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Quantitative Risk Assessment of Different Fire Scenarios of a Typical Isobutane Storage Facility

Ritika Mahmuda[1,3] , Maisa Rahman[1,3] , Mohammad Abdullah[2]
[1]Department of Chemical Engineering, Rajshahi University of Engineering & Technology
[2]Department of Mechanical Engineering, Rajshahi University of Engineering & Technology
[3]Department of Chemical Engineering, Bangladesh University of Engineering & Technology
E-mail: ritikamahmuda@gmail.com; maisa.rahman@che.ruet.ac.bd; mohammad.abdullah5382@gmail.com

Abstract

This study investigates the impact of atmospheric conditions on the dispersion and hazards associated with isobutane leakage from a storage tank using the ALOHA 5.4.7 modeling software. The analysis focuses on various release scenarios, assessing toxic, flammable, overpressure, jet fire and BLEVE (boiling liquid expanding vapor explosion) threat zones. Results indicate that climatic variations, particularly temperature and wind speed, play a crucial role in determining the extent of these hazard zones. During winter, the threat zones expand, posing greater risks to surrounding areas, while in summer, they contract. Statistical analysis using a paired t-test confirmed that these variations are significant, especially in toxic and flammable zones. The findings emphasize the necessity of incorporating environmental factors into risk assessments, hazard simulations and emergency planning to enhance safety protocols and minimize potential risks. This research provides key insights for effective management of isobutane storage and leakage incidents.

Keywords: Isobutane, Release Scenarios, ALOHA, Dispersion Modelling, Hazard Simulation, BLEVE.

1. Introduction

Quantitative Risk Assessment (QRA) is a leading approach used to anticipate potential fire and explosion incidents in the chemical process industry. By systematically evaluating these risks, QRA supports informed decision-making, helping authorities determine whether to issue operational safety permits. This process involves identifying and analyzing major accident scenarios that could lead to significant safety impacts[1], [2].

With rising demand for eco-friendly refrigerants, isobutane (R600a) has become widely used in refrigerator manufacturing due to its low global warming potential and negligible ozone impact [3], [4], [5] However, as a highly flammable gas, the large-scale storage of isobutane presents significant risks, highlighted by incidents like the 2016 leak at ExxonMobil's Baton Rouge refinery, which led to serious fire damage and injuries [6].

In Bangladesh, a country with unique six-season cycle, atmospheric conditions such as temperature, wind speed and humidity vary significantly throughout the year. These seasonal changes have the potential to influence isobutane dispersion during accidental leaks and significantly impact the size of hazard zones around storage facilities[7], [8]. While dispersion modeling is a standard approach in chemical risk assessment, there are limited studies specifically focusing on isobutane leakage risks, especially in climates with pronounced seasonal variations, such as Bangladesh.

This study aims to evaluate how varying seasonal atmospheric conditions affect isobutane dispersion in a typical storage facility in Bangladesh. Using ALOHA software, we simulated different release scenarios to analyze changes in toxic, flammable, overpressure, jet fire & BLEVE hazard zones across seasons. By identifying the key atmospheric factors that impact the severity and reach of these hazard zones, this research contributes valuable insights to support safer isobutane storage practices and enhance emergency preparedness in regions with similar seasonal climates.

2. Research Methodology

This study was conducted considering a typical isobutane storage facility located in Gazipur, Dhaka, Bangladesh. The area under the study was assessed for risks and consequences due to isobutane leakage under varying

atmospheric conditions from month to month throughout the year. Probable release scenarios were simulated in the study area to obtain the threat zones of isobutane storage tank releases, using the ALOHA 5.4.7 model developed by Office of Emergency Management, EPA & Emergency Response Division, NOAA [9], [10]

2.1 Atmospheric Data

Atmospheric data including monthly wind speed, monthly temperature, monthly humidity data were sourced from Bangladesh Meteorological Department (BMD), whereas cloud cover, wind direction data were sourced from Bangladesh Agro-Meteorological Information Service (BAMIS)[11], [12]. Both minimum and maximum monthly temperatures were separately considered for each month of the year. Wind measurement height was considered 10 meters, or around 33 feet, as that is the altitude at which wind speed is typically reported by the National Weather Service. Ground roughness was considered as open country for assessing the most widespread impact. The nighttime hour was considered for the simulation, when there is greater atmospheric instability, leading to a wider impact on regions due to chemical releases[8]. The input data were manually entered into the ALOHA software. The model then determined the most suitable stability class based on the provided information.

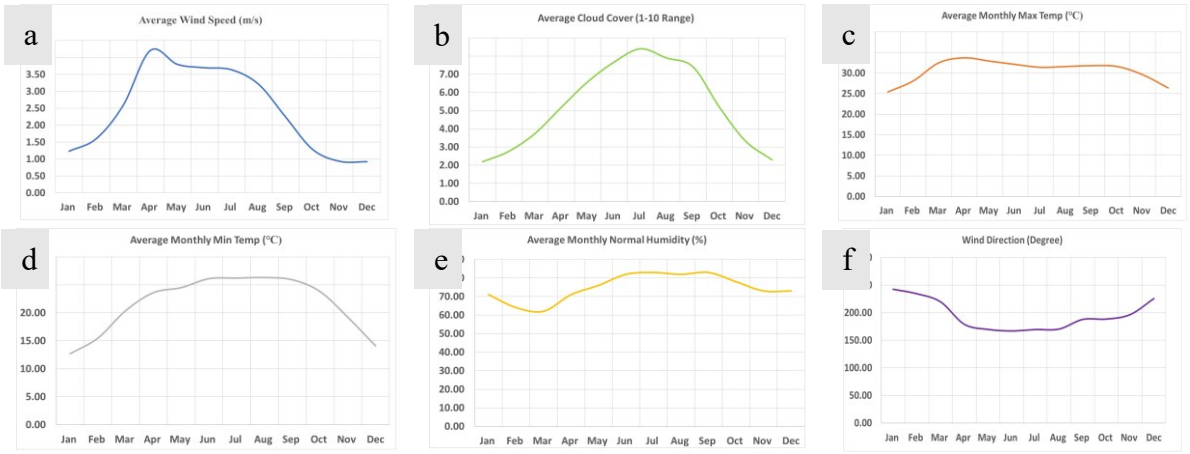


Figure 1: Monthwise all atmospheric input data for the isobutane leakage simulation (a)Average Monthly Wind Speed(m/s); (b)Average Monthly Cloud Cover(1-10); (c)Average monthly Maximum Temperature(ºC); (d) Average monthly Minimum Temperature(ºC); (e) Average Monthly Normal Humidity(%); (f) Average Monthly Wind Direction(º)

2.2 Source Data

A horizontal isobutane storage tank was selected as the leakage source in this study. Tank characteristics including its diameter, length and mass in the tank, the state of the chemical, ambient temperature and the shape inputs were selected based on the information of a standard isobutane storage facility. The inputs for the tank information are listed in the **Table 1**:

Input parameter	***Value***
Diameter	10 ft
Length	15 ft
Mass in the tank	8000 kg
State of chemical in the tank	Liquid

The opening of the isobutane tank causing the leak was considered as a circular hole of 2-inch diameter, which is situated at 2ft above the bottom of the tank.

3. Result & Discussion

3.1 Effect Analysis

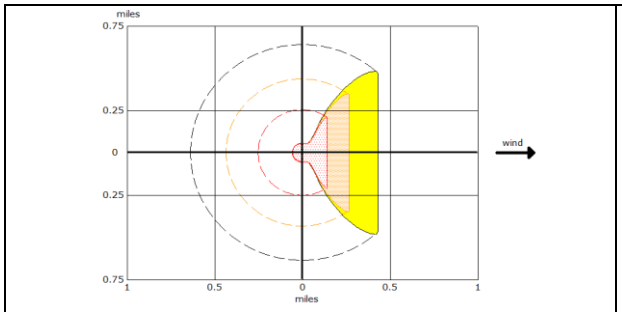
The study reveals that the varying climatic conditions of Bangladesh, particularly temperature and wind speed, significantly impact isobutane gas dispersion during storage tank leaks. Simulations using the ALOHA 5.4.7 model revealed that in winter, toxic, flammable, and overpressure hazard zones expand, increasing risk to nearby areas, while in summer, these zones contract, reducing risk. However, jet fire and BLEVE zones remained stable across seasons. These findings highlight the critical importance of incorporating atmospheric conditions into risk assessments and emergency planning to improve safety and mitigate hazards effectively.

3.1.1. Dispersion & Toxic Effect Analysis

The threat zones for the toxic effects were categorized in different Protective Action Criteria (PAC)- levels, shown in the following Table 2. Under the minimum temperature conditions, the toxic threat zone ranges were generally

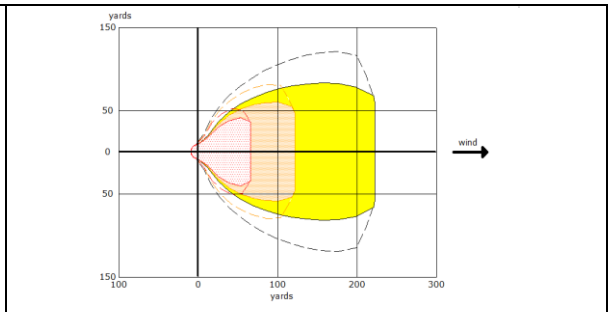
smaller than those at higher temperatures. The greatest toxic threat zone range was recorded in November during the maximum temperature condition [Figure 2(a)], whereas the smallest range was observed in May under the minimum temperature condition [Figure 2(b)].

Table 2: Categorization of toxic threat zones	
Red zone	Concentration greater than 53000ppm (PAC-3)
Orange zone	Concentration greater than 17000ppm (PAC-2)
Yellow zone	Concentration greater than 5500ppm (PAC-1)



Red:247 yards; Orange: 468 yards; Yellow: 759 yards

Figure 2(a): Hightest range of toxic threat zone at maximum temperature in November (shown in miles)



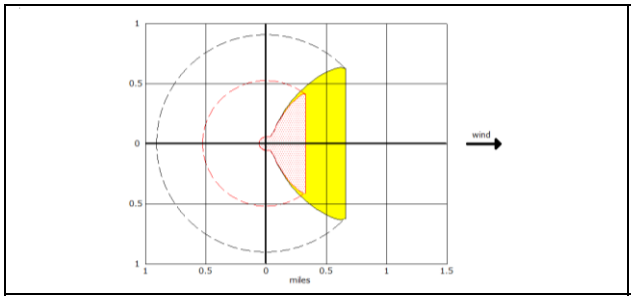
Red: 66 yards; Orange: 122 yards; Yellow: 223 yards

Figure 2(b): Lowest range of toxic threat zone at minimum temperature in May (shown in yards)

3.1.2 Dispersion & Flammability Effect Analysis

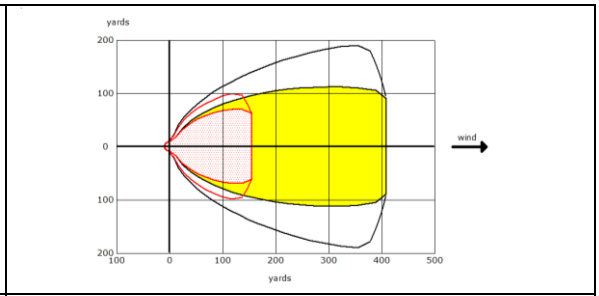
Even when the average concentration is below the Lower Explosive Limit (LEL), the ALOHA simulation considers that a local area of flame can still develop. Aloha uses 60% of the LEL to locate the flammable area. A similar pattern was observed for the flammable threat zone. The largest flammable threat zone range was recorded in November under maximum temperature condition [Figure 3(a)], while the smallest range occurred in May under minimum temperature condition [Figure 3(b)].

Table 3: Categorization of flammable threat zone	
Red zone	Concentration greater than 10800ppm (60% LEL= Flame pockets)
Yellow zone	Concentration greater than 1800ppm (10% LEL)



Red: 575 yards; Yellow: 1161 yards

Figure 3(a): Hightest range of flammable threat zone at maximum temperature in November (shown in miles)



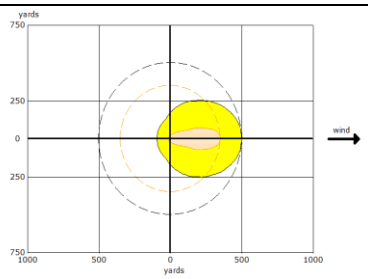
Red: 156 yards; Yellow: 410 yards

Figure 3(b): Lowest range of flammable threat zone at minimum temperature in May (shown in yards)

3.1.3 Dispersion & Blast Effect Analysis

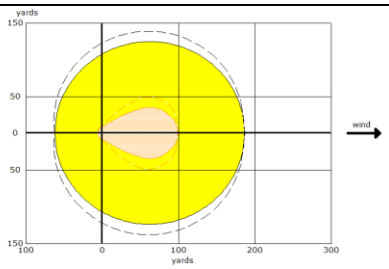
The overpressure (blast) zones are shown in Table 4, the blast pressure zones followed a similar trend, with the widest threat zone range occurring in November at maximum temperature condition [Figure 4(a)], and the narrowest range appearing in May during minimum temperature condition [Figure 4(b)].

Table 4: Categorization of overpressure (blast force) threat zone	
Red zone	Pressure greater than 8.0 psi = destruction of building
Orange zone	Pressure greater than 3.5 psi = serious injury likely
Yellow zone	Concentration greater 1 psi = shatters glass



Red: LOC was never exceeded
Orange: 351 yards; Yellow: 501 yards

Figure 4(a): Hightest range overpressure(blast) threat zone at maximum temperature in November



Red: LOC was never exceeded
Orange: 100 yards; Yellow: 187 yards

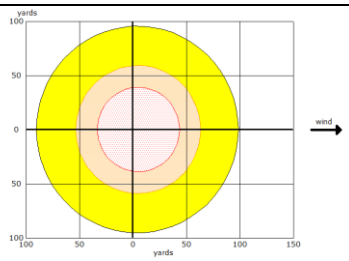
Figure 4(b): Lowest range of overpressure(blast) threat zone at minimum temperature in May

3.1.4 Jet Fire Effect Analysis

A jet fire occurs when a high-pressure release of flammable gas or liquid ignites, producing a strong, directional flame. This can happen when the fuel leaks from a pressurized pipe or vessel, and the gas or liquid burns continuously as long as there is a steady supply [13]. The thermal radiation threat zone ranges, shown in Table 5, for the jet fire, remained nearly consistent throughout the year, with a slight increase in April at maximum at maximum temperature condition, reaching the highest value [Figure 5(a)], and a slight decrease in January during minimum temperature condition, marking the lowest value [Figure 5(b)].

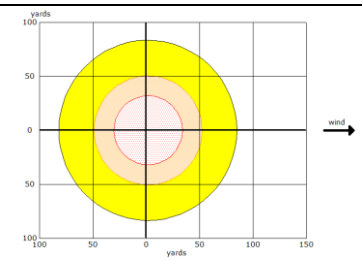
Table 5: Categorization of jet fire thermal threat zone

Red zone	Thermal radiation greater than 10.0 kW/ (sq m) = potentially lethal within 60 sec
Orange zone	Thermal radiation greater than 5.0 kW/ (sq m) = 2nd degree burns within 60 sec
Yellow zone	Thermal radiation greater than 5.0 kW/ (sq m) = pain within 60 sec



Red: 44 yards; Orange: 63 yards; Yellow: 99 yards

Figure 5(a): Hightest range jet fire thermal threat zone at maximum temperature in April

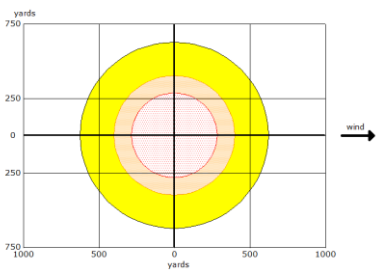


Red: 34 yards; Orange: 52 yards; Yellow: 85 yards

Figure 5(b): Lowest range of jet fire thermal threat zone at minimum temperature in January

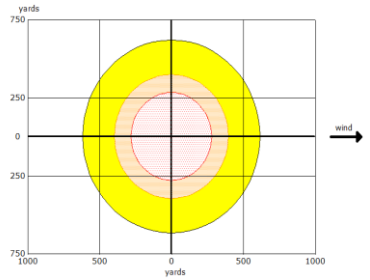
3.1.5 BLEVE Effect Analysis

A Boiling Liquid Expanding Vapor Explosion (BLEVE) is a powerful type of explosion that happens when a container holding a pressurized liquid is exposed to extreme heat or external stress. The liquid inside the container begins to boil rapidly, leading to a buildup of vapor pressure. If the container fails due to this pressure, the liquid rapidly expands and vaporizes, causing a violent explosion [14] For BLEVE, the thermal radiation threat zone, same as Table 5, range was similarly stable throughout the year, with a slight peak in January under maximum temperature condition at its highest value [Figure 6(a)], and a minor dip between July and August at minimum temperature condition, marking the lowest value [Figure 6(b)].



Red:283 yards; Orange:399 yards; Yellow:623 yards

Figure 6(a): Hightest range BLEVE thermal threat zone at maximum temperature in January



Red:280 yards; Orange:396 yards; Yellow:617 yards

Figure 6(b): Lowest range of BLEVE thermal threat zone at minimum temperature in July & August

3.2 Theat Zone Trends Analysis

The threat zone data reveals a similar trend in the change of ranges for both maximum and minimum temperature conditions across the red, orange, and yellow zones. Specifically, the toxic threat zone, flammable threat zone, and overpressure (blast) threat zone displayed a similar pattern of change. The ranges of these three threat zones decreased from January to April, followed by a period of stability or minimal variation from May to August. After August, the ranges expanded until November, and then slightly contracted from November to December. The observed trend suggests that the seasonal variations significantly influence the extent of these threat zones. The most substantial reductions were noted in the first quarter of the year, with the greatest expansions occurring in the final quarter. This pattern underscores the impact of changing environmental conditions on these threat zones. This trend indicates that the threat zones are more expansive during the winter months, posing a heightened risk due to the larger affected areas, while in the summer, the zones contract, resulting in a reduced risk. On the other hand, the jet fire and BLEVE thermal radiation threat zones exhibited a consistent trend throughout the year. The ranges of these zones remained relatively stable with very little or no change in values. This suggests that these specific hazards might be less sensitive to temperature fluctuations compared to the toxic, flammable, and overpressure threat zones.

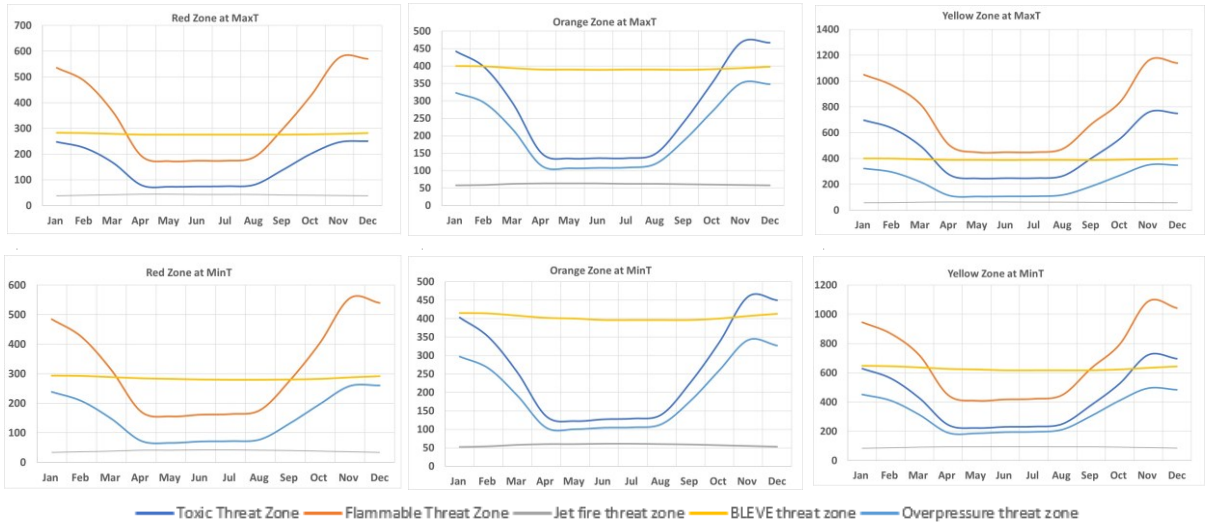


Figure 7: Overall threat zone change trend for all three zones (red, orange, yellow) under maximum & minimum temperature condition across the year

3.3 Analysis of Maximum vs Minimum Temperature Effects

To determine whether the variation between the threat zone ranges at maximum and minimum temperatures is statistically significant or not, paired t-test analysis was conducted between two sets of data at maximum and minimum temperatures for each threat zone including toxic threat zone, flammable threat zone, and overpressure (blast) threat zone, jet fire and BLEVE thermal radiation threat zone.

Table 6: Effects of Maximum & Minimum Temperatures over the Threat Zones

		Mean Difference($\bar{d}$)	**Standard Deviation of Differences (S_d)**	**t-Statistic**	**p-Value**
Toxic threat zone	Red	−106.17	58.62	−6.27	6.06×10^{-5}
	Orange	19.42	13.60	4.95	4.39×10^{-4}
	Yellow	37.33	21.21	6.10	7.78×10^{-5}
Flammable threat zone	Red	26.33	16.52	5.52	1.8×10^{-4}
	Yellow	60.5	30.55	6.86	2.72×10^{-5}
Overpressure (blast) threat zone	Orange	13.58	9.23	5.10	2.9×10^{-4}
	Yellow	16.67	8.85	6.54	3.0×10^{-5}
Jet fire thermal threat zone	Red	2.67	1.15	8.01	< 0.0001
	Orange	3.33	1.49	9.29	< 0.0001
	Yellow	4.67	2.14	7.58	< 0.0001
BLEVE thermal threat zone	Red	-7.58	2.71	-9.69	< 0.0001
	Orange	-10.75	3.73	-9.95	< 0.0001
	Yellow	4.67	2.14	-10.18	< 0.0001

Although Tseng et al. observed minimal temperature effects on toxic substance dispersion in their study[7] ,our statistical analysis showed a different outcome, demonstrated in Table 6. The p-values for all three threat zones

(toxic, flammable, and overpressure) were less than 0.05, rejecting the null hypothesis and confirming that temperature significantly affects these zones. Similarly, temperature variations also had a statistically significant impact on the jet fire and BLEVE thermal radiation zones. These findings emphasize the importance of accounting for atmospheric conditions in hazard simulations, risk assessments and safety protocols to improve emergency response strategies.

4. Conclusion

In conclusion, this study underscores the vital role of atmospheric conditions in influencing the dispersion and hazards associated with isobutane leaks from storage tanks in Bangladesh. Using the ALOHA 5.4.7 model to simulate various release scenarios, we found that temperature and wind speed are key factors determining the size and severity of toxic, flammable, and overpressure threat zones. Specifically, colder winter months result in more expansive hazard zones, increasing risks to nearby areas, while warmer summer months see a contraction of these zones, reducing potential harm. Despite of the fluctuations in climatic conditions, jet fire and BLEVE thermal radiation zones remained relatively stable throughout the year. The statistical significance of these findings, confirmed through paired t-test analysis, highlights the necessity of factoring atmospheric conditions into hazard simulations, risk assessments, and safety protocols. By incorporating seasonal variability, this study emphasizes the importance of timely simulations and proactive emergency planning to mitigate risks and enhance preparedness during isobutane release incidents. The study emphasizes that timely simulations and proper planning could help mitigate the risks by identifying the areas that are susceptible to significant risk during these types of release incidents.

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