Original Article

Consequence Analysis and Safety Assessment of an Ethylene Oxide Unit in a Petrochemical Complex

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Abstract

Aim: This study focuses on the consequence analysis and safety assessment of an ethylene oxide (EO) unit in a petrochemical complex. This study evaluates the potential consequences of process accidents in the tankage, tank truck loading, and cylinder filling areas of an EO unit. **Methods:** The analysis was conducted using DNV's PHAST software (2023), which models and quantifies the consequences of chemical releases by considering various factors such as material characteristics, storage tanks, weather conditions, and the number of people at risk. This study considers scenarios such as fire, flammable and toxic gas dispersion, and vapor cloud explosion. **Results:** The results provide insights into the safety measures and precautions required in different areas of the petrochemical complex. The analysis of hazard zones allows for the prioritization of protective measures and ongoing monitoring of operational hazards. **Conclusion:** This study provides a comprehensive assessment of the consequences and risks associated with the use of the EO unit in a petrochemical complex.

Keywords: Consequence analysis, ethylene oxide, petrochemical complex, PHAST, safety assessment

INTRODUCTION

Risk encompasses all potential factors that may pose a threat to the integrity of a process, system, or project.[1] The initial phase of risk assessment involves the identification of potential risks and hazards within the process.[2] Despite extensive preventive measures implemented within industries such as oil, gas, and petrochemicals, the risk of various accidents, including fire, explosions, and gas leaks, remains inherent.[3] The outcomes derived from risk identification, modeling, and assessment, along with the resultant scenarios and the influence of meteorological variables, assume a pivotal role in risk management.[4] At present, risk management finds application not solely within the chemical and oil sectors but also across numerous organized human endeavors such as economic activities and large-scale construction projects.[5,6]

In many petrochemical procedures, the utilization of ethylene oxide (EO) as a catalyst is imperative. It serves as a crucial element in the synthesis of various petroleum derivatives, including ethylene, glycol (a primary ingredient in antifreeze), polyethylene oxide, monoethylene glycol ethers, amino derivatives, surface-active agents, lubricants, and plasticizers.[7,8] Unfortunately, instances of uncontrolled temperature elevation, resulting in plant shutdowns, are prevalent in the ethylene epoxidation process. These occurrences often lead to the combustion of both the reactor and catalyst, compromising their functionality. Failure to promptly enact effective emergency procedures may escalate the situation to a severe explosion.[9]

Due to its considerable toxicity, EO poses significant risks to human health and safety, capable of causing catastrophic accidents resulting in casualties, extensive damage, and destruction across wide distances under acute operational conditions. Studies focusing on EO's occupational hazards,

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particularly its respiratory effects, reveal a notable decline in lung function even at low exposure levels. Moreover, owing to its potent explosive properties and propensity for leakage, EO gas explosions can lead to fatalities and substantial disasters.[10,11] The insufficient evaluation of safety risks associated with EO units within petrochemical complexes presents a substantial hazard to public safety and environmental integrity. Current research fails to provide a comprehensive understanding of the potential outcomes of accidental releases, impeding the formulation of effective emergency response plans (ERPs) and risk mitigation strategies. Addressing this knowledge gap is imperative to safeguard the well-being of workers, communities, and ecosystems surrounding petrochemical facilities.

Predicting the behavior of hazardous chemicals released from storage tanks and assessing the resulting damages from fires and explosions hold significant importance.[12] Consequence modeling methods are utilized to ascertain the potential hazards associated with the ignition and explosion of hazardous substances. These methods involve simulating the release and dispersion of materials into the environment and forecasting the repercussions of fire or explosion incidents.[13] Various software packages exist for modeling explosions and fires and assessing their impacts. However, many of these software solutions lack sufficient flexibility due to the extensive computational requirements, time-intensive implementation processes, and limited ability to perform multifaceted tasks.[14,15]

The PHAST software is specifically designed for modeling incidents within chemical processes and assessing their repercussions. It excels in predicting the intricate consequences of accident scenarios resulting from chemical releases from storage tanks. By incorporating various factors such as material properties, tank characteristics, terrain elevations, and meteorological conditions, PHAST quantifies and models the potential outcomes of hazardous substance releases. The software's modeling capabilities aid in determining critical parameters such as the radius of fire and explosion, extent of damage inflicted by the incident, pressure exerted by the blast wave, population at risk, and the establishment of safe zones surrounding the chemical spill site.[16,17]

There exists a pressing demand for methodologies to conduct consequence analysis and safety assessments of EO units within petrochemical complexes, with the aim of bolstering emergency preparedness and response capabilities. This study offers invaluable insights for evidence-driven emergency response planning, comparative risk assessments, and the formulation of efficacious mitigation strategies to alleviate the potential hazards stemming from chemical releases within petrochemical complexes. The primary objective of this study was to assess the consequences of process-related accidents occurring in the tankage, tank truck loading, and cylinder filling zones within the EO unit of a petrochemical complex.

MATERIALS AND METHODS

The study was carried out in 2023 within a petrochemical industry located in southern Iran. Its objective was to assess the repercussions of process-related accidents occurring within the tankage, tank truck loading, and cylinder filling zones of the EO unit within a petrochemical complex. To achieve this goal, the potential severity of incidents was modeled and analyzed using DNV's PHAST 8.2 software package, adhering to criteria outlined in "TOTAL GS EP SAF 253: Fire Zone, Restricted and Impacted Area."

Consequence modeling and analysis involve the computation or estimation of numerical values (or graphical representations) that depict the plausible physical outcomes resulting from loss-of-containment scenarios involving flammable, explosive, and toxic substances, considering their potential impact. Various conditions and scenarios within certain facilities may precipitate unintended releases that, given specific conditions, could escalate into significant accidents, posing risks to employee safety, neighboring residents, property, and the environment. To assess the consequences of such accidents, several tasks need to be undertaken. Figure 1 offers a concise outline of the steps involved in consequence modeling and analysis, with detailed information provided in subsequent sections.

RESULTS

Weather data

In this study, four distinct weather categories were examined, derived from site-specific meteorological data. The raw weather data utilized in the consequence analysis study were sourced from the meteorological station. Annual averages of key meteorological parameters were employed, and atmospheric stabilities were determined based on the Pasquill–Gifford Stability Classes. Table 1 illustrates the meteorological categories for both day and night periods, as per the plant meteorological data. Each category is delineated by the characteristic wind speed in meters per second, followed by the corresponding atmospheric stability class.

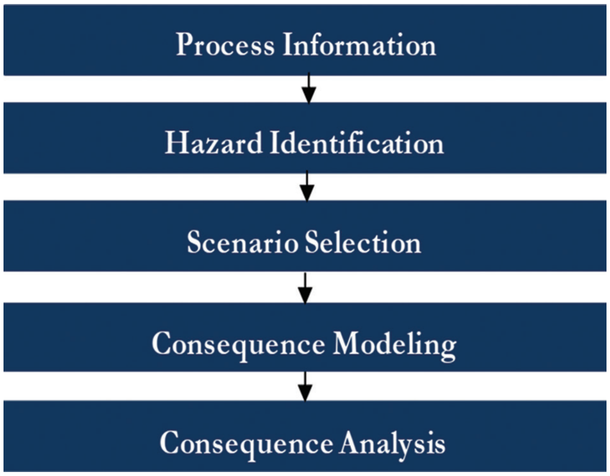

Figure 1: Consequence modeling and analysis flow diagram

Figure 2 displays the wind rose of the Mahshahr meteorological station, providing information on weather conditions and the frequencies associated with each wind direction.

Scenarios

For all installations examined in this study, investigations into fire propagation, flammable material dispersion, and toxic gas dispersion were conducted, focusing on scenarios involving significant quantities of flammable, combustible, and toxic substances. Details regarding scenario data are provided in Table 2.

For overpressure calculations, any module or the largest confined (or congested) space within the fire zone should be considered half-full or full of gas at stoichiometric concentration, depending on the scenario. Specifically, for the fire zone, the congested space should be considered half-full, while for the restricted and impacted area, it should be considered full of gas at stoichiometric concentration. This assumption holds true regardless of whether the flammable gas cloud extends beyond the confined space. In such cases, the flammable air-gas mixture at stoichiometry is modeled as a half-sphere tangent to the edge of the unit on its side facing the target. The geographical center of the explosion is assumed to be the center of this sphere, denoted as the radius of R0, as depicted in Figure 3.

Half of the calculated volume is utilized to estimate the overpressure distribution employing the TNO multi-energy model. The maximum explosion overpressure within congested units is capped at 500 mbar, while for less congested units, it is limited to 350 mbar.

For the vapor cloud explosion (VCE) and overpressure study, congested volumes are estimated based on relevant plot plan dimensions. The maximum acceptable overpressure on

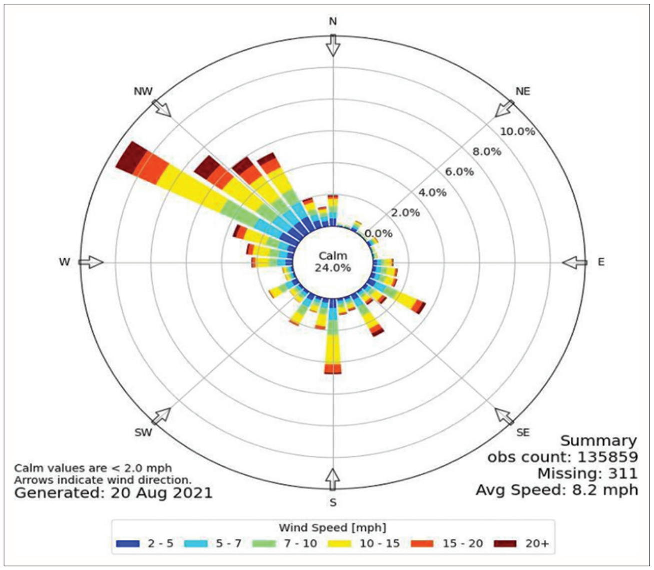

Figure 2: Bandar Mahshahr Wind Rose for six weather conditions in 16 directions (Obtained from IOWA STATE UNIVERSITY website)

Table 1: Weather categories

Weather category (D* AND F**)	Atmosphere stability	Wind speed (m/s)	Temperature (c)	Humidity (%)	Solar radiation (kw/m^2)
F2	F	2	20	80	0
D5	D	5	30	80	1.01
D16	D	16	30	80	1.01
D20	D	16	30	80	1.01

*D2–D20, "D" being the neutral atmospheric condition with wind speed varying from 2 to 20 m/s, **F2, "F" being the very stable atmospheric condition with low wind speeds (onshore and coastal areas)

Table 2: Study selected scenario data

Fire zone number	Scenario number	Involved equipment	Phase	Vapor fraction (%)	Temperature (c)	Pressure (Barg)	Connection size (inch)	Total inventory (kg)	Pool diameter (m)
FZ-01	IPS-01-SC01	20-E-9020	L	0	20	10.5	4	1458.12	-
FZ-01	IPS-02-SC01	20-D-9010 A/B-feed	L	0	−5	10.2	4	172,441.69	-
FZ-01	IPS-02-SC02	20-D-9010 A/B product	L	0	−5	3	6	180,977.27	-
FZ-01	IPS-02-SC03	Product tank-catastrophic rupture	L	-	Ambient	Atmosphere	-	134.77 (m^3)	-
FZ-01	IPS-02-SC04	Product tank-BLEVE	L	-	−5	3	-	134.77 (m^3)	-
FZ-01	IPS-02-SC05	Product tank-dike	L	-	Amb.	Atm.	-	-	19.05
FZ-01	IPS-03-SC01	20-P-9010 A/B	L	0	−6.2	17.9	6	10,010.25	-
FZ-01	IPS-04-SC01	20-E-9010 A/B	L	0	−6.2	11.2	4	9399.32	-
FZ-01	IPS-05-SC01	Venting lines	G	100	55	5.1	3	1e + 6	-
FZ-01	IPS-05-SC02	Product tank-PSV	G	100	65	5.1	4	22,604.13	-
FZ-01	IPS-06-SC01	Pipe rack	G	100	Amb.	Atm.	-	1e + 6	-
FZ-02	IPS-04-SC02	20-Z-9015	L	0	−6.2	11.2	4	6983.9	-

PSV: Pressure safety valve

adjacent fire zones is set at 200 mbar for storage equipment and 300 mbar for process equipment. The estimation of congested volumes is detailed in Table 3.

For all units and areas within the plant, each is assigned a dedicated fire zone number. However, studies pertaining to fire, explosion, flammable, and toxic gas dispersion have been specifically conducted for fire zones where significant quantities of flammable, combustible, and toxic materials are present.

Fire zone study results

In accordance with TOTAL GS EP SAF 253, the following credible criteria are considered to establish fire zone safety distances, as outlined in Table 4.

Table 5 presents a summary of the fire zone study results. It includes the flammability (distance to 100% lower flammable limit), jet fire, and pool fire analyses for four weather categories, along with the results of VCE scenarios. The calculated extents and boundaries of the fire zones are provided, with the maximum calculated distance for each scenario selected to illustrate the extent of the fire zone. These results are valuable for assessing the necessary safety measures and precautions in various areas of the petrochemical complex. In addition, they offer insights into the design and construction requirements for different areas or structures within the complex.

Restricted area study results

Based on TOTAL GS SAF 253, the following credible criteria are considered for establishing restricted area safety boundaries:

In this context, specific assumptions for various types of incidents likely to occur have been considered to model their related consequences. Consequently, conceivable effects such as flammable gas dispersion, toxic gas dispersion, thermal radiation, or thermal dose have been studied based on available criteria, which are outlined in the following table, derived from TOTAL GS SAF 253. These criteria encompass the consequences of all incidents deemed probable to occur. The calculated extents and boundaries of the restricted area are delineated in Tables 6-11.

Tables 6-11 display the distances to the thermal radiation of 4.7 kW/m², Lower flammable limit (LFL) concentration, and toxic gas dispersion distance to LC1% concentration. For each scenario, the maximum calculated distance was selected to illustrate the extent of the restricted area.

Impacted area results study

Based on TOTAL GS EP SAF 253, the following credible criteria are considered to establish impacted area safety boundaries:

The calculated extents and boundaries of the affected area are outlined in Tables 12-14. Tables 11-14 present the distances to the thermal radiation of 3.2 kW/m² and the toxic gas dispersion distance to Immediate danger to life and health (IDLH) concentration.

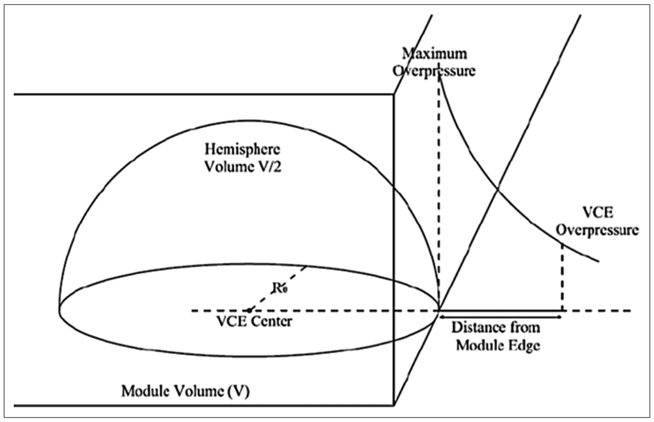

Figure 3: Vapor cloud explosion illustration

Table 3: Selected scenario data for the vapor cloud explosion

Congested zone number	Fire zone	Area (m²)	Full congested		Half congested	
			Volume (m³)	R0 (m)	Volume (m³)	R0 (m)
CZ-01	FZ-01	125	500	6.2	250	4.9

Table 4: Credible criteria for fire zone spacing

Type	Specification	Criteria Fire zone margin
Flammability	20 mm leak diameter Initial release rate for 10 min Release height 1 m horizontal jet and horizontal impacted jet	LFL concentration
Jet fire	20 mm leak diameter Initial-release rate for 10 min Release height 1 m Horizontal release direction	15.9 kW/m²
Pool fire	Spill tank fire	15.9 kW/m²
Overpressure	Half of the congested zone within fire zone at stoichiometric concentration	200 m bar

LFL: Lower flammable limit

DISCUSSION

Fire zone

The hazard zone analysis results from various accidental release scenarios involving fires and explosions at an industrial facility provide crucial insights into risk assessment. Distances to critical hazard thresholds, such as the Lower flammable limit (LFL) and thermal radiation levels under different weather conditions, enable a quantitative assessment of risks. In general, the more stable atmospheric categories, such as F2 and D5, exhibit significantly larger hazard zone distances compared

Table 5: Fire zone extent results: Flammability, fire, and vapor cloud explosion

Fire zone number	Scenario number	Distance to 100% LFL (horizontal)				Distance to 100% LFL (horizontal impingement)				Distance to 15.9 kW/m^2 jet fire				Distance to 15.9 kW/m^2 pool fire				Distance to 200 mbar VCE
		Weather category																
		F2	D5	D16	D20	F2	D5	D16	D20	F2	D5	D16	D20	F2	D5	D16	D20	
FZ-01	IPS-01-SC01	24.86	16.61	15.45	15.21	15.20	35.97	10.58	10.49	53.23	45.03	42.28	42.41	39.74	41.75	44.59	44.99	NA
	IPS-02-SC01	36.92	46.96	21.45	14.22	47.32	43.75	28.86	19.62	54.11	45.8	43.18	43.31	32.27	36.07	39.00	39.46	NA
	IPS-02-SC02	32.12	28.06	8.90	7.80	34.36	25.36	6.91	6.92	12.14	13.10	15.66	16.45	32.28	36.07	39.00	39.47	NA
	IPS-02-SC03	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	IPS-02-SC04	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	IPS-02-SC05	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	34.32	36.50	39.00	39.38	NA
	IPS-03-SC01	82.50	63.73	31.75	24.89	76.31	55.77	44.26	37.98	59.95	50.63	47.33	47.45	72.56	66.01	NR	NR	NA
	IPS-04-SC01	73.28	57.94	25.69	19.66	63.84	46.70	38.40	31.83	54.67	46.25	43.58	43.71	68.56	62.77	34.50	NR	NA
	IPS-05-SC01	NR	NR	NR	NR	NR	NR	NR	NR	8.88	7.48	6.90	6.87	NA	NA	NA	NA	NA
	IPS-05-SC02	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	IPS-06-SC01	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	29.08
FZ-02	IPS-04-SC02	72.10	57.93	25.67	19.66	61.56	45.51	38.34	31.83	54.67	46.25	43.58	43.71	62.56	58.67	33.68	NR	NA

LFL: Lower flammable limit, NA: Not available, VCE: Vapor cloud explosion, NR: Not reported

Table 6: Credible criteria for restricted area boundary determination

Type	Specification	Criteria restricted zone margin
Flammability	Leak diameter versus pipe diameter: 0.2 pipe diameter	LFL concentration
Flammability and toxicity	Limited to a minimum leak size of 20 mm and a maximum leak size of 150 mm	LFL toxic gas IDLH15 min
Cold vent emergency operation (unignited release)	Average release rate or release rate versus time Release height 1 m Horizontal jet and horizontal impacted jet Emergency flow rate Release direction according to the tip direction	
Toxicity	Leak diameter versus pipe diameter: 0.2 pipe diameter Limited to a minimum leak size of 20 mm and a maximum leak size of 150 mm Average release rate or release rate versus time Release height 1 m Horizontal jet and horizontal impacted jet	Toxic gas LC1%
Thermal radiation or thermal dose		
Jet fire from gas two-phase or liquid release	Leak diameter versus pipe diameter: 0.2 pipe diameter limited to a minimum leak size of 20 mm and a maximum leak size of 150 mm Average release rate or release rate versus time Release height 1 m Horizontal jet	4.7 kW/m^2
Pool fire in retention basin	Size of the retention basin	
BLEVE	Volume of liquid under pressure in sphere or bullet	140 m bar
Overpressure		
VCE in confined unit	Unit volume of flammable gas at stoichiometric concentration	140 m bar

VCE: Vapor cloud explosion, LFL: Lower flammable limit, IDLH: Immediate danger to life and health

to the less stable D16 and D20 categories. This is attributed to wind speed and instability enhancing mixing and radiation. Scenarios IPS-01-SC01, IPS-04-SC01, and IPS-03-SC01 demonstrate the largest hazard zones, exceeding 50 m for LFL and 30 m for thermal radiation, even under adverse weather conditions [Figures 4 and 5]. This indicates their potential for widespread impacts. On the contrary, scenarios such as IPS-02-SC02 and IPS-05-SC01 present significant localized risks, with LFL zones confined to under 15 m. The variation in hazard zone sizes with weather category underscores the importance of real-time meteorological factors in emergency response planning. While scenarios like IPS-01-SC01 may necessitate long-term mitigation strategies, others can be managed safely and operationally. This quantitative risk assessment offers valuable insights into relative risks from different areas/processes, aiding in prioritizing protective measures and maintaining safety. Moreover, it can be applied to the ongoing monitoring and review of operational hazards.

Table 7: Restricted area extent results for fire and flammability

Fire zone number	Scenario number	Leak size (mm)	Distance to 100% LFL (horizontal)				Distance to 100% LFL (horizontal impingement)				Distance to 4.7 kW/m² jet fire				Distance to 4.7 kW/m² pool fire				Distance to 140 mbar VCE
			Weather category																
			F2	D5	D16	D20	F2	D5	D16	D20	F2	D5	D16	D20	F2	D5	D16	D20	
FZ-01	IPS-01-SC01	20.32	25.35	16.08	15.70	15.55	45.65	36.36	11.61	10.67	69.98	60.97	57.43	57.41	58.77	56.65	56.99	57.46	NA
	IPS-02-SC01	20.32	36.89	36.77	22.35	15.04	47.61	43.96	29.52	20.27	71.36	62.14	58.54	58.51	54.81	56.32	56.01	55.58	NA
	IPS-02-SC02	30.48	36.89	38.26	12.05	10.58	38.26	32.28	14.79	10.13	64.69	59.54	57.58	57.05	54.80	56.31	56.01	55.58	NA
	IPS-02-SC03	NA	76.48	92.75	157.44	182.68	NA	NA	NA	NA	NA	NA	NA	NA	65.86	67.43	66.91	66.35	NA
	IPS-02-SC04	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	IPS-02-SC05	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	57.41	58.61	58.93	58.84	NA
	IPS-03-SC01	30.48	118.35	105.40	68.91	61.19	97.71	73.45	60.71	64.72	112.55	98.32	92.68	92.65	128.68	118.60	91.94	NR	NA
	IPS-04-SC01	20.32	74.45	59.10	26.87	20.55	64.55	47.26	38.99	32.81	72.04	62.74	59.11	59.08	110.80	94.62	44.70	NR	NA
	IPS-05-SC01	20	NR	NR	NR	NR	NR	NR	NR	NR	11.64	9.58	9.16	9.19	NA	NA	NA	NA	NA
	IPS-05-SC02	150				NR					NR	39.13	52.13	55.58	NR	NR	NR	NR	NR
						NR					82.40	71.28	68.72	69.18	NR	NR	NR	NR	NR
	IPS-06-SC01	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	41.02
FZ-02	IPS-04-SC02	20.32	73.16	59.10	26.87	20.56	62.20	46.05	38.95	32.81	72.04	62.74	59.11	59.08	100.86	88.13	43.22	NR	NA

NA: Not available, LFL: Lower flammable limit, VCE: Vapor cloud explosion, NR: Not reported

Research by Sharif and Razak highlights that atmospheric stability significantly influences hazard zone distances, with more stable atmospheric conditions resulting in larger hazard zones.[18] This finding aligns with our results, demonstrating that stable atmospheric categories F2 and D5 have larger hazard zones compared to less stable categories D16 and D20.

Barjoee *et al*. explored the influence of weather conditions on the dimensions of hazard zones in industrial facilities. They noted that wind speed and atmospheric instability can amplify mixing and radiation, thereby resulting in larger hazard zones. This observation supports the notion that weather conditions play a critical role in determining hazard zone sizes.[19] In addition, Witlox *et al*. delved into the potential repercussions of various accidental-release scenarios on hazard zones and risk assessment. They underscored the significance of real-time meteorological factors in emergency response planning, echoing the findings of our study.[20] Moreover, Benson *et al*. emphasized the importance of continuous monitoring and evaluation of operational hazards to prioritize protective measures and uphold safety standards.[21] This aligns with our recommendation of utilizing quantitative risk assessment for safety planning.

Restricted area

Table 7 presents the results of the hazard zone analysis conducted for different leak scenarios involving the release of EO vapor. Distances to the lower flammability limit concentration of 1% EO are provided for varying weather stability categories and leak sizes. Larger hazard distances are observed under stable atmospheric conditions of category F2 compared to the less stable categories D5, D16, and D20 due to better dispersion. Scenarios IPS-03-SC01 and IPS-01-SC01 exhibit the largest hazard zones, exceeding 200 m even in adverse weather conditions, indicating high risk. Conversely, scenarios such as IPS-02-SC02 and IPS-05-SC01 present much smaller hazards with distances below 100 m.

The impact of meteorological conditions and leak size on hazard zones is clearly illustrated. Larger leaks, such as those with a diameter of 30.48 mm as seen in scenario IPS-03-SC01, resulted in extensive hazard footprints. Conversely, intermediate leak sizes ranging from 20 to 20.32 mm led to variable risks depending on scenario-specific details. This quantitative risk assessment facilitates the comparison of relative risks between areas and aids in prioritizing mitigation efforts. It underscores the importance of scenario-based emergency plans that consider weather and inventory parameters. Continued monitoring and modeling can enhance risk management practices by accounting for site-specific conditions. Naemnezhad *et al*. conducted research on the impact of leak sizes and meteorological conditions on hazard distances in industrial facilities. They found that larger leak sizes resulted in more extensive hazard footprints, which is consistent with our findings. In addition, they highlighted the influence of meteorological conditions on dispersion, supporting the observation that stable atmospheric conditions

Table 8: Restricted area extent results for toxicity

Fire zone number	Scenario number	Leak size (mm)	Distance to LCL1% EO, 2428 ppm (horizontal) (m)				Distance to LCL1% EO, 2428 ppm (horizontal impingement) (m)			
			Weather category							
			F2	D5	D16	D20	F2	D5	D16	D20
FZ-01	IPS-01-SC01	20.32	158.55	138.62	106.71	96.51	109.72	105.79	95.24	88.23
	IPS-02-SC01	20.32	171.24	165.14	152.25	141.90	115.55	133.71	155.28	146.01
	IPS-02-SC02	30.48	141.79	131.32	109.85	96.45	94.83	97.70	104.16	99.07
	IPS-02-SC03	NA	161.91	227.19	389.61	447.78	NA	NA	NA	NA
	IPS-02-SC04	NA	NA	NA	NA	NA	NA	NA	NA	NA
	IPS-03-SC01	30.48	377.86	323.67	270.23	270.20	205.13	205.91	216.19	243.60
	IPS-04-SC01	20.32	225.95	194.02	171.29	163.79	145.82	148.32	155.83	161.57
	IPS-05-SC01	20	44.85	23.72	NA	NA	50.34	28.72	NA	NA
	IPS-05-SC02	150	NA	NA	NA	NA	NA	NA	NA	NA
			NA	NA	NA	NA	NA	NA	NA	NA
	IPS-06-SC01	NA	NA	NA	NA	NA	NA	NA	NA	NA
FZ-02	IPS-04-SC02	20.32	224.42	194.02	171.30	163.80	143.00	140.75	155.92	161.57

EO: Ethylene oxide, NA: Not available, LCL1%: Lethal concentration limit 1%

Table 9: Restricted area extent results for toxicity for cold vent (pressure safety valve)

Fire zone number	Scenario number	Discharge size (mm)	PSV tip direction	Distance to IDLH (15 min) EO, 800 ppm (m)				Distance to IDLH (15 min) EO,800 ppm (impingement) (m)			
				Weather category							
				F2	D5	D16	D20	F2	D5	D16	D20
FZ-01	IPS-05-SC02	152.4	Vertical	NR	NR	NR	NR	NA	NA	NA	NA
			Horizontal	835.53	579.63	NR	NR	NA	NA	NA	NA

IDLH: Immediate danger to life and health, EO: Ethylene oxide, PSV: Pressure safety valve, NR: Not reported

Table 10: Restricted area extent results for the BLEVE

Fire zone number	Scenario number	Distance to IDLH (15 min) EO, 800 ppm (m) Weather category			
		F2	D5	D16	D20
FZ-01	IPS-02-SC04	25.68			

IDLH: Immediate danger to life and health, EO: Ethylene oxide

like category F2 led to larger hazard distances compared to less stable categories.[12]

Table 8 provides a quantitative hazard zone analysis for various accidental release scenarios involving fires, explosions, and leaks of flammable/toxic substances. The analysis evaluates the variation in hazard distances to critical thresholds such as the Lower flammable limit (LFL), thermal radiation levels, and toxic gas concentrations under changing weather conditions and scenario specifics. It illustrates that more stable weather categories yield significantly larger hazard zones, whereas less stable conditions promote rapid dispersion and smaller zones. Larger leaks and more severe incident scenarios present much greater risks, represented by an extensive hazard footprint. The results offer valuable insights into the relative risks posed by different facility areas/processes and operational parameters, allowing for the prioritization of protective measures through an understanding of how meteorology and event sizes can influence safety outcomes. Bahmani *et al*. conducted research on the relationship between event size and hazard footprint in chemical-release scenarios. Their study underscored the importance of considering the specific characteristics of the released substance in determining hazard distances. This insight could provide valuable information on the variability of hazard zones based on the type of substance involved in accidental releases.[22]

Table 9 and Figures 6 and 7 present the hazard zone analysis results for scenario IPS-05-SC02, which involves the release of EO vapor through a vertically oriented pressure safety valve (PSV) with a size of 152.4 mm. Distances to the immediate danger to life and health (IDLH) concentration of 800 ppm EO are reported under different weather stability categories. Significant variations in hazard distances are observed, with numerous zones exceeding 500 m calculated under stable category F2 conditions due to better atmospheric dispersion. However, the zones could not be determined (NR) under less stable categories, indicating rapid dispersion and minimal hazards. While vertical discharge leads to greater atmospheric mixing and reduces risks to some extent, this scenario still poses substantial dangers, as indicated by the extensive hazard footprint under favorable meteorological conditions. The analysis underscores how meteorological

Table 11: Credible criteria for impact area boundary determination

Type	Specification	Criteria Restricted zone margin
Toxicity	Leak diameter versus pipe diameter: 0.2 pipe diameter Limited to a minimum leak size of 20 mm and a maximum leak size of 150 mm Average release rate or release rate versus time Release height 1 m Horizontal jet and horizontal impacted jet	Toxic gas IDLH
Thermal radiation or thermal dose		
Jet fire from gas, two-phase or liquid release	Leak diameter versus pipe diameter: 0.2 pipe diameter limited to a minimum leak size of 20 mm and a maximum leak size of 150 mm Average release rate or release rate versus time Release height 1 m Horizontal jet	3.2 kW/m^2
Pool fire in the retention basin	Size of the retention basin	
BLEVE	Volume of liquid under pressure in a sphere or bullet	50 m bar
Overpressure		
VCE in confined unit	Unit volume of flammable gas at stoichiometric concentration	50 m bar
Toxicity		
Cold vent-emergency operation (ignited release)	Emergency flow rate Release direction according to the tip direction	Toxic gas IDLH 30 min 2kW/m^2

VCE: Vapor cloud explosion, IDLH: Immediate danger to life and health

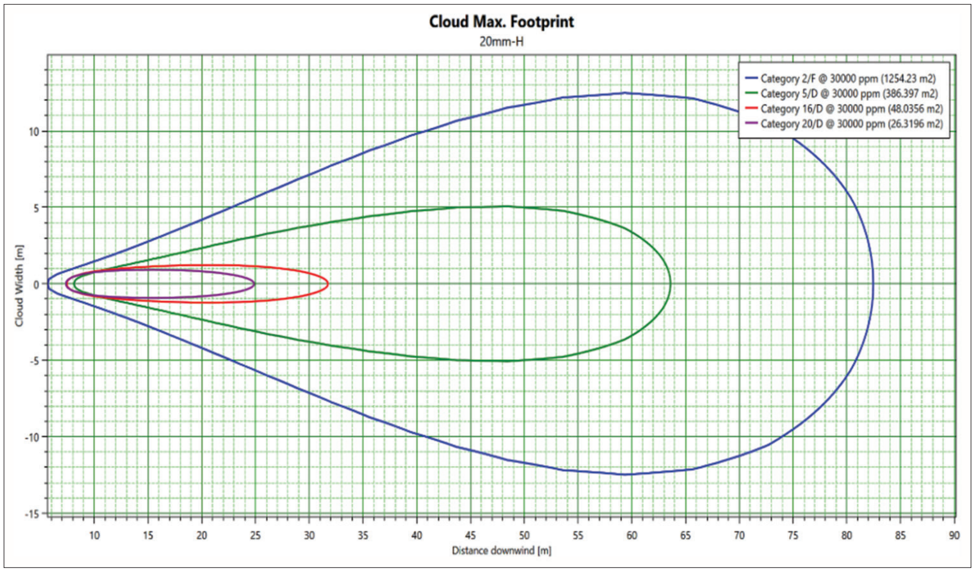

Figure 4: Fire zone distances-FZ01 and IPS-03-SC01

categorization and flow discharge properties influence public safety impacts from toxic releases. This finding is consistent with the results of a study conducted by Ruiz-Sanchez *et al*., which also found that atmospheric dispersion plays a significant role in determining hazard distances for toxic releases.[23]

Table 10 and Figures 8 and 9 present the hazard zone analysis results for a single scenario (IPS-02-SC04) involving the release of EO gas. The distance to the immediate danger to life and health (IDLH) concentration of 800 ppm EO is reported under different weather stability categories. The hazard distance calculated under stable category F2 conditions is approximately 26 m. More stable atmospheres allow for less atmospheric mixing and dilution of the toxic plume, resulting in smaller hazard zones compared to less stable categories where no distances are reported, indicating rapid dispersion. Although only limited data are available from this single scenario assessment, it highlights how weather strongly influences toxicity hazards from chemical releases.

Impacted area

Table 12 and Figures 9-11 present the results of the hazard zone

Table 12: Impacted area extent results: Toxicity and fire

Fire zone number	Scenario number	Leak size (mm)	Distance to the IDLH EO 800 ppm (horizontal) (m)				Distance to the IDLH EO 800 ppm (horizontal impingement)				Distance to 3.2 kW/m^2 jet fire (m)				Distance to 3.2 kW/m^2 pool fire				Distance to 50 mbar VCE
			Weather category																
			F2	D5	D16	D20	F2	D5	D16	D20	F2	D5	D16	D20	F2	D5	D16	D20	
FZ-01	IPS-01-SC01	20.32	224.56	194.26	149.80	135.00	204.22	156.13	134.63	123.94	76.41	67.31	63.60	63.52	66.70	64.24	61.99	62.17	NA
	IPS-02-SC01	20.32	261.41	230.01	213.15	198.45	226.93	188.22	218.52	204.92	77.98	68.61	64.79	64.70	64.35	64.92	63.15	62.47	NA
	IPS-02-SC02	30.48	244.29	185.06	153.97	134.89	248.17	145.70	147.23	140.20	70.88	65.67	63.49	62.84	64.34	64.91	63.15	62.47	NA
	IPS-02-SC03	NA	246.27	299.14	489.67	545.79	NA	NA	NA	NA	NA	NA	NA	NA	77.32	77.80	75.56	74.73	NA
	IPS-02-SC04	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	IPS-02-SC05	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	65.71	66.83	64.83	63.83	NA
	IPS-03-SC01	30.48	489.54	446.48	377.36	380.83	368.40	303.22	301.57	341.30	122.94	108.63	102.82	102.73	148.93	134.91	100.92	NR	NA
	IPS-04-SC01	20.32	317.23	270.88	244.26	232.79	357.39	211.73	218.21	229.36	78.71	69.28	65.43	65.34	128.85	108.06	47.79	NR	NA
	IPS-05-SC01	20	104.63	79.64	18.38	13.41	83.86	47.79	13.48	12.00	11.94	10.46	10.11	10.15	NR	NR	NR	NR	NA
	IPS-06-SC01	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	104.31
FZ-02	IPS-04-SC02	20.32	313.45	270.88	244.26	232.80	330.82	204.30	218.29	229.36	78.71	69.27	65.43	65.34	117.19	100.54	46.12	NA	NA

VCE: Vapor cloud explosion, NA: Not available, IDLH: Immediate danger to life and health, EO: Ethylene oxide, NR: Not reported

analysis for various accidental release scenarios involving fires, explosions, and leaks. Distances to hazard thresholds such as the immediate danger to life and health (IDLH) concentration of EO (800 ppm), thermal radiation levels (3.2 kW/m²), and overpressure (50 mbar) are reported under different weather stability categories and leak sizes. Larger hazard zones are observed under stable category F2 weather, with some scenarios, such as IPS-03-SC01 and IPS-01-SC01, posing risks exceeding 300 m. Conversely, unstable weather yields smaller footprints. Furthermore, larger leaks of 30.48 mm generate more extensive hazards compared to smaller releases of 20–20.32 mm. This quantitative risk assessment demonstrates the influence of meteorological conditions and incident severity on public safety distances. It provides valuable insights for evidence-based emergency response planning by comparing risks across different operational areas. The observation that larger leaks result in more extensive hazards aligns with the findings of Wang *et al*., which also highlighted the importance of incident severity in determining the extent of public safety distances for chemical releases.[24] With careful consideration of the influence of meteorological conditions and leak sizes on hazard zones, this study offers valuable insights for evidence-based emergency response planning and risk assessment comparisons across different operational areas. This aligns with the research by Sharifi and Razavian, which emphasizes the importance of considering multiple factors in assessing public safety risks from chemical incidents. By integrating these factors into the risk assessment process, stakeholders can make informed decisions to mitigate risks effectively and prioritize safety measures.[25]

Table 13 presents the hazard analysis results for the release scenario involving EO vapor discharge through a vertically oriented PSV. This study investigates the influence of stack elevation and orientation on toxicity and thermal radiation hazards under different stability categories. No hazard distances were reported under horizontal discharge conditions, indicating that risks could not be adequately assessed. However, significant toxic zones of over 68 m were calculated for vertical release under category D5–D20 weather, demonstrating greater mixing and dilution. Thermal hazards are minimized to below 90 m with vertical dispersion, suggesting that stack parameters effectively limit dangers. Although limited data are provided, the analysis conveys how meteorology and release properties interact to control hazard footprints. The hazard analysis results presented in this section for the scenario involving EO vapor discharge through a vertically oriented PSV are consistent with the findings of a study by Truong *et al*., which also explored the impact of stack elevation and orientation on toxicity and thermal radiation hazards under different weather stability categories. Both studies highlight the importance of vertical release for achieving greater atmospheric mixing and dilution of toxic plumes, resulting in larger hazard zones compared to horizontal discharge conditions.[26]

Table 14 presents the hazard zone analysis results for a single scenario (IPS-02-SC04) involving the accidental release of

Table 13: Impacted area extent results for toxicity and thermal radiation for cold vent pressure safety valve

Fire zone number	Scenario number	Leak size (mm)	Discharge elevation (m)	PSV tip direction	Distance to IDLH EO 800 ppm (horizontal) (m)				Distance to IDLH EO 800 ppm (horizontal impingement)				Distance to 3.2 kW/m² jet fire (m)			
					Weather category											
					F2	D5	D16	D20	F2	D5	D16	D20	F2	D5	D16	D20
FZ-01	IPS-05-SC02	12.5	Vertical	NA	NA	NA	NA	NA	NA	NA	NA	NA	68.84	70.35	78.06	78.13
			Horizontal	NA	NA	NA	NA	NA	NA	NA	NA	NA	100.96	89.72	88.60	89.30

PSV: Pressure safety valve, IDLH: Immediate danger to life and health, EO: Ethylene oxide, NA: Not available

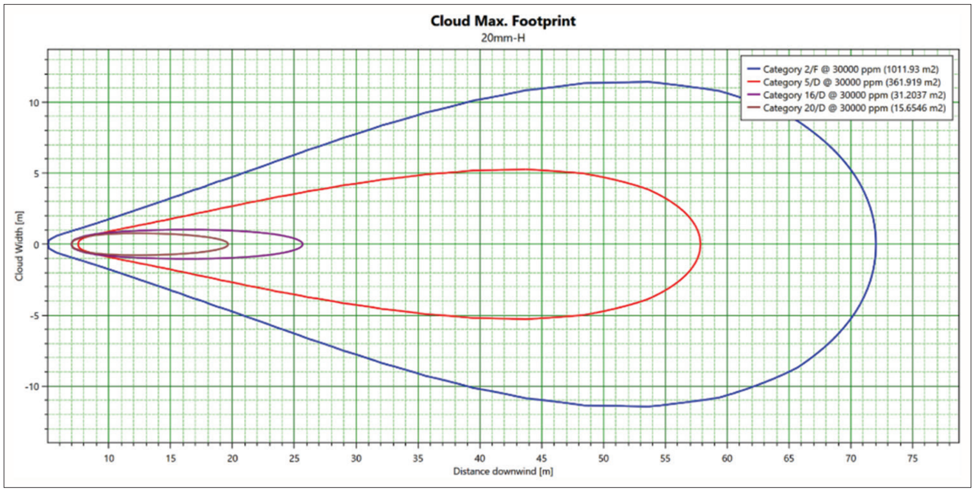

Figure 5: Fire zone distances-FZ02 and IPS-04-SC02

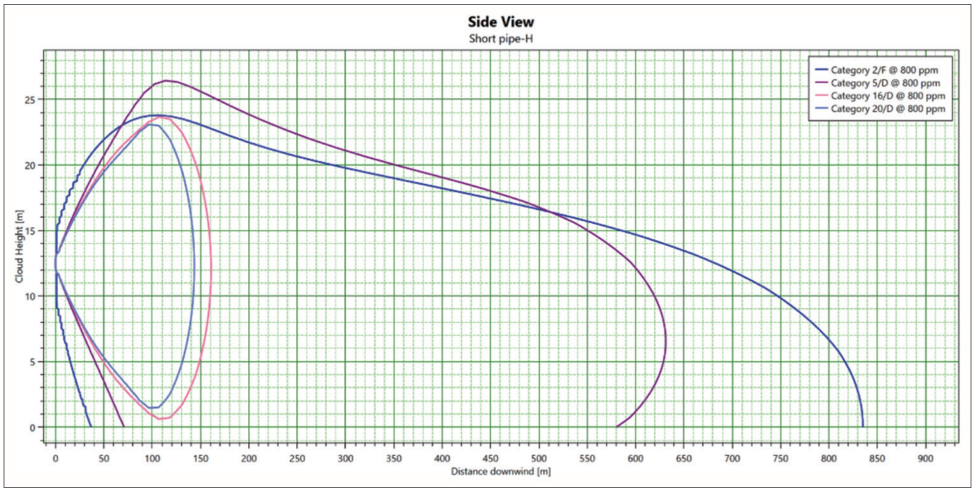

Figure 6: Restricted area distances (FZ01, IPS-05-SC02-horizontal)

EO gas. The distance to the immediate danger to life and health (IDLH) concentration of 800 ppm EO is reported under different weather stability categories. The hazard distance calculated under the very stable category F2 conditions is approximately 56 m. Stable atmospheres impede atmospheric dispersion and dilution of the toxic plume, resulting in a larger hazard zone compared to less stable categories where data are not shown, likely indicating rapid mixing and minimal risk. Although only one scenario was assessed, this highlights the significant influence of meteorological conditions on toxicity hazards.

Study limitations

His study primarily focuses on analyzing hazard zones and risks associated with specific accidental release scenarios, which may limit the generalizability of the findings to other industrial facilities or chemical processes. In addition, the study does not address the need for real-time monitoring and modeling of hazard zones, which could enhance the accuracy

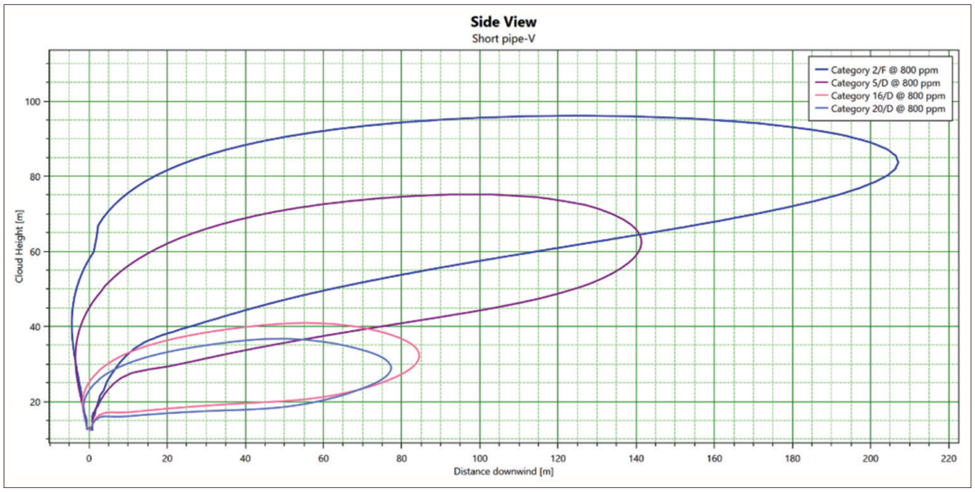

Figure 7: Restricted area distances (FZ01, IPS-05-SC02-Vertical)

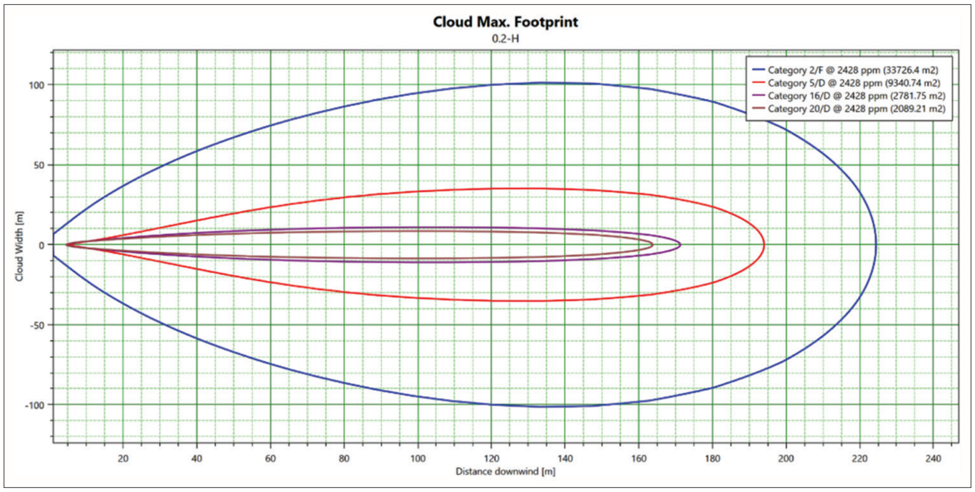

Figure 8: Restricted area distances (FZ02 and IPS-04-SC02)

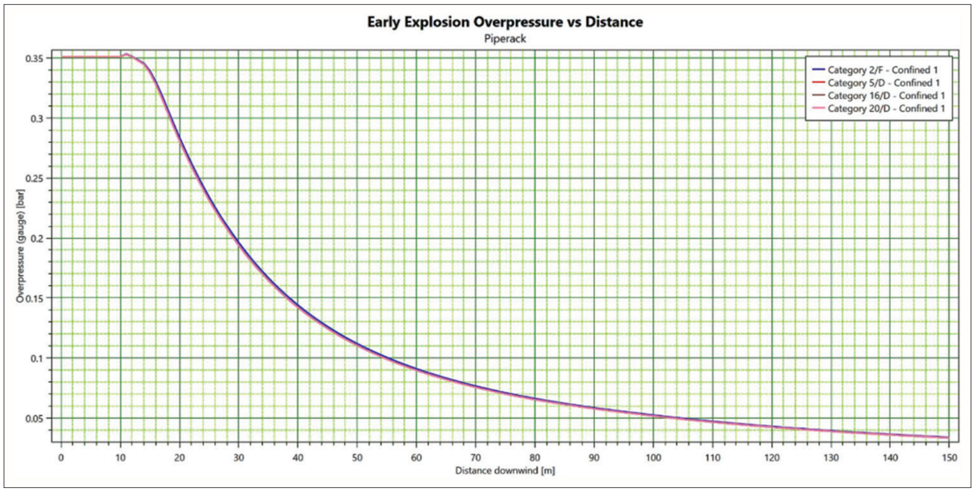

Figure 9: Restricted area distances (FZ01 and IPS-06-SC01)

of risk assessments and emergency response planning in dynamic operational environments. Incorporating real-time monitoring and modeling capabilities would enable continuous assessment and adaptation to changing conditions, thereby improving the effectiveness of emergency response measures and overall safety protocols. Future research could explore

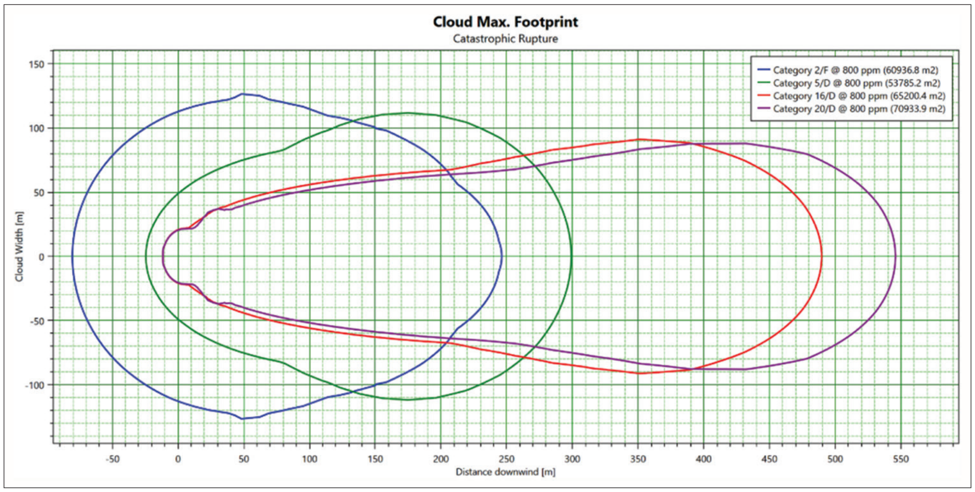

Figure 10: Impacted area distances (FZ01, IPS-02, and SC03)

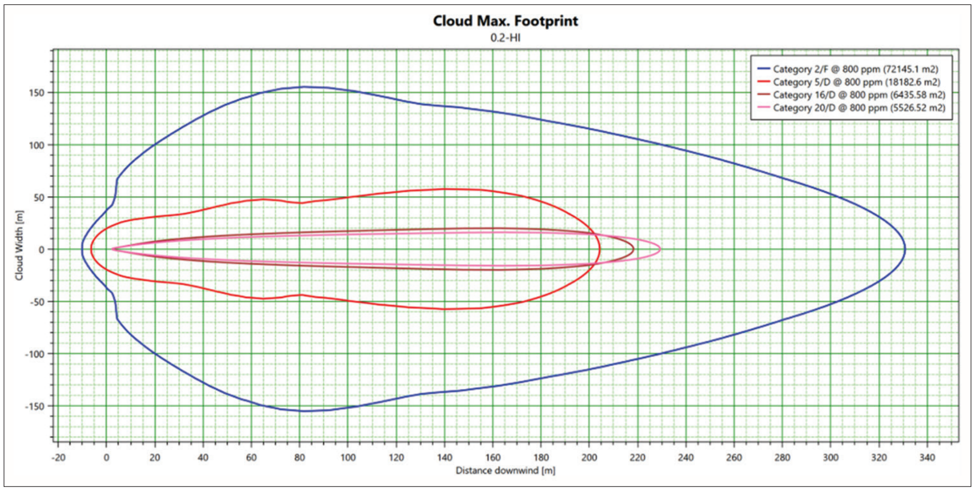

Figure 11: Impact area distances (FZ02 and IPS-04-SC02)

Table 14: Restricted area extent results for the BLEVE

Fire zone number	Scenario number	Distance to the IDLH EO 800 ppm (horizontal) (m) Weather category			
		F2	D5	D16	D20
FZ-01	IPS-02-SC04	55.69			

IDLH: Immediate danger to life and health, EO: Ethylene oxide

these aspects to provide a more comprehensive understanding of risk management in industrial settings.

CONCLUSION

Based on the results and process conditions, it is determined that the tankage area (FZ-01) and truck loading station (FZ-02) are situated in independent fire zones, with appropriate safe distances considered in site layout planning.

Regarding the modeling of credible scenarios for restricted area boundaries, it is observed that the radius of the restricted area extends beyond the facility's fence. To address this, it's recommended that the discharge pipes of the EO storage tank PSVs be installed vertically or measures be taken to ensure control over this area to mitigate social risk. Following the appropriate discharge direction for the PSVs could potentially reduce the radius of the restricted area to approximately 448 m in the event of a catastrophic rupture scenario of the storage tank. In addition, to mitigate toxic gas dispersion in adjacent manned areas, such as the control room situated on the east side of the tank area, the implementation of a fire water curtain could be beneficial to absorb or dilute EO gases.

The modeling of credible scenarios for impacted area boundaries indicates that there are no permanently manned areas (residential areas) within the impacted area, alleviating concerns regarding risk to the population outside the company. It is recommended that no residential areas be constructed in these regions. However, if the impacted area could be endangered by adjacent plants or complexes, a common ERP should be developed to outline all escape and evacuation plans in the event of a major failure. Furthermore, the EO cylinder filling building (FZ-03) should be designed and constructed to withstand an overpressure of approximately 84 mbar, as observed in the pipe rack VCE scenario from the restricted area study.

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Nil.

Ethics code

The research method was approved by the HSE Committee of the petrochemical complex in the southern region of the country. However, due to not using human samples in this research, an ethical code was not obtained.

Conflicts of interest

There are no conflicts of interest.

Authors' contributions

Sayed Vahid Esmaeili: Investigation, methodology, writing original draft, resources. Reza Esmaeili: Investigation, methodology, writing original draft. Ali Mohsenian: Writing review and editing. Ali Alboghobeish: Conceptualization, writing review and editing, supervision, project administration, validation, visualization.

Availability of data and materials

The datasets generated and/or analyzed during the current study are not publicly available due to confidentiality in process industries but are available from the corresponding author on reasonable request.

REFERENCES

1. Soltanzadeh A, Mahdinia M, Jafarinia E, Golmohammadpour H, Sadeghi-Yarandi M. Occupational safety risk analysis in construction sites based on fuzzy analytic hierarchy process: A case study in a large construction project. Work 2023;76:771-82.
2. Karuppiah K, Sankaranarayanan B, Ali SM. A fuzzy anp-dematel model on faulty behavior risks: Implications for improving safety in the workplace. Int J Occup Saf Ergon 2022;28:923-40.
3. Nwankwo CD, Arewa AO, Theophilus SC, Esenowo VN. Analysis of accidents caused by human factors in the oil and gas industry using the HFACS-OGI framework. Int J Occup Saf Ergon 2022;28:1642-54.
4. Stavroglou SK, Ayyub BM, Kallinterakis V, Pantelous AA, Stanley HE. A novel causal risk-based decision-making methodology: The case of coronavirus. Risk Anal 2021;41:814-30.
5. Khajevandi AA, Shafiei Z, Zamani-Badi H, Hanani M, Esmaeili SV. Assessing the safety status of Kashan university of medical sciences faculties by audit method in 2018. Int Arch Health Sci 2021;8:165-9.
6. Lawson SM, Masterson EA, Azman AS. Prevalence of hearing loss among noise-exposed workers within the mining and oil and gas extraction sectors, 2006-2015. Am J Ind Med 2019;62:826-37.
7. Zhou XG, Yuan WK. Optimization of the fixed-bed reactor for ethylene epoxidation. Chem Eng Process Process Intensification 2005;44:1098-107.
8. Kim YC, Park NC, Shin JS, Lee SR, Lee YJ, Moon DJ. Partial oxidation of ethylene to ethylene oxide over nanosized Ag/α-Al2O3 catalysts. Catalysis today, 2003;87:153-162.
9. Choi JY, Byeon SH. Case study: Safety assessment of plant layout between ethylene storage tanks and process equipment according to capacity and weather conditions. Int J Environ Res Public Health 2020;17:2849.
10. Park RM. Associations between exposure to ethylene oxide, job termination, and cause-specific mortality risk. Am J Ind Med 2020;63:577-88.
11. Neghab M, Soleimani E, Hassanzadeh J. Toxic responses of different organs following occupational exposure of employees of a plant to ethylene oxide. Toxicol Environ Chem 2012;94:1591-600.
12. Naemnezhad A, Isari AA, Khayer E, Esfandiari Birak Olya M. Consequence assessment of separator explosion for an oil production platform in South of Iran with phast software. Model Earth Syst Environ 2017;3:1-12.
13. Cheraghi H, Soltanzadeh A, Ghiyasi S. Consequence modeling of the ethylene oxide storage tanks explosion using the phast software (a case study in a petrochemical industry). Iran J Health Environ 2018;11:261-70.
14. Mousavi J, Parvini M. Analyzing effective factors on leakage-induced hydrogen fires. J Loss Prev Process Ind 2016;40:29-42.
15. Dadashzadeh M, Khan F, Hawboldt K, Amyotte P. An integrated approach for fire and explosion consequence modelling. Fire Saf J 2013;61:324-37.
16. Jafari MJ, Mohammadfam I, Zarei E. Analysis and simulation of severe accidents in a steam methane reforming plant. Int J Occup Hyg 2014;6:120-30.
17. Harati B, Karimi A, Askari A, Dehghani F, Nasrollahi A. Modeling and evaluation of safety consequences of propylene oxide leakage, a petrochemical company. J Health Saf Work 2018;8:2.
18. Sharifa MM, Razaka MA. Consequence modelling and analysis of hydrogen release from methyl ester hydrogenation plant using phast. J Occup Saf Health 2018;15:2.
19. Barjoee SS, Elmi MR, Varaoon VT, Keykhosravi SS, Karimi F. Hazards of toluene storage tanks in a petrochemical plant: Modeling effects, consequence analysis, and comparison of two modeling programs. Environ Sci Pollut Res Int 2022;29:4587-615.
20. Witlox HW, Fernández M, Harper M, Oke A, Stene J, Xu Y.. Verification and validation of phast consequence models for accidental releases of toxic or flammable chemicals to the atmosphere. J Loss Prev Process Indus 2018;55:457-70.
21. Benson C, Obasi IC, Akinwande DV, Ile C. The impact of interventions on health, safety and environment in the process industry. Heliyon 2024;10:e23604.
22. Bahmani R, Pouyakyan M, Khodakarim S, Bidel H, Salehi A. Risk assessment and consequence analysis of fire and explosion in a vinyl chloride monomer tank by phast. J Saf Promot Inj Prev 2021;8:208-18.
23. Ruiz-Sanchez T, Nelson PF, François JL, Cruz-Gomez MJ, Mendoza A. Application of the accident consequence analysis in the emergency system design of an SI cycle hydrogen production plant. Int J Hydrogen Energy 2012;37:6965-75.
24. Wang K, Liu Z, Qian X, Huang P. Long-term consequence and vulnerability assessment of thermal radiation hazard from LNG explosive fireball in open space based on full-scale experiment and phast. J Loss Prev Process Indus 2017;46:13-22.
25. Sharifi SR, Razavian F. Hazard identification and consequences analysis of possible accidents in the tank farm & flare of the ILAM gas refinery by ETBA and phast soft wear. J Environ Sci Technol 2020;22:309-22.
26. Truong SC, Lee MI, Kim G, Kim D, Park JH, Choi SD, *et al*. Accidental benzene release risk assessment in an urban area using an atmospheric dispersion model. Atmos Environ 2016;144:146-59.