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Consequence Analysis of An Industrial Accident at a Fuel Station

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Keywords

Consequence Modelling
Model Validation
Hazard Identification
Risk Analysis
Fuel Station

Abstract

Major industrial accident is a type of technological disaster that may require extraordinary intervention in areas outside the facility, in addition to those affected within the facility. It causes damage to the environment and loss of life at the time it occurs or afterward. Studies to be carried out to prevent these accidents Zor to reduce their effects are important. In this study, a case study for the consequences of an industrial accident that may occur in a fuel station was analyzed. Firstly, possible accident scenarios were created by obtaining chemical, atmospheric and source data. The LPG (Liquefied Petroleum Gas) storage tank (40m3) was considered in modeling a fuel station in the Korfez district of Kocaeli province, where the industry is dense in Turkey. The average atmospheric data of the province for the months of August and January were used to represent summer and winter conditions, respectively. Threat zones were produced with ALOHA (Areal Locations of Hazardous Atmospheres) software based on a release to atmosphere without burning, a jet fire as a result of a leak in the LPG tank and BLEVE scenarios. The two most dangerous scenarios were determined as a possible jet fire in August and a possible BLEVE (Boiling Liquid Expanding Vapor Explosion) in January. Overpressure effects were also obtained using the BST (Baker-Strehlow-Tang) method, thus ensuring the validation. With the software, the vapor cloud explosion distance as a result of the leak in August was obtained as 456m and 268m for the yellow (6.89kPa) and orange (24.13kPa) threat zones, respectively. Overpressure in an area of 500 meters was calculated as 5.06kPa with BST method. This calculated overpressure has the potential for damage that can lead to glass and window breakage in parallel with the ALOHA output. It has been determined that indirect injuries may occur to living beings.

Cite

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1. INTRODUCTION

In parallel with the development of science and technology, chemicals and chemical processes, the use of which increases as the number of industrial facilities increases, not only facilitates production processes and life, but also poses risks for both humans and the environment. Due to the use of hazardous chemicals, many major industrial accidents have occurred, and enormous material and moral losses have also occurred that cannot be recovered or compensated. In particular, as a result of major industrial have started.

Hazardous chemicals have the potential to affect not only the people or organizations that use these substances directly, but also the population, the environment and natural life in case of possible industrial accidents. In the literature, it has seen that consequence analyzes are made through various software and methods in industrial establishments containing various hazardous chemicals. Consequence analyzes provide important inputs for effective risk assessment. In the study by Yu et al. (2023), the risk assessment of the hydrogen-gasoline hybrid refueling station was conducted with the Accident Risk Assessment Method (ARAMIS) and an improved probabilistic failure model was used. Accident consequences were simulated using CFD methods. The risk levels on the road near the station building and the refueling area were within the acceptable range.

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A fire accident caused by the leakage of alcohol-based fuel vapor was analyzed by Wang et al. (2023). Multiple physical space loads were determined by on-site examination and CFD. A hazardous gas distribution after a leak accident was simulated through CFD by Wu et al. (2023). The effects of source location and ventilation path on the distribution characteristics were analyzed. Additionally, the relationship between individual mortality risk and source density by using H_2S as a toxic substance source was measured. Critical risks and effective safety measures for pipelines were qualitatively analyzed by Nakayama et al. (2022). 183 accident scenarios were identified through the hazard identification and preventive and mitigating safety measures were presented. Hydrogen dispersion simulations were revealed that low-pressure hydrogen dispersion leaking through small holes and cracked pipes in public spaces can lead to alarming risks depending on the size, direction, location of the leak, obstructions and ignition source. An integrated risk assessment procedure based on accident consequences and local people's sensitivity was presented by Guan et al. (2022) and then applied to a small town in China. A hazard map was obtained from the footprint of regional hazards. Population susceptibility was determined from resident exposure, sensitivity, and adaptability. On the other hand, population exposure indicators were determined from population density and residential environment. The effects and consequences of toluene release were modeled by Barjoee et al. (2022) through the ALOHA and PHAST programs. Maximum threat zone distances associated with the high toxicity, flammability and thermal radiation hazards of toluene were obtained, with the highest probability of death being 92% determined at a distance of 1 m during cold seasons. With the PHAST program, higher values than those determined in ALOHA were detected. In the study by Sun et al. (2021), the safety distances of petrochemical equipment in both underground and underground vaults were investigated. Accident consequence analyzes were performed for typical substances in the tank, such as liquid oxygen, hydrogen, LPG, LNG (Liquefied Natural Gas), and gasoline. The PLL (Potential loss of life index) was calculated to consider the average risk of district personnel. It was observed that the PLL value decreased by 36.7% when the gasoline storage tank alone was underground, and by 6.33% when only the LPG tank was underground. In the study by Ahn et al. (2020), accidents involving flammable materials such as benzene, toluene, xylene, methyl ethyl ketone and ethyl acetate were modeled with free ALOHA software and KORA software. ALOHA software applies the BST method as a VCE (Vapor Cloud Explosion) modeling technique. KORA supports TNO multi-energy method for pool fire and VCE models. Modeling results under similar conditions produced similar damage radius. It has been emphasized that chemical accidents are highly correlated with the physicochemical properties of the chemicals, and the similarity of the physicochemical properties of the investigated chemicals. In the study by Ma and Huang (2019), a quantitative risk analysis was performed to assess human safety of explosion accidents at gas stations. A case study was conducted for explosion accidents that occurred during refueling from a fuel tanker to a gas station. PHAST was used to simulate explosions. Wind directions and wind speeds were not considered. The BST model was chosen while performing the explosion analysis. For the leak scenarios, 18 cases that occurred in Western Australia between 1996 and 2008 were considered. When an area with an overpressure greater than 0.689 bar reached the nearest distributor (approximately 10 m) and storage area (20 m), the severity was determined as medium and large, respectively. In the study by Sierra et al. (2019), the problem of assessing the safety of chemical plants was examined by considering the physical layout as well as equipment types and materials processed. Focusing on the safety issues posed by VCEs, a methodology based on probabilistic modeling was proposed to evaluate the consequences of domino effects. A case study was conducted with five gas tanks and five different settlement scenarios. The probability of a tank being exposed to VCE was obtained higher than the threshold given by the value of the cumulative distribution function governing the occurrence of VCE in each tank. In the study by Lee et al. (2019), the safety distance regulations in Korea for BTX items were compared with other countries, and it was evaluated whether there was a possibility of domino explosion with the current safety distances in Korea. TNT, TNO and BST methods were used to model the explosions. The amount of flammable material stored in the tanks (L=4 m, D=2 m) was accepted as 50 000 kg. It was found that the probability of a domino explosion was low when the safety distance was longer than the distance that the 24 kPa overpressure can reach. There was no significant difference between the distances reached by the overpressure determined by each method. In the study by Witlox et al. (2018), modeling studies were carried out for the accidental release of flammable or toxic chemicals into the atmosphere. Validation was done with PHAST. Many different chemicals (including water, LNG, propane, butane, ethylene, ammonia, CO_2, hydrogen, chlorine, HF, etc.) were considered. In the by Huang and Ma (2018), a grid-based risk mapping method was used to enable effective and detailed risk screening in an area where explosion and fire accidents occurred at a hydrogen refueling station. PHAST was chosen to simulate explosions. Distributions of all leaks and wind directions were considered in the analysis. Since the storage volume inside the station was quite small, it was determined that the spread would not exceed the hydrogen station and therefore it was assumed that the congestion would remain the same. No explosion was observed when the leakage volume was less than 3 kg.

Industrial accidents result in fire, explosion or toxic emission. Explosion events stand out with both serious losses of life and property damage. It has seen in the literature that explosion models continue to be developed in both model and experimental studies. Rocourt et al. (2023) compared the values of overpressure and flame speed in small-scale flash experiments with the values predicted from the TNO-ME method and BST method. Experiments were carried out in hydrogen-air mixtures in cylindrical compact volumes ranging from 1.77 L to 7.07 L. Reactivity was controlled by the hydrogen-air equivalence ratio. The estimated flame speed values obtained from the BST method were found to be in agreement with almost half of the experimental results, and the method exhibited consistency in most of the tested configurations. The use of the TNO ME method was validated in a small-scale experiment to predict maximum overpressures resulting from flaring of medium- and large-scale H_2/air clouds. A hybrid deep learning probabilistic model was proposed by Shi et al. (2023) to predict the spatial explosion overpressure of the offshore platform in real time using the observed overpressures. Data from both the experimental natural gas explosion and the offshore platform were used to create the comparative data set. The results showed that the model exhibited good real-time capability. In the study by Shi et al. (2021), a quantitative evaluation correlation (QEC) of flame velocity was established based on the numerical models of the three geometric scales and the CSC correlation verified by the FLACS software, in the method that can only subjectively select the detonation curve. Based on a petrochemical plant, positive phase peak pressure and impulse at different distances were estimated with the BST flame velocity table and the TNT EM, TNO MEM, FLACS and BST curve suggested. The overpressure estimated from the BST curve was shown to be closer to that obtained from FLACS. In the study by Bai et al. (2021), a triangular pyramid explosion risk model based on explosion overpressure (p), duration (t) and frequency (f) was created for petrochemical buildings. A case study was conducted for a petrochemical building and the hydro cracking unit next to it. Based on the overpressure-cumulative frequency curve and the explosion risk curve, BRDLs were determined quantitatively. Computational Fluid Dynamics (CFD) method was used in the calculation process. The main factors affecting the explosion load were the characteristics of the hazardous environment, process operating conditions, degree of obstruction, leak hole size and explosion source distance. In the study by Liu et al. (2020), the primary explosion gas cloud and the secondary explosion of the gas cloud were analyzed using pressure and flow field monitoring. Methane was preferred for experimental safety. Polyvinyl chloride was used to create a spherical gas cloud, then used to produce the impulse effect of multiple gas cloud explosions to evaluate the detonation process. Double gas cloud and multiple gas cloud explosion experiments were performed under different conditions and the consequences were compared. It was shown that the larger the size of the primary explosion gas cloud, the smaller the distance between the primary explosion gas cloud and the secondary explosion gas cloud, and the greater the explosion density of the two gas clouds were determined. A detailed comparison of the TNO multi-energy, BST and CAM models was made by Fitzgerald (2001). BST model estimations were reported to be highly reliable and the easiest to implement of the three methods.

In this study, a case study based on the consequence modeling of a possible industrial accident at a fuel station in Turkey was carried out for the first time. It was assumed that a LOC (Loss of Containment) occurred in the LPG storage tank, which is the most critical equipment in the fuel station. The possible physical effects of the LPG tank leakage were modeled over different accident scenarios for different leak hole diameters and atmospheric conditions with ALOHA software. In accident scenarios, jet fire, BLEVE and release to atmosphere without burning were considered. Overpressure effects, in which the largest and serious effects were determined, were also analyzed with the BST method, and the software results were supported.

2. MATERIAL AND METHOD

2.1. Data Supply

Hazardous Properties

In Turkey, typical LPG mixture contains 30% propane and 70% butane. Due to the limitation of modeling this mixture of the ALOHA software, modeling studies were carried out based on the highest content of butane.

Butane is used as a fuel, refrigerant, aerosol propellant and intermediate in the chemical industry. Its chemical formula is C_4H_{10}. Its CAS number is 106-97-8. Its flammability and health effects scores are 4 and 1, respectively (Figure 1). These properties make the chemical extremely dangerous (BP Group, 2021). The important physical and chemical properties of butane are shown in Table 1.

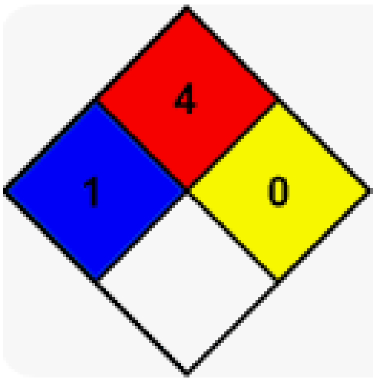


Figure 1. *Hazard diamond of butane*

Table 1. *Physical and chemical properties of butane*

Physical state	Liquefied gas
Molecular weight	58.12 g/mol
Color	Colorless
Smell	Sulphurous
Melting point	-138°C (-216.4°F)
Boiling point	<-2°C (<28.4°F)
Critical temperature	-60 °C
Flash point	In closed container:<-50°C (<-58°F)
Auto ignition temperature	365°C (689°F)
Relative gas density	1.9 - 2.1 [Air = 1]
Explosive limits	1.9 -9%

The explosive lower limit of the chemical is quite low. This highlights the danger of flammability.

Characteristics of Fuel Stations

According to the Workplace Hazard Classes Communiqué on Occupational Health and Safety, fuel stations are in the very dangerous class. As a condition of establishment of fuel stations, they must meet the Turkish Standard (TS) 12820 Fuel Stations Safety Requirements Standard. Most of the precautions taken against explosions at fuel stations are also valid in cases where LPG will be sold, and additional precautions are specified in the TS 11939 LPG Supply Stations Safety Requirements Standard and other standards required by this standard. In accordance with the relevant legislation and standards, a fuel station should not be established and operated without making a dealership agreement with the company holding the distribution license granted by EMRA (Energy Market Supervision Agency). Fuel is stored in tanks at the stations. It is manufactured as single or double walled, single compartment or multi compartment. The inner tank (main tank) of double-walled tanks is surrounded by an outer tank, the tank walls are physically separate and at a certain distance from each other, and in case of a leak in the inner tank, it is aimed to protect this leak in the space between both tanks. A maximum of 300 000 L of fuel can be stored at the fuel station, provided that it does not exceed 50 000 L per tank. For this reason, filling is done every day or every two days at large stations (Tuncay, 2014). Fuel stations containing highly dangerous chemicals pose a risk to humans and the environment. For this reason, safety distances are defined. (Table 2)

Table 2. *Minimum safety distances for underground tanks (Demircan, 2010)*

Tank volume (L)	Distance of underground tanks to neighboring plot boundary, main traffic roads or railways (m)*	The distance of the tanks to each other (m)*
≤500	0	0
500-3000	3	1
3001-10 000	5	1
10 001-50 000	7.5	1
50 001-120 000	10	1.5
120 001-250 000	15	1⁄4 of the sum of the diameters of the tanks adjacent to each other
250 001-600 000	15	
600 001-1 200 000	15	
1 200 001-5 000 000	15	
≥5 000 001	15	

* Distances are the shortest distance measured from the outer wall of the tank

While the distance between the tanks within the station is 1.5 m at most, the distances to the neighboring borders and access roads can reach 15 m. Safety distance is an important measure for risks, but it is not enough. Depending on the physiochemical properties of the hazardous chemical, the effects of fire, explosion or toxic emission of possible accidents can reach kilometers distance. Consequence analyzes need to be considered for emergency plans and fuel station locations (Ahn et al., 2020).

The schematic representation of the tank size for LPG storage tanks in the relevant standard is given in Figure 2, and the tank size data is given in Table 3 (GBS, 2019).

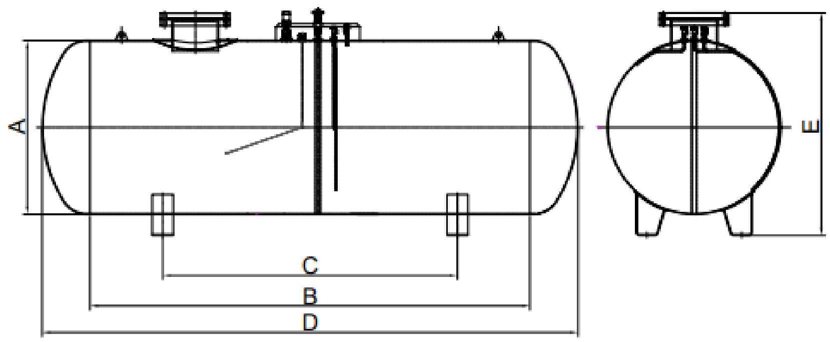


Figure 2. *Tank size schematic ıllustration*

Table 3. *Data on tank size (GBS, 2019)*

Volume (L)	A (mm)	B (mm)	C (mm)	D (mm)	E_{max} (mm)
10 000	1 600	4 500	3 300	5 392	2 160
10 000	1 900	2 850	1 850	3 974	2 420
22 000	2 350	4 500	3 300	5 745	2 850
40 000	2 400	8 000	4 000	9 350	2 900
50 000	2 400	10 500	5 250	11 850	2 900

The volume per tank at fuel stations is allowed to be 45-50 m^3. LPG storage tank volumes can be preferred in smaller sizes upon request.

2.2. Determination of the Accident Scenario and Related Assumptions

It was assumed that there was a LOC in the LPG storage tank located at a fuel station in Kocaeli. The reason for choosing Kocaeli as the location is that it is an industrial area, the fuel stations are close to the settlements and the probability of a domino effect is high. Modeling studies were carried out in two different atmospheric conditions, summer and winter, with the foresight that atmospheric conditions may change the LPG release. Meteorological data of January for the winter condition and August for the summer condition were used.

The chemical source was accepted as the tank. Fuel stations sold on LPG must comply with the TS 11939 LPG Supply Stations Safety Requirements Standard, together with the TS 12820 (2006) Fuel Stations Safety Requirements Standard. It is stated that at a fuel station conforming to this standard, a maximum of 300 000 L of fuel can be stored, provided that it does not exceed 50 000 L per tank (TS 12820, 2006). Therefore, when the tank standards are examined, it is seen that 40 000 liter tanks are suitable for the accident scenario. The volume of the tank is 40 000 L (40 m^3), the width of the tank is 2 400 mm and the height of tank is 2 900 mm. Since it is necessary to automatically prevent the tanks at the LPG refueling station from being filled above 85% of the nominal water volume, the tank filling rate was taken as 80% (Tuncay, 2014).

2.3. Modeling with ALOHA Software

The main purpose of ALOHA software is to provide emergency response by estimating of the effect distances of chemical releases (Jones et al., 2013). The software has its own library of chemicals, but is used for modeling pure substances and few mixtures (Cetinyokus, 2017). ALOHA software links direct, tank, puddle or gas piplene source models to a dispersion model to predict the effect distances of toxic clouds, flammable vapors and explosive vapor clouds.

With the ALOHA software, at first location and chemical selection was made. Then, atmospheric conditions of the selected region were considered and accident scenarios were created and modeled according to the source selection.

Location and Chemical Selection

ALOHA software is limited in modeling many mixtures. For this reason, modeling was done on high content butane considering the mixture of LPG consisting of 30% propane and 70% butane. Kocaeli province was selected as the location in the software.

Atmospheric Options

Meteorological data of January for winter conditions and August for summer conditions were used (Directorate General of Spatial Planning, 2018). Atmospheric data of Kocaeli province are given in Table 4.

Table 4. *Atmospheric data*

	January	August
Air temperature	6.2°C	23.9°C
Wind speed	1.5 m/s	1.4m/s
Wind direction	West North West	South East
Cloud cover	Partly Cloudy	Partly Cloudy
Humidity	75.8%	70%
Ground roughness	Open country	Open country
Atmospheric stability	F	E
Altitude	1 m	1 m

In the software, the ground roughness was chosen as the open country where there were no congested structures around, and the selection was made for the impact distances to be at the human level. The software automatically set the atmospheric stability class as F for January and E for August. Selections were made with no inversion and humidity of 75.8% and 70% for January and August, respectively.

Chemical Source and Scenario Selection

Modeling studies were performed over three basic scenarios, considering different leak hole diameters and atmospheric conditions. Values such as tank size and tank filling rate were taken the same for each scenario. Modeling was done by assuming the hole that caused the leak as a circular form, both while using the ALOHA software and applying the BST method (Table 5).

Table 5. *Accident scenarios*

Scenario (1): In August/January, leaking tank, chemical is not burning as it escapes into the atmosphere.
Leak hole diameter= 4 cm
Leak hole diameter= 10 cm

Scenario (2): In August/January, leaking tank, chemical is burning as a jet fire
Leak hole diameter= 4 cm
Leak hole diameter= 10 cm

Scenario (3): In August/January, BLEVE, tank explodes and chemicals burn in a fireball

2.4. Modeling with the BST Method

The BST method was used to determine overpressure and impulse estimates from vapor cloud explosions. The method is based on only the congested or partially congested portions of a flammable vapor cloud contribute to the overpressure. It estimates the detonation energy (E) based on the average stoichiometric fuel-air mixture. It also uses a family of curves to determine ΔP_s as a function of the combustion energy scaled distance and a numerically determined continuous pressure and pulse curves that take the flame Mach number as a parameter. The strength of the blast wave is proportional to the maximum flame speed in the cloud. The appropriate Mach number, M_f, for each special case modeled can be taken from Table 6 (Casal, 2018).

Table 6. *Mach numbers (M_f) to be used in the BST method (Casal, 2018)*

		Congestion		
Flame expansion	Reactivity	Low	Medium	High
2D	High	0.59	DDT	DDT
	Medium	0.47	0.66	1.6
	Low	0.079	0.47	0.66
2.5D	High	0.47	DDT	DDT
	Medium	0.29	0.55	1.0
	Low	0.053	0.35	0.50
3D	High	0.36	DDT	DDT
	Medium	0.11	0.44	0.50
	Low	0.026	0.23	0.34

DDT: transition from deflagration to detonation

In Table 6, no plane limiting flame expansion is considered 3D. Presence of a single bounding plane means 2D flame expansion. The 2.5D restraint category corresponds to situations where the restraint is made from a frangible panel or nearly rigid restraint. If the congestion is below 10%, it is considered low, between 10% and 40% medium, and above 40% high. Three different categories for the reactivity of fuels were recommended as highly reactivity fuels (hydrogen, acetylene, etc.), low reactivity fuels (methane and carbon monoxide) and medium reactivity fuels (all other gases and vapors) (Casal, 2018).

Scaled distance,

$$d_n = \frac{d}{M^{1/3}} \quad (1)$$

where

d_n : scaled distance (m $kg^{-1/3}$)

d : actual distance from the center of the explosion to the point at which the overpressure should be estimated(m)

M : charge mass (kg)

When two explosives with similar geometry of the same explosive but different dimensions are detonated in the same atmosphere, similar peak overpressures are produced at the same scaled distance. This is the simplest and most common form of burst scaling. Another approach suggested by Sachs to use below. The blast wave can be expressed as a function of the scaled overpressure and is calculated by (Eq. 2)(Casal, 2018).

$$\Delta P_s = \frac{Ps}{P0} \quad (2)$$

Combustion energy -scaled distance is calculated with (Eq.3).

$$R = \frac{d}{(\frac{E}{P_0})^{1/3}} \quad (3)$$

It is calculated with the Sachs scale impulse coefficient (Eq.4).

$$i_s = \frac{iu_s}{P_0{}^{2/3} E^{1/3}} \quad (4)$$

where

i : incident impulse (Pa s)

E : energy involved in the explosion (J)

P_0 : atmospheric pressure (Pa)

ΔP_s : side-on peak overpressure (Pa)

P_s : peak pressure (Pa)

u_s : speed of sound in air (m/s) (Casal, 2018).

The chemical mass determined in the ALOHA software was taken as the vapor volume. The explosion energy (E) was calculated by multiplying the volume by 3.5 x 10^6 J m^{-3}. The scaled distance (R) was then calculated. The appropriate Mach number was selected from the values listed in the method, and finally the peak pressure was determined. The vulnerability caused by the peak pressure was interpreted.

3. RESULTS AND DISCUSSION

3.1. Evaluation of ALOHA Software Modeling Results

Horizontal and cylindrical tank (L=9.35m, D=2.4m, V=42.3m^3) was selected based on the LPG storage tanks specifications in the fuel stations. LPG is gaseous under normal conditions, but is liquefied under pressure during filling into storage tanks. For this reason, it was chosen that the tank contained liquid and was stored according to the ambient temperature. The filling rate of the tank was taken as 80%. The leak shape was circular and the leak type was taken as a hole. Since the weakest points in a storage tank are the filling and discharge openings, it was assumed that a potential leak would occur from the filling and discharge points. The diameters of the filling and discharge openings in LPG storage tanks are approximately 5 cm for each 50 m^3 tank volume (Acikgoz, 2012). Considering this ratio, the leak hole diameter was determined as 4 cm. Model studies were also carried out by choosing a larger leak hole diameter of 10 cm. The effect distances obtained as a result of the modeling studies carried out for the months of August and January at different leak hole diameters are given in Table 7 and Table 8, respectively.

Table 7. *All effect distances obtained as a result of modeling studies carried out for August*

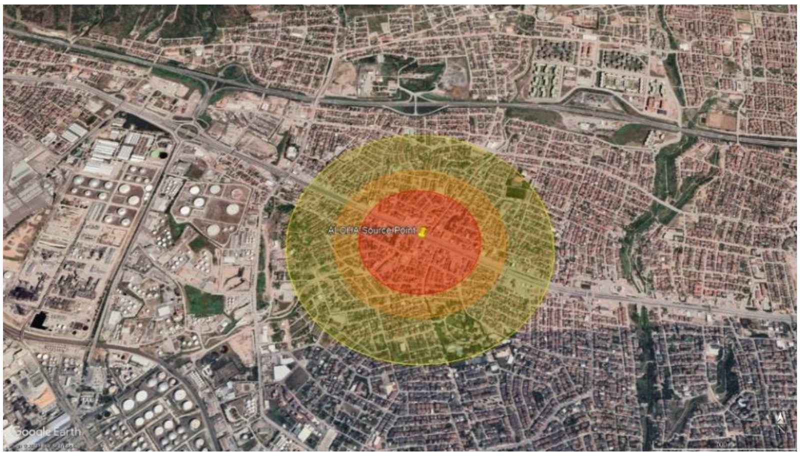
Leaking tank, chemical is not burning as it escapes into the atmosphere (Scenario 1)						
	4cm leak hole diameter			10cm leak hole diameter		
	Red Threat Zone	*Orange Threat Zone*	*Yellow Threat Zone*	*Red Threat Zone*	*Orange Threat Zone*	*Yellow Threat Zone*
Vapor Cloud Toxic Effects	75m	118m	194m	208 m	329 m	506 m
Vapor Cloud Flammable Effects	151m	-	348m	410 m	-	821 m
Vapor Cloud Explosion Effects	-	105m	185m	-	268 m	456 m
Leaking tank, chemical is burning as a jet fire (Scenario 2)						
	4cm leak hole diameter			10cm leak hole diameter		
Thermal Radiation Effects	23m	35m	57m	53 m	83 m	135 m
BLEVE, tank explodes and chemicals burn in a fireball (Scenario 3)						
	Red Threat Zone		*Orange Threat Zone*		*Yellow Threat Zone*	
Thermal Radiation Effects	346 m		488 m		761 m	

Table 8. *All effect distances obtained as a result of the modeling studies carried out for January*

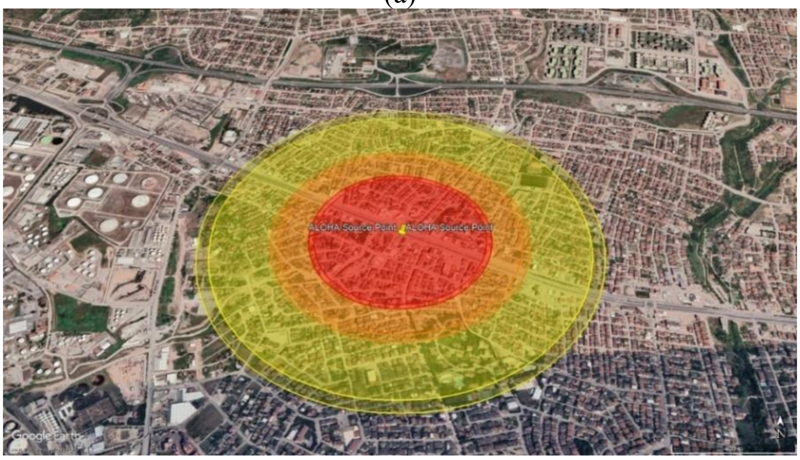
Leaking tank, chemical is not burning as it escapes into the atmosphere (Scenario 1)						
	4cm leak hole diameter			10cm leak hole diameter		
	Red Threat Zone	*Orange Threat Zone*	*Yellow Threat Zone*	*Red Threat Zone*	*Orange Threat Zone*	*Yellow Threat Zone*
Vapor Cloud Toxic Effects	55m	83m	137m	155 m	240 m	385 m
Vapor Cloud Flammable Effects	106m	-	250m	303 m	-	674 m
Vapor Cloud Explosion Effects	-	75m	134m	-	208 m	348 m
Leaking tank, chemical is burning as a jet fire (Scenario 2)						
	4cm leak hole diameter			10cm leak hole diameter		
Thermal Radiation Effects	15m	24m	39m	36 m	57 m	94 m
BLEVE, tank explodes and chemicals burn in a fireball (Scenario 3)						
	Red Threat Zone		*Orange Threat Zone*		*Yellow Threat Zone*	
Thermal Radiation Effects	367 m		519 m		810 m	

LOCs for toxic domains are specific to chemicals. For LPG, the red zone: >53000ppm(AEGL-3[60min]), the orange zone:>17000ppm(AEGL-3[60min]) and the yellow zone: :>5500ppm(AEGL-3[60min]) represent threshold values. In AEGL-3, the general population suffers from serious life- or death-threatening problems from toxic spread. In AEGL-2, the general population suffers irreversible and severe effects; in AEGL-1, the general population suffers from serious non-harmful and reversible effects. For the flammable effects, the red zone and yellow zone represent >9600 ppm (60% LEL), >1600 ppm (10% LEL), respectively. LEL (Lower Explosion Limit) refers to the minimum vapor rate of flammable substances that should be in the air. Overpressure effects in three phases in the software are evaluated as red zone: 55.16kPa (building collapse), orange zone: 24.13kPa (serious injuries), and yellow zone: 6.89kPa (breaking glass). Threshold values for thermal radiation correspond to red zone: >10.0 kW/m^2, orange zone: >5.0 kW/m^2 and yellow zone: >2.0 kW/m^2. From the tables, as the leak hole diameter increased, the effect distances increased due to the increase in the amount of hazardous chemicals released into the environment. The effect distances determined for Scenario (1) and Scenario (2) in August were found to be higher than the effect distances determined in January. However, in the case of Scenario (3), the effect distances in August was less than in January. Since the gas diffusion around the cold environment was reduced, more dense gas in the limited area had led to this consequence. The most dangerous scenario was identified as the BLEVE in January. In the above tables, each effect distance was found to be significantly higher than the related safety distances (Table 2). Determining the effect distances, considering the relevant physicochemical properties and accident scenarios, is extremely important in preventing loss of life and property (Lee at al., 2019; Sierra et al., 2019).

It was observed that the thermal radiation area that will be formed by the explosion of the tank in Kocaeli can be of a dangerous size. The Google Earth images of the BLEVE threat zones determined for August and January are presented in Figure 3.



(a)



(b)

***Figure 3**. Google Earth images of BLEVE threat zones determined for **a)** August and **b)** January (Scenario 3)*

The explosion of the LPG tank was modeled at a fuel station in Guney neighbourhood, located in Korfez district of Kocaeli province. The reason for choosing this region is its proximity to the Körfez refinery area. In addition, there are approximately 40 LPG storage, tube-tanker filling, fuel storage and filling, ammonia production and storage facilities and ports belonging to these facilities located around the refinery. In parallel with the increasing influence with the development of industry in the Korfez, a rapid urbanization dynamic has occurred, which has led to the rapid growth of the city and the random increase in residential areas. The explosion at the fuel station located close to this place both affected the population and showed the possibility of internal and external domino effects. From the Google Earth images, it was seen that the affected neighborhoods were Kuzey, Esentepe, Barbaros, Guney and Yeniyalı. According to data of Turkish Statistical Institute, the number of households is 2 063 in Kuzey, 2 900 in Esentepe, 1 349 in Barbaros, 5 513 in Guney, and 3 476 in Yeniyalı. Many residences, workplaces and buildings were in threat zones. When the average number of people living in the household was taken as 3 and the most affected area according to the map was the Guney neighborhood, the affected population was determined as 16 539 people. From -Figure 3, it was seen that the effect distances in January were higher than in August. ALOHA software calculated the liquid LPG in the tank as 20 161 kg in January. In August, this was 19 492 kg. It was observed that the increase in the effect distance depended on the amount of LPG.

3.2. Evaluation of BST Method Modeling Results

Calculations were made at different limiting planes (2D, 2.5D, 3D) and at different target distances (d=300m, 500m and 650m) for comparison with ALOHA software outputs (vapor cloud explosion areas). Medium reactivity and medium congestion were considered. The temperature was included in the calculations in parallel with the ALOHA software, considering the months of January and August. Consequences of overpressure based on damage to buildings and structure and also people can be found in related referance tables (Casal, 2018).

BST Modeling results for four different target distances for August and January are presented in Table 9 comparatively.

Table 9. *Comparison of BST Modeling results on peak pressures(kPa) at different target distances for August and January*

	2D			*2.5D*			*3D*		
	300 m	500 m	650 m	300 m	500 m	650 m	300 m	500 m	650 m
August (T=23.9°C)	10.13	8.11	6.08	9.12	7.09	4.05	8.11	5.06	3.04
January (T=6.2°C)	8.11	7.09	4.56	8.11	7.09	3.04	8.11	3.04	2.03

In Table 9, it was observed that the overpressures decreased as the confining plane increased. It was obtained that the overpressure values in August were higher than in January. It was determined that the overpressure effects in summer will be greater than in winter. The results obtained with the BST method showed parallelism with the results of the ALOHA software (vapor cloud explosion areas). This is a natural consequence of the software being based on the BST method (Bai et al., 2021). However, the software also allows different selections (wind speed, wind direction, etc.) and simultaneously provides thermal radiation effects as well as overpressure effects. In ALOHA software, the vapor cloud explosion distance was 456m (6.89kPa) and 268m (24.13kPa) as a result of the leak in August. In Table 9, an overpressure of 5.06kPa occurred in an area of 500 meters for 3D. From the reference table (Casal, 2018), it was seen that this overpressure caused glass and window breakages in parallel with the ALOHA software result. It is important to ensure reasonable safety that people stay away from windows so that they are not affected by these glass and window breakages, and that they can lie on the ground if inside or outside a reinforced structure.

Hazards should be identified at stations and risk assessments should be carried out on a regular basis. Employees at the stations should be informed about workplace environmental factors, working conditions, hazards and risks, precautions to be taken, and training should be provided. The people of the region close to the fuel stations should be informed and their awareness should be increased within the scope of accident effects and emergency plans for possible accidents. The participation of the surrounding population in emergency plans should be ensured. LPG pipes installed above and underground, the placement of pipes, valves, sealing elements and other elements used in the installation must have ATEX properties in accordance with the relevant standards. The railway line passing between the flammable and explosive material storage facilities and the refinery makes it difficult to control the region and increases the risk of sabotage. Damage to these facilities may cause a domino effect and may cause explosions at nearby fuel stations.

4. CONCLUSION

Consequences analyzes were carried out at a fuel station in Turkey, which is located in a dense population and industry area. The LPG tank was taken as a critical equipment, and models were made with ALOHA software in different leak hole diameters and atmospheric conditions. Physical effects were determined by modeling a LPG leak in the tank based on not burning chemical release into atmosphere, jet fire and BLEVE scenarios. The two most dangerous scenarios were determined as the release of LPG without burning in August and BLEVE in January. It was observed that with the increase in the diameter of the leak, all the effect distances increased due to the release of more hazardous chemicals into the environment. BLEVE threat zones, where the largest effect distances for August and January, were transferred to Google Earth and affected areas were analyzed. It was shown that there may be serious exposures and domino effects may occur inside and outside the establishment in Guney neighborhood, which is located in Korfez district of Kocaeli province. Overpressure values were calculated with the BST method and the effects on the loss of property and life were investigated. In August, the vapor cloud explosion distance was determined as 456 m for 6.89kPa overpressure. With the BST method, an overpressure of 5.06 kPa was obtained in an area of 500 m with medium reactivity and congestion (3D). It has been determined that this overpressure may cause glass and window breaks and may cause injuries to living beings exposed to broken glass. In order to prevent these effects, it is important for living beings to stay away from windows and lie on the ground inside a reinforced structure or outside if they are outside to ensure safety. It was shown by this case study that the software and correlation results were compatible with each other. It was determined that the relevant safety distances at the stations were insufficient in risk assessment studies. It has been shown that the physicochemical properties of the chemical that may be involved in the accident, equipment specifications, atmospheric conditions and scenario selection, as well as the relevant facility environmental factors should be taken into account especially in risk assessment studies.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ABBREVIATIONS

ALOHA	: Areal Locations of Hazardous Atmospheres
ATEX	: Atmosphere Explosible
BLEVE	: Boiling Liquid Expanding Vapor Explosion
BST	: Baker-Strehlow-Tang
CFD	: Computational Fluid Dynamics
D	: Diameter(m)
DDT	: Transition from Deflagration to Detonation
E	: Explosion Energy(J)
EMRA	: Energy Market Supervision Agency
L	: Length (m)
LEL	: Lower Explosion Limit
LNG	: Liquefied Natural Gas
LOC	: Loss of Containment
LPG	: Liquefied Petroleum Gas
M_f	: Mach Number
PLL	: Potential Loss of Life Index
R	: Combustion Energy Scaled Distance (m)
TS	: Turkish Standard
VCE	: Vapor Cloud Explosion

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