitatively compared with findings reported in previous aviation fuel consequence assessment studies and showed similar hazard patterns, the predicted hazard distances remain dependent on the assumptions, input parameters, and algorithms incorporated within the ALOHA model.

Therefore, the predicted Threat Zones should be interpreted as model-based consequence estimates intended to support emergency preparedness and risk assessment rather than regulatory safety distances or legally enforceable exclusion zones. Actual hazard extents may vary depending on site-specific conditions, meteorological variability, release characteristics, and model assumptions. Although ALOHA is suitable for rapid screening-level consequence assessment and emergency planning, advanced models such as PHAST, FLACS, and CFD may provide more detailed predictions in complex industrial or urban environments. Future studies should incorporate model validation using accident records or field measurements, evaluate extreme meteorological conditions and multiple release scenarios, and apply advanced consequence modeling techniques to improve the robustness and accuracy of hazard assessments. For practical emergency planning, the results should be integrated with GIS-based spatial information, evacuation planning, emergency response procedures, and applicable regulatory requirements.

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