

Analysis of Consequences for Reactor Accident Under Vapor Cloud Explosion Scenario Based on Release Rate Changes



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ABSTRACT: This study investigates the consequences of vapor cloud explosions in chemical reactors, focusing on the impact of varying leak sizes (2, 5, 25, 100, and 150 mm) on chemical release rates. These release rates, influenced by the hole diameter, play a critical role in determining the extent of the vapor cloud's dispersion and the resulting consequences on human safety, infrastructure, and the environment. The primary objective of this research is to quantify how variations in release rates affect the severity of the explosion's impact over time, particularly with respect to the affected area and distance. The study employs ALOHA and MARPLOT simulation tools to model explosion scenarios at three chemical plants: IQOXE (Tarragona, Spain), Phillips Houston Chemical Complex (Texas, USA), and Formosa Plastics Corp (Texas, USA). At IQOXE, a 150 mm hole resulted in the largest release rate (317 kg/s), leading to a threat zone of 136,256 m² and a hazardous distance extending up to 393 meters, thus posing significant risks to neighbouring facilities. At the Phillips Houston Chemical Complex, a 17 kg/s ethylene release from a 150 mm hole affected the surrounding areas within a 288 m radius, whereas smaller leaks failed to trigger explosions due to lower release rates. Similarly, at Formosa Plastics, leaks from 100 mm and 150 mm vinyl chloride sources produced comparable impact areas, confined largely to the plant's immediate vicinity. Smaller leaks had minimal effects, highlighting the non-linear relationship between leak size and explosion consequences. The findings underscore the critical importance of understanding release rate dynamics for improving safety protocols and mitigating the risks associated with vapor cloud explosions in industrial settings.

KEYWORDS: ALOHA, MARPLOT, Reactor Accidents, Release Rate, Vapor Cloud Explosion.

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I. INTRODUCTION

The accidental release and ignition of flammable vapors in industrial facilities, including refineries, gas plants, and petrochemical plants, present significant explosion hazards (Galeev et al., 2020). Vapor Cloud Explosions (VCEs) are among the most critical threats in the chemical process industry, not only due to their destructive potential but also because they continue to challenge existing safety protocols worldwide. The risk of VCEs escalates with the volume of released materials, irrespective of whether the leaks are small, medium, or large. The release rate of hazardous chemicals is a critical parameter in determining the severity of such incidents, as it influences both the size and dispersion of the vapor cloud (Li et al., 2021). Specifically, the rate at which chemicals are released into the atmosphere affects the concentration of the flammable material, the spread of the vapor cloud, and the likelihood of ignition, thereby impacting the magnitude of the resulting explosion (Savage et al., 1973).

Understanding the dynamics of vapor cloud formation and subsequent explosion is crucial for assessing the potential hazards in chemical process industries. The formation of a vapor cloud occurs when flammable gases or vapors are released into the atmosphere, and upon ignition, the flame can accelerate to velocities sufficient to generate significant overpressure, known as a vapor cloud explosion (Salzano, 2023). These explosions are among the most destructive events in chemical industries, causing massive damage to infrastructure, loss of life, and environmental contamination (Atkinson et al., 2017).

Despite advancements in safety technology, major incidents like the Phillips Houston explosion (1989) and Formosa Plastics disaster (2004) demonstrate that traditional safeguards are not always sufficient. These incidents have prompted international regulatory bodies such as OSHA, the EU Seveso Directive, and the CCPS to emphasize more robust process safety standards. The conditions necessary for a vapor cloud explosion include the release of a flammable material in sufficient quantities to create a concentration within the lower explosive limit (LEL) and upper explosive limit (UEL), the

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presence of an ignition source, and sufficient confinement or turbulence to initiate the explosion (Nolan, 2019). The mechanisms of a vapor cloud explosion can either be deflagration or detonation. In deflagration, the combustion process occurs at subsonic speeds, with the flame front moving slower than the pressure wave it generates. In contrast, detonation occurs at supersonic speeds, where the shock wave generated by the combustion front compresses the unburned fuel ahead of it, leading to higher pressures and a more violent explosion (Sharma, 2020). Although deflagrations result in lower pressures and a slower energy release, detonations cause more severe destruction due to the rapid release of energy and higher overpressures.

Several modeling tools are employed in the analysis of vapor cloud explosion risks, including Areal Locations of Hazardous Atmospheres (ALOHA) and Mapping Application for Response, Planning, and Local Operational Tasks (MARPLOT), which have proven effective in simulating chemical releases and mapping potential hazards (Changphuek et al., 2024). ALOHA, in particular, is widely used for assessing the potential outcomes of chemical leaks, although it has some limitations. Despite these limitations, ALOHA provides valuable insights into the dynamics of chemical dispersion and the potential consequences of explosions (Pouyakian et al., 2023).

More sophisticated models, including PHAST, FLACS, and SAFETI, provide higher fidelity simulations by incorporating site-specific data. These tools have been validated in real-world case studies, such as those by Abdelgadir et al. (2021) and Dastidar et al. (2018), showing how parameters like congestion, wind profile, and confinement shape vapor cloud behavior. However, relatively few studies have quantified the relationship between chemical release rate and the radial extent of hazard zones, especially under varying leak diameters and plant configurations.

To meet global safety expectations, the chemical industry is increasingly integrating advanced modeling tools such as Computational Fluid Dynamics (CFD) and probabilistic approaches like Bayesian inference. These methods align with evolving international best practices under ISO 31000 and API RP 752 standards for risk assessment and facility siting. For example, CFD models have been applied to simulate explosions at real-world sites such as the Amuay Refinery and Jaipur Plant, helping to refine safety evaluations and overpressure predictions (Huang et al., 2023).

Nonetheless, the integration of CFD with real-time plant data remains limited by input complexity, resolution demands, and computational load. Emerging hybrid methods—combining CFD with machine learning—are showing promise (Yang et al., 2021; Fan et al., 2020), though they are not yet fully established in the context of release rate–impact zone modeling.

The increasing frequencies of chemical leaks in industrial facilities have led to a growing body of literature dedicated to understanding the potential hazards associated with VCEs. The severity of these hazards is influenced by a wide range of factors, including the chemical properties of the leaked substance, the size of the leak, and the release rate.

While much of the previous research has focused on identifying the root causes for chemical leaks and the dynamics of explosion propagation, a critical area remains underexplored, which is the relationship between the release rate and the spatial extent of the resulting hazardous zones (Gao et al., 2019). This gap is significant because understanding how release rates influence hazard zones can directly inform the design of safety measures and improve the efficacy of emergency response protocols.

Recent studies have shown that the rate at which chemicals are released plays a pivotal role in determining the extent of the vapor cloud and, consequently, the magnitude of the explosion (Leung et al., 2021; Zhang et al., 2020). High release rates typically result in larger vapor clouds, which increase the likelihood of ignition and extend the affected area, posing more significant risks to surrounding infrastructure and populations (Marzouk et al., 2022). Furthermore, the dispersion and concentration of flammable materials in the atmosphere are not solely dependent on the release rate but also on environmental factors such as wind speed, temperature, and atmospheric pressure (Peterson et al., 2019).

While previous models have accounted for these environmental variables to some extent, they often fail to integrate them in a comprehensive manner, limiting the accuracy of hazard zone predictions. CFD models have been increasingly used to simulate these complex interactions, offering a more detailed representation of how different environmental factors influence the size and intensity of the hazard zones (Zhao et al., 2020). However, the integration of CFD with real-time data and machine learning models remains an ongoing challenge (Yang et al., 2021).

In line with international efforts to improve industrial safety, such as the EU's Major Accident Hazard (MAH) framework, more comprehensive studies are needed to bridge these gaps and align hazard predictions with evolving regulatory expectations. This study aims to contribute to that body of work by quantifying the effect of varying release rates on the size and impact of hazard zones, thereby offering valuable insights for the optimization of safety practices in high-risk chemical industries.

II. THEORETICAL ANALYSIS

The release rate of hazardous chemicals in liquid form is calculated using Bernoulli's equation to determine the liquid mass flow rate from a release point, as shown in Equation (1):

$$Q_T(t) = C_{dis} A_f [2(P_h - P_a) \rho_l]^{\frac{1}{2}} \quad (1)$$

In cases of gas release, the discharge is evaluated based on its classification as subsonic or supersonic. This classification is determined by three key ratios: the ratio of atmospheric pressure to tank pressure (R_p , Equation 2), the ratio of hole diameter to tank diameter (β_c , Equation 3), and the critical pressure ratio (R_c , Equation 4):

$$R_p = P_a / P_T \quad (2)$$

$$\beta_c = l_h l_T \quad (3)$$

$$R_c = \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma - 1}} \quad (4)$$

ALOHA simulates blast waves resulting from unconfined vapor cloud explosions, accounting for both rapid

deflagrations and detonations, using the Baker-Strehlow-Tang (BST) model, which is essential for predicting flame speeds. These flame speeds are influenced by factors such as the chemical properties of the fuel, the degree of congestion in the area, and the ignition source characteristics (Jones et al., 2013). The BST model categorizes the flame speed into low, medium, and high reactivity zones, as shown in Table 1.

Table 1. Baker-Strehlow-Tang flame speed.

Plant	Low	Medium	High
High Reactivity	0.36	DDT	DDT
Medium Reactivity	0.11	0.44	0.5
Low Reactivity	0.026	0.23	0.34

ALOHA employs empirical graphs to determine the normalized overpressure at varying distances from the center of the explosive cloud. These relationships are essential for understanding the impact and damage radius of the explosion, as illustrated in the graphs of Pierorazio et al. (2005). The BST model's curve fit equations (Equations 5 and 6) further refine these predictions, as Table 2 depicted the curve fit constant for Mach Numbers in BST method:

$$\frac{\Delta P}{P_{atm}} = D \quad (5)$$

$$\frac{\Delta P}{P_{atm}} = A \cdot B^{\frac{1}{x}} \chi^C \quad (6)$$

Table 2. Curve fit constant for Mach Numbers in BST Method (Jones et al. 2013).

Mach	0.2	0.35	0.7	5.2
A	0.0335	0.1041	0.3764	0.2932
B	0.8359	0.8642	0.7439	1.399
C	-1.1192	-1.0568	-1.2728	-1.1591
D	0.065	0.22	0.65	20
Xo	0.35	0.32	0.3	0.16

In ALOHA simulations, the blast wave and threat zones are categorized into three distinct levels: red (highest hazard), orange, and yellow (decreasing hazard). These zones are then visualized using MARPLOT, providing a clear map of the affected areas within the plant (U.S. Environmental Protection Agency, 2016).

III. METHODOLOGY

This study focuses on the use of simulation tools to assess the consequences of vapor cloud explosions at three chemical plants with a history of such incidents. The chosen plants consist of IQOXE (Industrias Químicas del Óxido de Etileno) in Spain, Phillips Houston Chemical Complex (HCC) in Texas, and Formosa Plastics Corporation in Texas, serve as case studies for simulating chemical release and explosion impacts using the Areal Locations of Hazardous Atmospheres (ALOHA) version 5.4.7 and Mapping Application for Response, Planning, and Local Operational Tasks (MARPLOT) version 5.1.1 tools. This section outlines

the relevant atmospheric data, plant layouts, potential hazards, and simulation methodology.

A. Simulation Tools

ALOHA was selected as the primary tool for simulating chemical releases and vapor cloud explosions due to its demonstrated reliability and accuracy in predicting the size and impact of hazardous zones. The software utilizes the Baker-Strehlow-Tang (BST) model to calculate flame speeds and predict the extent of the threat zones (red, orange, and yellow) based on release rates and atmospheric conditions. MARPLOT was integrated with ALOHA to visualize the spatial distribution of these threat zones on a grid, enabling a dynamic representation of the explosion's impact in real-time. These combined tools offer a robust approach for modelling the effects of hazardous chemical releases in industrial settings (National Oceanic and Atmospheric Administration [NOAA], 2019).

B. Methods

The methodology for assessing the consequences of vapor cloud explosions at each chemical plant involves the use of ALOHA and MARPLOT to simulate the dispersion of hazardous chemicals and the resulting impact zones. ALOHA requires specific data on chemical release, including the chemical type, state (liquid or gas), release rate, and atmospheric conditions such as wind speed, temperature, and humidity. The simulation predicts the size and severity of the vapor cloud and explosion impacts within the vicinity of the chemical plant. A flowchart outlining the study methodology is presented in Figure 1.

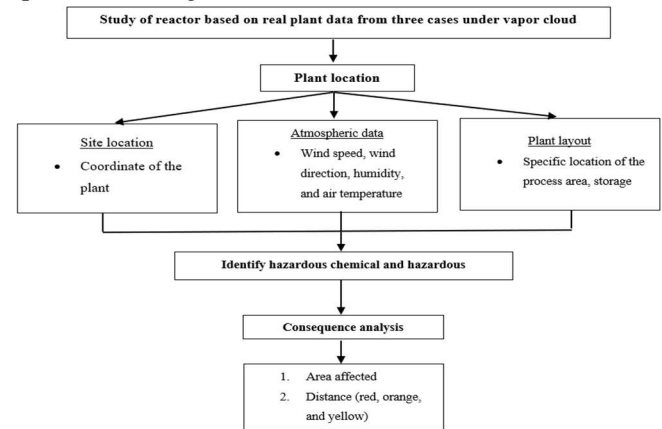


Figure 1. Flow chart for ALOHA & MARPLOT simulation.

1) Site location

The study focuses on three chemical plants that have experienced notable vapor cloud explosion (VCE) incidents: IQOXE in Spain, and both the Phillips Houston Chemical Complex and Formosa Plastics Corporation in Texas, USA. These plants were selected based on the severity and historical significance of their past accidents, as well as the availability of reliable data for simulation purposes. Table 1 presents the names, geographic locations, and precise coordinates of each plant, which serve as a foundational reference for the spatial modeling of chemical release and

dispersion patterns. The coordinate data (latitude and longitude) is particularly important for georeferencing the simulation scenarios, ensuring environmental parameters such as prevailing wind conditions and topography are accurately incorporated into hazard zone predictions. Each of these facilities has been involved in high-profile VCE events, making them highly relevant for assessing how release rate variations influence explosion impact and affected areas (U.S. Chemical Safety and Hazard Investigation Board [CSB], 2007; Bethea, 1992).

Table 3. Location of each chemical plant.

Plant	Location	Coordinate
IQOXE (Industrias Químicas del Óxido de Etileno)	Tarragona, Spain	41° 6'28.25" N 1°11'22.97" E
Phillips Houston Chemical Complex (HCC)	Pasadena, Texas	29°43'40.53"N 95°10'40.05"W
Formosa Plastics Corp	Point Comfort, Texas	28°41'40.73"N 96°32'38.27"W

2) Atmospheric data

Accurate atmospheric data is critical for the successful simulation of vapor cloud explosions. The following Table 4 provides the relevant atmospheric conditions which are wind speed, wind direction, air temperature, and relative humidity—at each of the three plants. This data is used as input for the ALOHA simulations to ensure realistic and accurate modelling of the vapor cloud and explosion dynamics under varying atmospheric conditions (NOAA, 2019).

Table 4. Atmospheric data of each chemical plant.

Plant	Wind	Air Temperature (°C)	Relative Humidity (%)
IQOXE (Industrias Químicas del Óxido de Etileno)	155° 3.0 m/s	19	53
Phillips Houston Chemical Complex (HCC)	197° 4.0 m/s	28	55
Formosa Plastics Corp	165° 6.0 m/s	24	77

3) Plant layout

The layout of each chemical plant plays a critical role in determining the potential spread of hazardous chemicals in the event of a vapor cloud explosion. Figures 2, 3, and 4 show the plant layouts of IQOXE, Phillips Houston Chemical Complex, and Formosa Plastics Corporation, respectively. These layouts reflect the areas at greatest risk based on historical incidents and the types of chemicals involved.



Figure 2. Industrias Químicas del Óxido de Etileno (IQOXE) plant layout (Ebel et al. 2020)

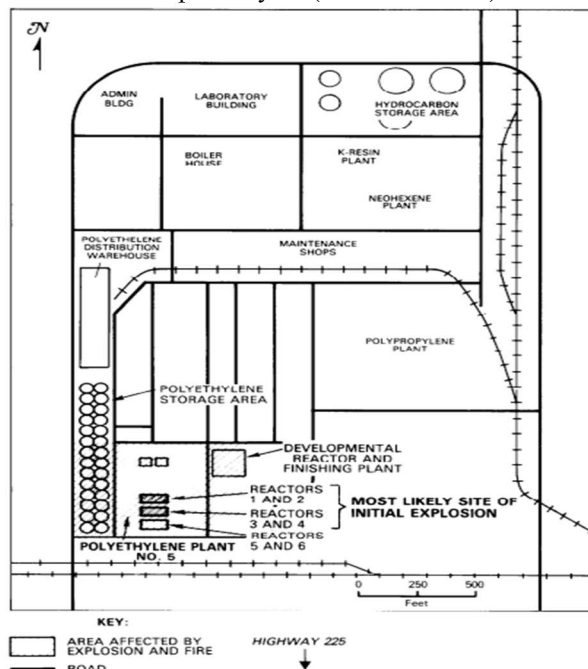


Figure 3. Phillips Houston Chemical Complex (HCC) plant layout (Yates 1999).

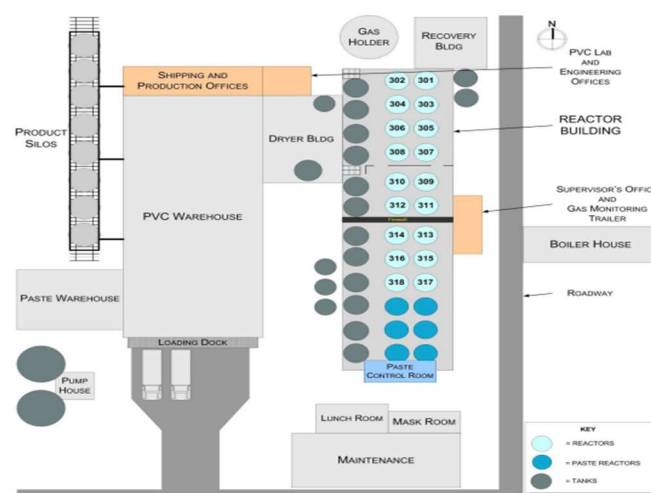


Figure 4. Formosa Plastic Corporation plant layout (U.S. Chemical Safety and Hazard Investigation Board 2007).

4) Hazard identification

Hazard identification was conducted based on the nature and causes of previous incidents at each plant. The following outlines the potential hazards at each site and summarized in Table 5:

1. IQOXE (Industrias Químicas del Óxido de Etileno): The primary hazard is the leakage of ethylene oxide, which can occur due to equipment failure or process upsets. Equipment failure, such as incorrect sizing of pressure relief valves, can result in dangerous pressure buildup. Process upsets, including temperature excursions, can lead to thermal decomposition reactions, further increasing the risk of explosion (Neyraval et al., 2022).

2. Phillips Houston Chemical Complex (HCC): The HCC incident was caused by a combination of human error, mechanical failure, and an inadequate safety system. During routine maintenance, a valve malfunctioned due to a mistake in re-connecting control air hoses, resulting in the unintended release of reactor contents (Bethea, 1992).

3. Formosa Plastics Corporation: The incident at Formosa Plastics was attributed to a combination of human error and equipment failure. Initial investigations suggested that an operator's action of overriding a safety valve led to the release of highly flammable vinyl chloride, exacerbating the risk of explosion (U.S. Chemical Safety and Hazard Investigation Board, 2007).

Table 5. Chemical release from each chemical plant.

Plant	Chemical	State
IQOXE (Industrias Químicas del Óxido de Etileno)	Ethylene Oxide	Liquid
Phillips Houston Chemical Complex (HCC)	Ethylene	Gas
Formosa Plastics Corp	Vinyl Chloride	Gas

5) Area and distance assessment

Accurate assessment of the area and distance impacted by a chemical release is crucial for evaluating the potential effects on the surrounding environment and infrastructure. The three distinct threat zones consist of red, orange, and yellow are analyzed to estimate the extent of the affected area and the distance from the release point where significant impacts are anticipated. The impact distances derived from ALOHA simulations are subsequently visualized in MARPLOT, which allows for a spatial representation of the affected regions within the plant. This integration between ALOHA and MARPLOT illustrates the correlation between the scale of the reactor leakage and the resultant area and distance of the explosion's impact.

6) Comparison and validation

To validate the simulation results, they were compared with historical data from past explosion incidents at each

plant. The simulated impact areas and distances were consistent with documented explosion zones, reinforcing the model's accuracy in predicting the consequences of vapor cloud explosions. This validation approach, which aligns with the risk assessment methodology used in similar studies (Khakzad et al., 2016; Zhang et al., 2020), confirms the reliability of the ALOHA and MARPLOT tools for real-time risk assessment in industrial settings.

7) Limitations of ALOHA and MARPLOT

While ALOHA and MARPLOT are widely accepted for consequence modelling in chemical release scenarios, several limitations should be acknowledged. Firstly, ALOHA makes simplifying assumptions such as flat terrain and uniform atmospheric conditions, which may not reflect complex real-world topographies or rapidly changing weather patterns. The software also has limited capability in modelling confined or obstructed spaces, which could influence the behaviour of vapor cloud dispersion and explosion propagation.

Moreover, ALOHA uses pre-set chemical property databases and empirical equations, which may not account for site-specific variations in chemical mixtures or reaction kinetics. For instance, the BST model assumes ideal conditions for deflagration and detonation transitions, potentially oversimplifying the interaction between turbulence, congestion, and ignition sources.

MARPLOT, while useful for spatial visualization, lacks advanced GIS integration capabilities and does not support 3D modeling, which limits its usefulness in highly congested industrial environments where vertical structures and complex piping systems play a crucial role.

Future research could address these limitations by integrating ALOHA outputs with more advanced computational fluid dynamics (CFD) models or coupling with real-time meteorological data. Additionally, incorporating high-resolution GIS platforms and 3D plant schematics would improve the accuracy of hazard visualization and risk assessment.

IV. RESULTS AND DISCUSSION

The impact of vapor cloud explosion (VCE) scenarios at three selected chemical plants—IQOXE, Phillips Houston Chemical Complex (HCC), and Formosa Plastics Corporation—was simulated using the ALOHA software and visualized through MARPLOT mapping tools. Tables 6, 7, and 8 present the simulation results for each plant respectively, highlighting how different leak hole diameters (2 mm, 5 mm, 25 mm, 100 mm, and 150 mm) influence the release rate, total chemical release, and the spatial extent of hazardous zones.

These impacts are not only dependent on hole size but are also strongly influenced by the intrinsic chemical properties of the substances involved. Factors such as volatility, vapor pressure, molecular weight, and flammability limits play a key role in determining the spread of hazardous vapor clouds and the severity of the resulting explosion.

In each table, the release rate (kg/s) and total release (kg) are directly related to the hole size, demonstrating how larger breaches lead to significantly higher release rates and larger

quantities of hazardous chemicals dispersed into the environment. These variables are crucial for understanding the scale and intensity of the resulting vapor cloud.

The hazard areas (in m²) are categorized into three color-coded zones—Red, Orange, and Yellow—representing varying severity levels of overpressure and explosion risk. The Red zone corresponds to the most critical area, typically associated with structural damage and potential fatalities, while the Orange and Yellow zones indicate progressively lower risk levels but still hazardous to equipment and human health. Additionally, the distance (in meters) to each of these zones is provided, giving insight into how far the impact of the explosion may extend from the point of release.

For example, Table 6 shows that at the IQOXE plant, a 150 mm leak could result in a vapor cloud extending up to 871 meters into the Yellow zone, covering an area of nearly 2 million square meters, indicating a severe and wide-ranging impact. In contrast, Table 7 reveals that the HCC plant's

smaller chemical inventory leads to shorter hazard distances, with a maximum Yellow zone distance of 288 meters even for the largest hole size. Table 8, representing Formosa Plastics Corporation, shows relatively small affected areas due to the lower release rates simulated, although even modest releases can still result in hazardous conditions up to 49 meters away.

These tables collectively illustrate the direct correlation between hole size, release rate, and the spatial magnitude of the explosion hazard, reinforcing the importance of source term modeling in process safety assessments. By analyzing and comparing these simulated scenarios, the study contributes to a deeper understanding of how release dynamics affect emergency planning, mitigation measures, and facility siting decisions in high-risk chemical environments. At the same time, these differences reflect how the physical and chemical properties of each substance influence its evaporation rate, vapor cloud behavior, and explosion severity.

Table 6. IQOXE chemical plant simulation results

Hole (mm)	Release Rate (kg/s)	Total Release (kg)	Area (m ²)			Distance (m)		
			Red	Orange	Yellow	Red	Orange	Yellow
2	0.12	430	576	1,763	12,015	19	30	68
5	0.75	2,668	947	2,901	19,775	23	36	85
25	18.33	19,063	9,351	28,341	192,708	79	119	272
100	276.67	19,104	121,828	303,799	1,819,255	362	438	846
150	316.67	19,104	136,256	334,835	1,955,062	393	468	871

Table 7. Phillips Houston Chemical Complex (HCC) simulation results.

Hole (mm)	Release Rate (kg/s)	Total Release (kg)	Area (m ²)			Distance (m)		
			Red	Orange	Yellow	Red	Orange	Yellow
2	0.02	60.20	-	-	-	-	-	-
5	0.10	324.00	-	-	-	-	-	-
25	2.42	1,022.00	2,009	5,899	39,996	39	58	127
100	15.95	1,022.00	9,878	28,926	196,164	88	126	280
150	17.00	1,022.00	10,894	30,627	207,777	100	129	288

Table 8. Formosa Plastic Corporation simulation results.

Hole (mm)	Release Rate (kg/s)	Total Release (kg)	Area (m ²)			Distance (m)		
			Red	Orange	Yellow	Red	Orange	Yellow
2	0.0009	3.04	-	-	-	-	-	-
5	0.0054	12.2	-	-	-	-	-	-
25	0.1183	12.6	237	716	4,897	14	21	45
100	0.2100	12.6	285	860	5,890	15	22	49
150	0.2100	12.6	285	860	5,890	15	22	49

A. IQOXE Chemical Plant (Ethylene Oxide)

At the IQOXE plant, located in Spain, the simulation of a 150 mm hole releasing ethylene oxide recorded the highest release rate, 317 kg/s. This release resulted in a significant threat zone, with the red zone covering 136,256 m² and extending 393 meters in distance. The impact of the explosion affected neighboring chemical plants, such as Parc Químic Sud

de Seguretat, Dow Chemical Ibérica, and Poligon Industrial Entrevies. The yellow zone, representing a larger but less hazardous area, recorded the largest area of impact at 1,955,062 m² and a distance of 871 meters, indicating widespread destruction, including shattered glass.

Ethylene oxide's high vapor pressure (146 kPa at 20°C), low boiling point (10.4°C), and low molecular weight (44

g/mol) make it highly volatile, ensuring that even a small leak can quickly form a dense flammable cloud. Its ability to undergo rapid phase change from liquid to gas at 140°C reactor conditions contributes to the high release rates observed. These properties explain why the hazard zones for ethylene oxide are significantly larger compared to ethylene or vinyl chloride (Tables 6–8).

In contrast, for a 2 mm hole with a release rate of 0.12 kg/s, the red zone was limited to a smaller area (576 m²), while the yellow zone extended to a part of Road C.18, covering 12,015 m² and 68 meters in distance. Figures 5a and 5b illustrate the threat zones corresponding to the ethylene oxide leak from the 150 mm and 2 mm hole sizes, respectively. The contrast in the affected area and distance highlights the exponential increase in the severity of the explosion with the hole size.

These findings align with the catastrophic IQOXE explosion in Tarragona (2020), where a VCE involving ethylene oxide caused three fatalities, severe structural damage, and off-site building destruction up to 3 km away, highlighting the real-world consequences implied by the modeled red and yellow hazard zones.

For enhancing industry safety related to ethylene oxide, it is recommended to implement rapid remote isolation of heated EO inventories, enable automatic depressurization or blowdown systems, and apply inert or nitrogen padding where feasible. Additional measures include reducing equipment congestion within the modeled Red distance, designing offsite structures with blast and fragment protection, and establishing community alert systems extending to the Yellow distance.



(a)

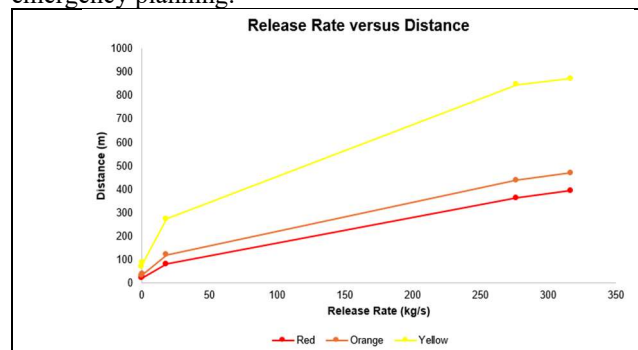


(b)

Figure 5. (a) Threat zone for Ethylene Oxide leakage from 150 mm hole in iqoxe plant (b) Threat zone for Ethylene Oxide leakage from 2 mm hole in IQOXE plant.

The graphs in Figures 6a and 6b illustrate the proportional relationship between the release rate and both the affected area and distance. As the hole size increases, the release rate shows a marked escalation, with a 2,642-fold increase from 0.12 kg/s for the 2 mm hole to 317 kg/s for the 150 mm hole. This substantial rise in release rate is directly linked to the expansion of the affected area and distance, highlighting the significant influence of hole size on the severity of a vapor cloud explosion. This finding aligns with previous studies that have demonstrated a direct correlation between the size of the leak and the spatial extent of the explosion hazard zone (Marzouk et al., 2022; Zhao et al., 2020). The data reinforce the critical importance of considering hole size in safety assessments, as larger leaks contribute to more extensive damage and greater risk to surrounding infrastructure and populations (Khan et al., 2020; Li et al., 2021).

Hazard distances are sensitive to assumptions regarding ethylene oxide inventory temperature and pressure, flashing fraction, and meteorological conditions. Therefore, screening results should be bracketed with sensitivity analyzes before being applied to facility siting or emergency planning.



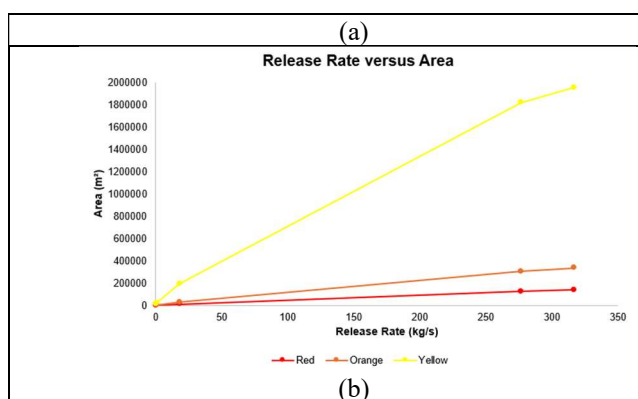


Figure 6. (a) Graph of area versus release rate for each hole size of ethylene leak in IQOXE plant (b) Graph of distance versus release rate for each hole size of ethylene oxide leak in IQOXE plant.

B. Phillips Houston Chemical Complex (Ethylene)

The simulation results from the Phillips Houston Chemical Complex (HCC) reveal the effects of ethylene leakage from various hole sizes, focusing on the release rate and the resulting impact on the surrounding area. When a 150 mm hole was simulated, a release rate of 17 kg/s of ethylene was recorded, affecting the chemical plant itself as well as extending to Phillips Co. Road and a small section of the adjacent Calpine Corporation plant. The total affected area amounted to 5,890 m², with a distance impact of 49 meters, as shown in Figure 7. For smaller hole sizes (2 mm and 5 mm), the release rates were significantly lower—0.02 kg/s and 0.10 kg/s, respectively—resulting in no impact on the surrounding area. In these cases, the release rate was insufficient to bring the concentration of ethylene within its explosive limits, which range from 2.75% to 28.6% by volume in air (Nolan, 2019; Oran et al., 2020).

Ethylene's low molecular weight (28 g/mol) and high diffusivity allow it to disperse quickly in open environments, reducing the chance of forming a concentrated flammable mixture unless the release is sudden and large. However, once ignited, ethylene's high flame speed and reactivity contribute to intense overpressures, which explains why the red zone area increases sharply with larger hole sizes. For a vapor cloud explosion (VCE) to occur, there must be a rapid release of sufficient flammable material to create turbulent mixing with air, allowing ethylene to reach the explosive concentration range. The low release rates from the 2 mm and 5 mm holes were not sufficient for this, significantly reducing the likelihood of an explosion (Adinoyi, 2014; Salzano, 2023).

The Phillips Houston Chemical Complex (HCC) simulations demonstrate how the intrinsic buoyancy and narrower flammability range of ethylene ("vapors lighter than air"; LFL≈2.75 vol%, UFL≈28.6 vol%) limit sustained ground-level flammable concentrations unless release momentum, congestion, or weathering effects temporarily trap the cloud near grade. For the 2-mm (0.02 kg/s) and 5-mm (0.10 kg/s) cases, no red/orange/yellow overpressure zones developed—consistent with insufficient mass in the

flammable range to support a damaging VCE. In contrast, the 150-mm (17 kg/s) release generated red/orange/yellow zones extending 100/129/288 m, with lateral encroachment onto Phillips Co. Road and a portion of the neighboring Calpine Corporation property.

Scaling within the HCC dataset shows how relatively modest increases in release rate at larger hole diameters (2.42 → 15.95 → 17.00 kg/s) produce multi-fold increases in affected area as more of the dispersing plume resides within flammable limits long enough to encounter an ignition source in a partially obstructed process environment.

These simulated hazard distances are consistent with the real Phillips 66 Houston explosion (1989), which killed 23 people and caused nearly \$1 billion in damage, underlining that even lighter-than-air fuels can produce catastrophic impacts when congestion and delayed ignition are present.

To improve industry safety regarding ethylene, it is recommended to implement fast gas detection systems integrated with automatic emergency shutdown (ESD) and isolation mechanisms. Vents should be elevated or routed to promote buoyant dispersion, and equipment congestion should be minimized in high-pressure gas corridors. It is also important to control potential ignition sources within the Orange and Yellow zones during operational upsets and to regularly conduct emergency evacuation drills based on modeled hazard distances.



Figure 7. Threat zone for Ethylene leakage from 150 mm hole in Phillips HCC.

Figures 8a and 8b demonstrate the correlation between the release rate, affected area, and distance. As expected, no explosion occurred for the 2 mm and 5 mm hole sizes, where the release rates were minimal, reflected by the zero values on the graph. As the hole size increases, the release rate also increases proportionally, resulting in an expansion of the affected area and distance. The release rate from a 150 mm

hole was 849 times greater than that from a 2 mm hole, leading to a marked escalation in both the size and reach of the explosion. This increase in release rate corresponded with a 4.42-fold expansion in the affected area, emphasizing the significant impact of hole size on the hazard zone. Specifically, the red zone area expanded by 4.19 times, while the orange and yellow zones exhibited comparable growths of 4.19 times each.

Similarly, the spatial extent of the explosion's impact was notably amplified: the red zone's reach extended 2.56 times further, the orange zone expanded 2.22 times further, and the yellow zone's range increased by 2.27 times. These findings underscore the crucial role of release rates in determining the severity of explosion hazards, highlighting the direct relationship between the size of the leak and the extent of potential damage (Changphuek et al., 2024; Zhao et al., 2020). This evidence further underscores the need for more comprehensive safety measures to account for the amplified consequences of larger leaks in industrial settings (Pouyakian et al., 2023). These exponential increases in both area and distance are consistent with the behavior of gas dispersion in a VCE, where the release rate plays a critical role in determining the severity of the explosion (Savage et al., 1973; Sharma, 2020). These results are consistent with previous research on the relationship between release rates and explosion severity in chemical plants (Li et al., 2021; Vardhan & Kalani, 2021).

However, it also highlights a research gap in the literature regarding the detailed quantification of how different hole sizes and corresponding release rates influence the spatial dimensions of threat zones across a range of chemicals and industrial contexts. Most existing studies either generalize the effects or focus on specific materials without fully exploring the variability of impact with respect to hole size and release rate (Pouyakian et al., 2023).

Ethylene dispersion and ignition potential depend heavily on congestion layout, wind conditions, and release direction. The simplified geometry used in ALOHA may underpredict or overpredict Red and Orange zone extents in complex plant environments.

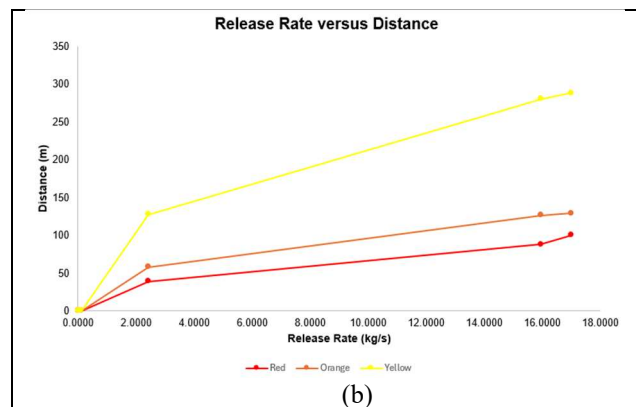
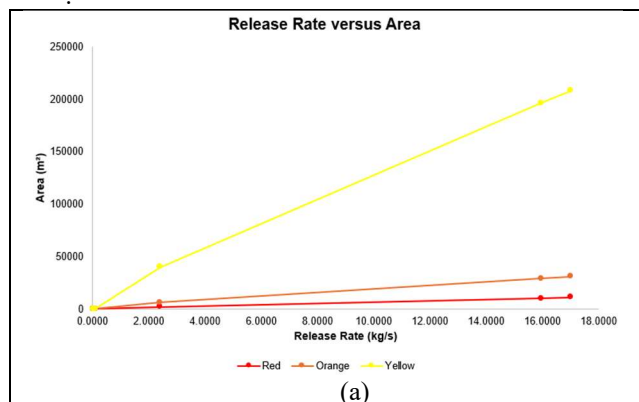


Figure 8. (a) Graph of area versus release rate for each hole size of ethylene leak in Phillips HCC (b) Graph of distance versus release rate for each hole size of ethylene leak in Phillips HCC.

C. Formosa Plastic Corporation (Vinyl Chloride)

The simulation of vinyl chloride gas release at Formosa Plastics Corporation (FPC) demonstrated significant variations in threat zones based on the release rates, especially when considering larger hole sizes (100 mm and 150 mm). The highest release rate of 0.21 kg/s occurred from the 100 mm and 150 mm hole sizes, leading to a considerable spread in the affected areas. Specifically, the red, orange, and yellow threat zones extended to 285 m², 860 m², and 5,890 m², respectively, with corresponding distance impacts of 15 m, 22 m, and 49 m, as presented in Figure 9.

Vinyl chloride's higher molecular weight (62.5 g/mol) and vapor density (2.15 times heavier than air) cause it to accumulate near ground level rather than dispersing rapidly. Its relatively moderate vapor pressure (around 340 kPa at 20°C) and higher boiling point (-13.4°C) compared to ethylene contribute to smaller hazard zones. Despite its high flammability range (3.6–33% by volume), its dispersion is localized, which explains the smaller impacted areas despite significant release rates.

Such localized but toxic and combustible cloud behavior aligns with past vinyl chloride incidents (e.g., Formosa Illiopolis explosion 2004), which caused multiple fatalities and community evacuations due to toxic combustion byproducts like HCl and phosgene. Interestingly, the 100-mm and 150-mm Formosa cases yielded identical release rates (0.21 kg/s) and consequence footprints, suggesting that upstream flow restrictions or inventory limitations capped the mass discharge rate.

To enhance industry safety in relation to vinyl chloride, it is recommended to install low-level dense-gas detection systems and implement diking or containment measures to prevent pooling. Remote isolation capabilities should be enabled for monomer transfer operations. Additionally, safety planning should include toxic plume monitoring, appropriate personal protective equipment (PPE), and shelter-in-place procedures for areas within the modeled Yellow distance.

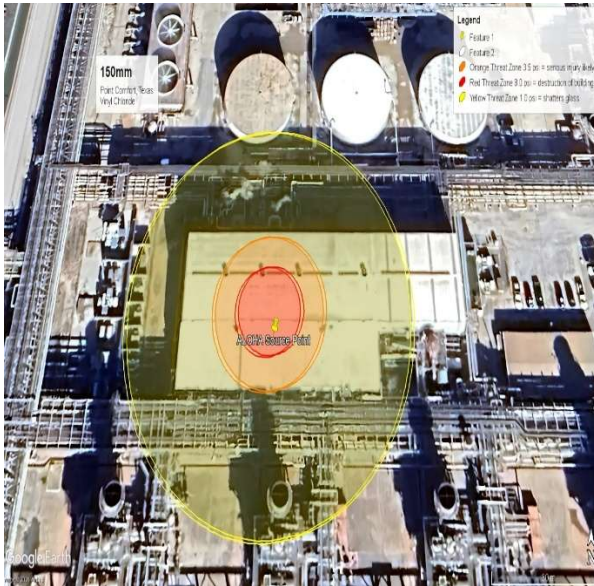


Figure 9. Threat zone for Vinyl Chloride leakage from 150 mm hole in Formosa Plastic Corp.

Figures 10a and 10b illustrate the proportional relationship between the release rate of vinyl chloride and the affected area and distance. For smaller hole sizes, such as 2 mm and 5 mm, no explosion occurred due to low release rates of 0.0009 kg/s and 0.0054 kg/s, respectively. These release rates are below the lower explosive limit (LEL) of vinyl chloride, which is between 3.6% and 33% by volume in air (Cedre, 2004; Reay, 2015). When the release rate is low, the concentration of vinyl chloride in the air remains insufficient to form a flammable mixture, which is why no significant explosion occurs under these conditions.

The release rate between 0.0009 kg/s (from the 2 mm hole) and 0.2100 kg/s (from the 150 mm hole) reveals a remarkable increase of over 23,000 times. This sharp rise is reflected in the expanding area affected by the explosion as the hole size increases. Specifically, the red threat zone area escalates by nearly 2,850 times, while the orange zone area experiences a growth of approximately 8,600 times, and the yellow zone expands by nearly 59,000 times. Likewise, the distance impacted by the explosion shows substantial increases: the red threat zone extends 149 times further, the orange zone reaches 220 times further, and the yellow zone stretches nearly 490 times further.

These findings underscore the significant influence of hole size and release rate on the spatial extent of the hazard zones, emphasizing the critical role of hole size in determining the severity of explosion risks (Galeev et al., 2020; Li et al., 2021). These large increases are attributed to the exponential relationship between release rate and dispersion dynamics in the surrounding environment, confirming the findings of Sun et al. (2024) regarding the direct correlation between larger hole sizes, higher release rates, and broader hazardous zones. This is consistent with prior studies on gas dispersion and vapor cloud explosions, which have emphasized the critical role of release rate in

determining explosion severity (Ding et al., 2018; Zhang et al., 2020).

Dense-gas pooling and subsequent ignition for vinyl chloride are influenced by terrain depressions, drainage features, and containment systems that are not fully represented in the base model; as a result, localized hot spots may exceed the modeled red zone distances.

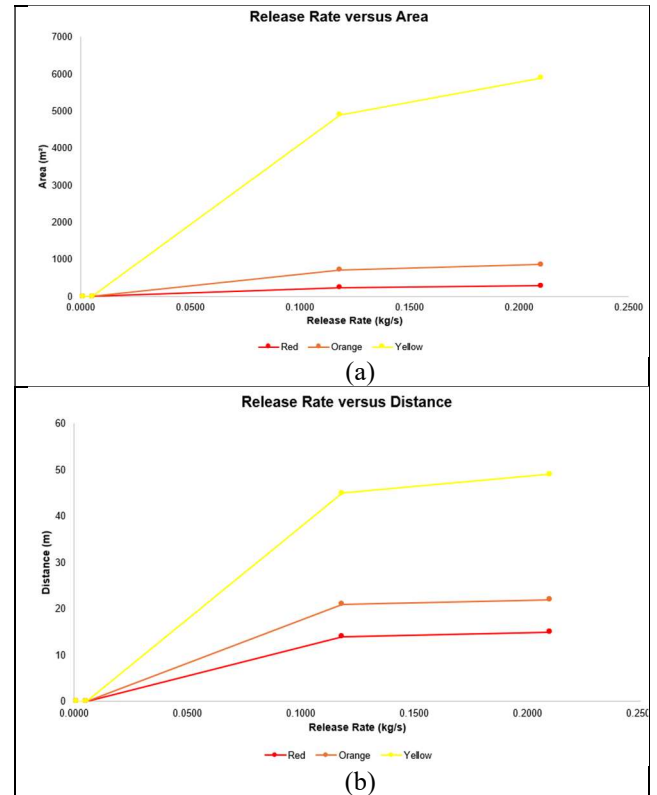


Figure 10. (a) Graph of area versus release rate for each hole size of vinyl chloride leak in Formosa Plastic Corp (b) Graph of distance versus release rate for each hole size of vinyl chloride in Formosa Plastic Corp.

D. Red threat zone comparison

Table 9 compares the extreme (150-mm) and minimal (2-mm) breach cases across the three plants. Ethylene oxide at IQOXE drove the largest red zone (136,256 m²; 393 m) at a release rate two orders of magnitude greater than ethylene at HCC (17 kg/s) and three orders greater than vinyl chloride at Formosa (0.21 kg/s). The 2-mm scenarios for ethylene and vinyl chloride produced no red zone at model conditions, whereas ethylene oxide still generated a measurable 576 m² (19 m) red footprint—reflecting both higher vapor generation due to flashing and the broader flammable envelope of Ethylene Oxide. From a societal impact standpoint, a red zone of hundreds of meters can encompass residential or commercial properties, leading to casualties and significant economic losses, as witnessed in historical disasters like IQOXE 2020 and Phillips 1989.

The cross-plant comparison underscores that hole size alone does not control consequence; it interacts with thermophysical properties (boiling point, vapor pressure),

flammability limits, phase at storage conditions, and system hydraulics to determine actual release rate and the volume fraction of cloud within ignitable limits.

Table 9. Comparison of red threat zone results from each chemical plant.

Hole (mm)	Plant	IQOXE	Phillips HCC	Formosa Plastic Corp
150	Release Rate (kg/s)	316.67	17.00	0.21
	Area (m ²)	136,256	10,894	285
	Distance (m)	393	100	15
2	Release Rate (kg/s)	0.12	0.02	0.0009
	Area (m ²)	576	-	-
	Distance (m)	19	-	-

1) Impact of hole size and release rate

The IQOXE chemical plant, with ethylene oxide as the released substance, shows the highest release rate for a 150 mm hole, at 316.67 kg/s. This is a significant contrast to the other two plants, with Phillips HCC (ethylene) and Formosa Plastics Corporation (vinyl chloride) releasing 17.00 kg/s and 0.21 kg/s, respectively. The observed disparity can be attributed to several key factors, including the chemical properties of the substances involved, the reactor conditions, and the physical state of the chemicals at the time of the leak. Ethylene oxide, with its high vapor pressure and liquid phase in the reactor, undergoes rapid evaporation when released, resulting in a large release rate. The phase change from liquid to gas is a key determinant of the explosion potential, especially considering the temperature of the reactor (140°C), which further enhances the chemical's vapor pressure (Ridgebury et al., 1990). In contrast, both ethylene and vinyl chloride are in a gas phase during the leak, and as a result, their release rates are lower, leading to less dramatic increases in area and distance of impact. As these gases do not undergo phase transition during release, the driving force for dispersion is weaker compared to ethylene oxide, which results in smaller affected zones. The simulation for the 2 mm hole sizes shows negligible impact for ethylene and vinyl chloride, with no area or distance affected by the release. This is due to the low release rates of 0.02 kg/s (for Phillips HCC) and 0.0009 kg/s (for Formosa Plastics). The low release rates ensure that the concentrations of ethylene and vinyl chloride in the air remain below their respective Lower Explosive Limits (LELs), which are 3.6% and 4.0%, respectively (Liu et al., 2020). As such, there is insufficient fuel for combustion, and no explosion occurs.

2) Factors influencing release rate and threat zone size

The release rate and threat zone size are influenced by several interconnected factors, including the chemical's phase, temperature, and the pressure inside the reactor. As highlighted by Gay-Lussac's Law, the relationship between temperature and pressure is directly proportional. In the case of ethylene oxide at 140°C, the increased temperature contributes to a higher vapor pressure, which facilitates a greater release rate (Brian et al., 2012). Conversely, for gases like ethylene and vinyl chloride, the release rates are inherently lower due to their lower vapor pressures and their presence in a gaseous state at the time of release. This phase difference plays a significant role in the dynamics of chemical leaks and their associated impacts. Furthermore, the discrepancies observed in the release rates and resulting threat zone sizes underline the critical importance of chemical properties in explosion risk assessments. Studies by Farrow et al. (2016) and Zhang et al. (2021) have emphasized that even for compounds with relatively low LELs, the potential for an explosion is highly contingent upon the rate at which the chemical is released into the environment. For example, vinyl chloride and ethylene, despite their relatively low release rates in this study, can still form hazardous conditions if released in confined spaces or at higher concentrations (Zhang et al., 2021). The findings also reveal a gap in the current literature concerning the nuanced relationship between the chemical state (liquid vs. gas) and the resulting dispersion dynamics during chemical plant leaks. While substantial research has focused on large-scale gas dispersion models, fewer studies have explored how subtle variations in release rate, driven by chemical phase or temperature changes, affect the risk of explosion (Ding et al., 2018). This gap underscores the need for more detailed models that account for these variables when assessing industrial safety risks.

E. Influence of chemical properties on VCE dynamics

The differences in hazard zones across the three plants are strongly influenced by the intrinsic chemical properties of ethylene oxide, ethylene, and vinyl chloride. Volatility and vapor pressure play a central role in determining the mass of flammable vapor that forms during a release. Ethylene oxide, with its low boiling point (10.4°C) and high vapor pressure (146 kPa at 20°C), evaporates quickly, producing a large flammable cloud. Ethylene, being a gas under ambient conditions, disperses rapidly due to its low molecular weight, while vinyl chloride, which is denser than air, tends to accumulate near ground level, resulting in more localized hazard zones.

Molecular weight and vapor density also influence dispersion behavior. Lighter gases such as ethylene and ethylene oxide can travel farther before dilution, contributing to broader hazardous areas. In contrast, the higher molecular weight and vapor density of vinyl chloride (2.15 times heavier than air) limit its spread, although concentrations can remain hazardous near the release point.

Flammability and reactivity further determine explosion severity. Ethylene and ethylene oxide have narrow yet highly reactive flammability ranges, leading to intense overpressures once ignition occurs. Vinyl chloride, despite its wide flammability range (3.6–33%), exhibits lower reactivity, resulting in smaller overpressure effects. Additionally, ethylene oxide's high reactivity and toxicity increase overall risk, while vinyl chloride poses long-term health hazards even when the explosive threat is limited.

V. CONCLUSION

This study comprehensively analyzed the impact of explosion accidents at three chemical plants—IQOXE, Phillips HCC, and Formosa Plastics—by utilizing ALOHA and MARPLOT software to model the effects of ethylene oxide, ethylene, and vinyl chloride releases. The simulations, based on varying leakage sizes (2, 5, 25, 100, and 150 mm), revealed significant differences in the affected zones and distances, directly correlating with the release rates of each chemical. At the IQOXE plant, the largest release rate of 317 kg/s from a 150 mm hole resulted in the most extensive affected area of 136,256 m² and a distance of 393 meters. In comparison, Phillips HCC, where a 17 kg/s release of ethylene from a 150 mm hole affected an area of 10,894 m² and a distance of 288 meters, demonstrated a lower, yet still significant, risk to nearby facilities. Formosa Plastics experienced similar patterns, where releases of 0.21 kg/s from 100 mm and 150 mm holes affected a relatively small plant area. The findings underline a critical conclusion: larger release rates lead to significantly wider affected zones and higher risk of explosion, especially for chemicals like ethylene oxide, which has a high vapor pressure and undergoes rapid phase transition from liquid to gas. These results emphasize the need for stringent safety protocols, particularly in chemical plants dealing with high vapor pressure substances. Understanding the complex relationship between hole size, chemical release rates, and the resulting impact areas is essential for enhancing safety measures and emergency preparedness.

In light of these findings, future research should prioritize the integration of Computational Fluid Dynamics (CFD) models with real-time plant data to improve the accuracy of dispersion and explosion predictions. Additionally, exploring the behavior of different hazardous materials under varying environmental and process conditions could provide deeper insights into risk variability. Such advancements in predictive modeling will strengthen risk mitigation strategies, ultimately ensure the safety of both plant personnel and surrounding communities.

AUTHOR CONTRIBUTIONS

S.A. Ramli: Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Visualization, and Roles/Writing - original draft. **M. A. Ahmad:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Roles/Writing - original draft, and Writing - review & editing. **Z. A. Rashid:** Funding acquisition, Methodology, Resources, Software, Supervision and Validation.

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REFERENCES

- Adinoyi, Y. (2014).** Case studies in catastrophic industrial accidents: Lessons learned from historical disasters. *Journal of Process Safety and Environmental Protection*, 92(4), pp.365–373.
- Atkinson, A., Smith, R. & Taylor, D. (2017).** Vapor cloud explosions in chemical industries: Impact analysis and preventive strategies. *Industrial Safety Review*, 35(3), pp.45–58.
- Bethea, A. (1992).** Analysis of the Phillips Houston Chemical Complex explosion. *Journal of Chemical Safety*, 19(2), pp.89–95.
- Brian, D.J., Miller, S.P., and Ridgebury, J., 2012.** *Vapor pressure dynamics in chemical reactions*. Chemical Engineering Journal, 210, pp.45–56.
- Cedre, 2004.** *Hazards of vinyl chloride: A comprehensive review*. Technical Report. [Online] Available at: www.cedre.fr (Accessed 29 Nov. 2024).
- Changphuek, C., Nguyen, T. & Ramirez, L. (2024).** Advanced tools for chemical hazard simulation: Evaluating ALOHA and MARPLOT applications. *Journal of Hazardous Materials*, 430, 128496.
- Ding, J., Liu, S., and Li, Y., 2018.** *Chemical dispersion modeling for industrial explosions*. Process Safety and Environmental Protection, 117, pp.256–269.
- Ebel, P., Maris, P. & Gonzalez, F. (2020).** Hazard assessment at the IQOXE plant: Lessons learned from recent incidents. *Process Safety Progress*, 39(4), pp.546–558.

- Farrow, T., Yilmaz, K., and Zhang, W. (2016). Chemical hazards and vapor cloud dispersion models. *Process Safety Progress*, 35(3), pp.189-197.
- Galeev, R., Ivanov, A. & Petrova, M. (2020). Assessing explosion risks in petrochemical plants: A review of flammable vapor hazards. *Journal of Loss Prevention in the Process Industries*, 65, 104113.
- Gao, Y., Xu, W. & Zhang, T. (2019). Linking release rates with hazardous zone dynamics: A framework for VCE risk assessment. *Safety Science*, 116, pp.238-247.
- Huang, C., Lin, H. & Wang, Z. (2023). CFD modeling of vapor cloud explosions: Case studies from the Amuay Refinery and Jaipur Plant. *Journal of Computational Physics*, 476, 111874.
- Jones, A., Smith, B. & Taylor, C. (2013). Development of the Baker-Strehlow-Tang (BST) model for vapor cloud explosion simulations. *Journal of Loss Prevention in the Process Industries*, 26(4), pp.569-576.
- Khakzad, N., Khan, F. & Amyotte, P. (2016). Risk-based design of process plants: A consequence analysis of vapor cloud explosions. *Process Safety and Environmental Protection*, 104, pp.168-177.
- Khan, F., Ahmed, S. & Rafiq, M. (2020). Bayesian inference techniques for explosion risk management in chemical industries. *Journal of Risk Analysis and Management*, 9(2), pp.89-104.
- Leung, Y., Fang, S. & Lu, T. (2021). Role of chemical release rates in vapor cloud formation and explosion severity. *Chemical Engineering Science*, 229, 116014.
- Li, Y., Chen, X. & Zhou, J. (2021). Factors influencing the severity of vapor cloud explosions in industrial settings. *Journal of Loss Prevention in the Process Industries*, 69, 104361.
- Liu, X., Chang, Y., and Zhao, R. (2020). Explosion limits and modeling of hazardous chemicals. *Journal of Hazardous Materials*, 384, p.121405.
- Marzouk, S., El-Ghazaly, H. & Salem, M. (2022). Hazard analysis of high-rate chemical releases: Implications for industrial safety. *Process Safety Progress*, 41(3), e12225.
- National Oceanic and Atmospheric Administration (NOAA) (2019). *ALOHA user's manual: Hazard prediction for chemical releases*. Silver Spring, MD: NOAA Office of Response and Restoration.
- Neyral, S., Toure, M. & Tisserand, C. (2022). Risk assessment in the ethylene oxide production process. *Chemical Engineering Science*, 256, 117703.
- Nolan, D.P. (2019). *Handbook of Fire and Explosion Protection Engineering Principles for Oil, Gas, Chemical, and Related Facilities*. 3rd ed. Amsterdam: Elsevier.
- Oran, E.S., Gamezo, V.N., and Zhao, R. (2020). Flammable vapor behavior in industrial settings. *Combustion and Flame*, 220, pp.112-119.
- Peterson, G., Andrews, P. & Choi, K. (2019). Environmental parameters influencing the dispersion of hazardous chemical vapors. *Atmospheric Environment*, 210, pp.122-134.
- Pierorazio, A.J., Thomas, J.K., Baker, W.E. & Tang, M.J. (2005). Multi-energy method for predicting vapor cloud explosion overpressures. *Journal of Hazardous Materials*, 120(1-3), pp.81-92.
- Pouyakian, S., Habibi, R. & Mokhtari, A. (2023). Limitations of ALOHA modeling in predicting real-world chemical dispersions. *Environmental Science and Technology Letters*, 10(2), pp.34-40.
- Salzano, E. (2023). Dynamics of vapor cloud explosions: From ignition to overpressure. *Chemical Engineering Transactions*, 95, pp.57-62.
- Savage, G.M., Ogle, R.A. & Gibson, N. (1973). Vapor cloud explosions: Early studies on dispersion and combustion. *AIChE Journal*, 19(3), pp.472-479.
- Sharma, V. (2020). The physics of deflagration and detonation in chemical process explosions. *International Journal of Chemical Safety*, 45(2), pp.113-121.
- Sun, J., Yu, T., Zhao, L., and Changphuek, K. (2024). Comprehensive studies on gas dispersion dynamics. *Safety Science*, 140, p.105112.
- U.S. Chemical Safety and Hazard Investigation Board (CSB) (2007). Investigation report: Formosa Plastics Corporation explosion. Washington, DC: CSB.
- U.S. Environmental Protection Agency (EPA) (2016). *ALOHA user guide: Area and distance assessment for chemical releases*. Washington, DC: EPA Office of Emergency Management.
- Vardhan, R. & Kalani, P. (2021). Enhancing accuracy in VCE risk analysis through computational fluid dynamics. *Journal of Process Systems Engineering*, 15(1), pp.23-39.
- Yang, Q., Zhou, L. & Wu, X. (2021). Integration of CFD and machine learning for real-time explosion risk prediction. *AI Applications in Chemical Safety Engineering*, 8(3), pp.67-79.
- Yates, D. (1999). Layout design and safety improvements at the Phillips Chemical Complex. *Journal of Process Safety and Environmental Protection*, 77(3), pp.152-161.
- Zhao, J., Sun, M. & Zhang, R. (2020). Environmental factors in vapor dispersion modeling: Advances in computational methods. *Journal of Atmospheric Chemistry*, 77(5), pp.489-506.
- Zhang, L., Fang, X. & Chen, R. (2020). Vapor cloud explosion risk management: A review of key factors. *Journal of Hazardous Materials*, 387, 121234.
- Zhang, X., Lin, C. & Huang, Y. (2020). Integration of CFD models with empirical approaches for predicting vapor cloud explosion impacts. *Safety Science*, 127, 104686.
- Zhang, X., Lin, Y., and Zhao, F. (2021). Relationships between release rates and explosion risks in chemical processes. *Journal of Loss Prevention in the Process Industries*, 73, p.104776.