SAFETY AND HEALTH RISK ASSESSMENT OF REFILLING GAS STATIONS

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Abstract

Objective: Gas refilling stations are increasingly established across Arar, Northern Borders, to meet rising domestic and industrial energy demands. However, the potential occurrence of fire and explosion illustrates critical safety and health issues, especially in populated regions. The report provides an analysis and assessment of gasoline concentration released at different gas stations using quantitative analytical methods in order to estimate thermal radiation impact and fatality rate.

Methods: The key parameters determined incorporate trend analysis, frequency analysis, basic statistics, and interactions affecting the analysis, all conducted using fireball modelling and probit analysis.

Results: The research highlights the fireball radii proportional to gas capacity. It is increasing with time concerning over gas emissions, which are considered a significant factor contributing to health diseases and are associated with cancer. The investigations show that large gasoline capacity generated fireball lift heights exceed more than 1000 m with higher fatality rate. In addition, the distance from the center of fireball to the target object exceeded the measure of the object distance, indicating substantial thermal radiation impact damage. Data showed that explosion thermal dose generate high risk for near populated zones.

Conclusion: The data analysis results align with existing literature, showing that excessive capacity result in increasing the rate of emission which alter air quality and pose health risks. The study figure out that the increasing demand of gas filling station due to the increasing production of automobiles and industrial usage will increase the risks of fire and explosion if authorized agents will not set stricter regulations, i.e. emergency response and design an acceptable distances.

Keywords: gasoline; risk; analysis; fireball; probit; emission; health.

1. Introduction

Gasoline has emerged as one of the largest energy sources in Kingdom of Saudi Arabia due to the huge number of petroleum refineries plants. It is increased rapidly during the current era since the number of the drivers increased sharply due to the governmental allowances rule for women to drive. Gas filling stations have been widely prompted by private sector and energy stakeholders.

In Northern Saudi Arabia, particularly in Arar, Rafha, Turyef and Owygela, urban expanding, rising population density, and increased commercial activities have simulated rapid proliferation of gasoline storage and refilling station.

This expansion has improved access to supported economic activities, small scale industries, and transportation. However, the accelerated development of gasoline and LPG infrastructures has induced safety concerns. For instance, refilling stations have been established near populated areas where residential, schools, markets, healthcare facilities located.

Despite the economic and the degree of efficiency of fuel, air pollution has become one of the most urgent global environmental issues, which require a rapid response from authorities to tackle this problem. It has obviously affected the human body and natural resources. Moreover, as the industrial sector increased and urban grown, the number of vehicles increased, thus an increase in gas emission noted. A carcinogenic fuel such as gasoline which involve serious threats to public health and air quality stimulate authorities to design a valid monitoring and mitigating strategies. According to The World Health Organization (WHO) [1], seven million per year were affected due to gas emission and air pollution. Across Kingdom of Saudi Arabia, people have always been content with excessive heat, dust storms, shortage of rainfall, and harsh geography. The industrial revolution, that started in the 18th century and rising emission, has already occurred. Nevertheless, environmental pollution was exacerbated by rapid industrialization in the 20th century. Therefore, pollution has become global problem [2].

It is well understood that air pollution is responsible for many aspects of human health and the loss of environmental productivity. The purpose of this research is to provide an analysis and assessment of gasoline concentration released at different gas stations using quantitative analytical methods in order to estimate thermal radiation impact, fatality rate in gas stations and investigate their impacts on human health, mainly gasoline.

$$2C_8H_{18(l)} + 25O_{2(g)} \rightarrow 16CO_{2(g)} + 18H_2O_{(g)} \quad (1)$$

The equation illustrates a complete combustion reaction of gasoline in an oxygen-rich environment. Gasoline, when burnt, reacts with oxygen (O_2) to produce carbon dioxide (CO_2) and water (H_2O). This process is extremely important in terms of air pollution, greenhouse gas and climate change.

Gasoline release from vehicles, refueling activities, refineries and vehicle exhaust. These are major sources of air pollution. Gas stations have been reported to be a continuous source of volatile organic compounds [3], and refilling is one of the emission sources of VOCs [3, 4]. Gasoline emissions in urban environment are largely due to automobile exhaust. Elevated gas emission levels in residential areas near gas stations, suggesting a persistent source of pollution that will remain until additional measures are in place to eradicate it [5].

Recent studies reinforce that long exposure to benzene, even under low concentrations, represents an important risk factor for increased dispersal of hematologic malignancies and immuno-system suppression [6, 7]. Furthermore, recent epidemiological studies have also confirmed a direct correlation between occupational benzene exposure and the development of acute myeloid leukemia. Public health concerns related to benzene emissions from transportation and industrial activities continue to be of concern in urban and semi-urban environments [8, 9]. This knowledge highlights the importance of more stringent regulatory measures to limit workers and communities residing around gas stations from being exposed.

Field and modelling studies have recently been conducted and validated the persistence of hydrocarbon vapors as a local source from refueling stations. The hydrocarbon releases from fuel storage and transfer at gas stations and their environmental and health effects were reviewed by Hilpert et al. [3] and direct implications of the measured vent-pipe emissions from underground storage tanks, which were many times larger than previously assumed, were made for setback distances [10]; and clusters of neighboring stations further increase the estimated lifetime cancer risk from benzene for neighboring residents [8]. High levels of benzene have been found and associated health hazards in the vicinity of petrol stations in Greece [4] and Spain [11], in a service-station environment in Australia [12] and at gasoline and CNG refuelling stations in Iran [13]. BTEX were identified as the primary emission source from vehicles in the urban atmosphere of Jeddah, Saudi Arabia [14] and high concentrations of benzene, toluene and xylene around fuel stations in urban cities of the Kingdom were found, resulting in high cancer risk to the residents and workers nearby [9]. Globally, millions of people have been estimated to be dying prematurely due to exposure to outdoor pollution [2]. Also, emissions occur from vehicle operation and hot-soak, spills, and leaks from connectors and components. The focus of this study is to evaluate the impacts of gasoline emissions from gas stations on human health and environmental safety; over time, benzene exposure also results in fire and explosion events.

Gasoline is a chemical substance since its physical properties can be modified as a function of vapor pressure, resulting in the production of dangerous toxic gases. Human exposure to benzene has been associated with a range of acute and long-term adverse health effects and diseases. Chronic exposure to benzene can reduce the production of both red and white blood cells from bone marrow in humans, resulting in aplastic anemia and a reduction of birth weight [6, 15, 16].

According to the classification system developed by the International Agency for Research on Cancer (IARC), gasoline belongs to carcinogenic physical factors for humans that cause acute leukemia, which could lead to an increased risk of mortality from leukemia [17, 18]. Therefore, special attention must be paid to the degree and duration of benzene exposure because safe levels of benzene are uncertain and depend on other factors, such as absorption susceptibility.

It is listed as an ACGIH suspect human carcinogen with the properties given in Table 1.

Table 1. Physical and chemical properties of gasoline

Property	**Value**
Molecular weight (Mw)	114.1
Boiling point	27–224 °C
Density	740 kg/m^3
Vapor pressure	305
Flash point	12.2 °F
Auto-ignition temperature	228–470 °C
Research Octane Number (RON)	95

It is a toxic pollutant known to cause cancer. It was declared a hazardous air pollutant under section 112 of the Clean Air Act. According to a record Environmental Protection Agency (EPA) source inventory, more than eighty percent of gasoline emissions in the K.S.A. are from mobile sources, of which the majority is from exhaust and the remaining of approximately 15% from evaporative emissions.

The second measurement series for the evaporation of the exposure of particular classes of workers to gasoline takes into account the threshold limit value (TLV) of 300 ppm (900 mg/m^3) proposed by ACGIH, which replaces the present value of 32 mg/m^3 (Table 2).

Table 2. Occupational exposure limits and toxicity data for gasoline

Parameter	**Value**
Threshold Limit Value (TLV/TWA)	900 mg/m^3 (300 ppm)
Permissible Exposure Limit (PEL)	900 mg/m^3 (300 ppm)
Short-Term Exposure Limit (STEL)	1500 mg/m^3 (500 ppm)
LD_{50} (oral, rat)	4894 mg/kg
LD_{50} (oral, mouse)	4700 mg/kg
LD_{50} (IPR, rat)	2.9 mg/kg
LC_{50} (IBHL, mouse, 7 h)	9980 ppm

Acceptable maximum peak above the acceptance ceiling concentration for an eight-hour shift = 150 ppm for 10 minutes.

$(PEL)_{Ceiling}$ = 500 ppm for eight hours. 750–3500 ppm for 5 hours produces some illnesses such as headache, weakness, nausea, vomiting, dizziness, narcosis, suffocation, and central nervous system depression. Inhalation of vapor may cause severe irritation of burns of the respiratory system, pulmonary edema, or lung inflammation.

Liquid may be irritating skin and eyes. Prolonged skin contact may result in dermatitis. Eye contact may result in temporary corneal damage.

2. Environmental Exposures

Benzene is highly volatile, and most exposure is through inhalation. It is degraded rapidly in the upper atmosphere. Because of its solubility in water, a minor amount may be removed by rain to contaminate surface waters and soil. However, it is not persistent in surface water or soil, either volatilizing back to air or being degraded by bacteria.

2.1 Sources of Exposure

Gasoline is released from several man-made sources. The primary sources of environmental benzene are automobile exhaust emissions, evaporative losses, and refueling emissions. Gasoline in automotive exhaust is a mixture of incompletely burned gasoline produced in the motor during combustion through the dealkylation of toluene and xylenes. From industrial sources, it primarily enters the environment as fugitive emissions from industrial intermediate

production and processing operations and through air emissions from wastewater treatment plants.

However, automobile emissions are a significant pollution source and a source of gasoline emissions that warrant regulatory attention because benzene is widely used and emitted in large quantities. Examples include (1) oil refineries, (2) industrial production and processing of gasoline, (3) coking plants, (4) stationary combustion of fossil fuels for energy production, (5) road traffic, (6) evaporative losses, and (7) gas stations [3].

Although the use of gasoline has been gradually reducing over the last decade, exposure to gas emission still constitutes an environmental health stress due to the relatively elevated concentrations such as gas filling stations.

In addition to direct releases, the broader fuel supply chain that can lead to refilling stations can result in secondary pollution impacts that should be part of a comprehensive assessment of risk. Fuel quality can be improved by lignin derived heterogeneous catalytic oxidative desulfurization under mild condition [19] and other liquid fuels can be supplied by other thermochemical processes, such as product selective pyrolysis [20], catalytic pyrolysis of waste polystyrene over Fe–B composite catalysts [21] and co-pyrolysis of waste frying and engine oil to produce diesel like fuels [22], and the production of methanol from the coal gasification can be evaluated using energy, exergy, economic and environmental indicators [23]. Additionally, refinery-type sulfidic and thiosulfate-containing effluents have been treated by catalytic oxidation with hydrogen peroxide [24] or using iron salts [25], by aeration which involves an ultrasonic vibration [26] and by catalytic/oxidative removal of thiosulfate [27, 28] reaching the aquatic environment as well. Historically, leaded gasoline has been considered as a source of heavy metals in wastewater, which can be clean up by adsorption on Saudi Arabian clay [29]. On the station side, car-wash systems used to be significant consumers of fresh water, and effective water reclaiming systems based on lamella settlers [30] are available at low cost; on the other hand, heterojunction assisted photocatalytic oxidation is considered as a decentralized method for the treatment of organic contaminants in such effluents [31]. According to this research, the environmental effects of gasoline distribution go beyond the petrol pump, and should be considered in regional environmental management plans in the Northern Borders.

2.2 The Aim of the Review

A review of gasoline emissions from gas stations and automobile exhaust emissions has been written, and their impacts on human health have been evaluated. The purpose of this chapter is to describe quantitatively the mechanical failure, corrosion, poor maintenance, external fire, impact damage, or over-pressurization from which a catastrophic consequence could occur. One of the most severe accident scenarios resulting from a pressurized gasoline tank is the Boiling Liquid Expanding Vapour Explosion (BLEVE). It occurs when a vessel containing superheated liquid ruptures suddenly. This leads to rapid depressurization and instantaneous flash vaporization of the liquid contents. The first phase of transition generates a strong explosion.

The physical impacts of BLEVE are multidimensional and devastating. When the vapor expands in the presence of an ignition source, a fireball occurs, emitting strong thermal radiation.

In developing regions, including many parts of Arar, Northern Borders of Kingdom of Saudi Arabia, rapid urbanization frequently outpaces regulatory planning and high land demand often leads to hazardous facilities being sited without adequate separation distances from vulnerable receptors. Limited application of advanced hazard modeling tools during licensing and approval processes reduces the ability of authorities to accurately predict impact zones associated with worst-case scenarios.

A Quantitative Risk Assessment (QRA) is essential to evaluate both the probability and consequences of BLEVE scenarios. It provides a scientific basis for estimating fireball dimensions, radiation intensity, and probability of fatality. This assessment supports evidence-based decision-making criteria, strengthens regulatory standards, and enhances public safety planning.

In Northern Saudi Arabia, the application of QRA is not only technically suitable but essential for sustainable energy development, since there are no obvious standards to follow and apply to different fuel stations to limit gasoline releases.

Consequence modelling can be highly dependent on the representation of heat transfer and thermal radiation. Numerical tools to describe the radiative heat flux from a fireball towards a receptor nearby can be adapted from studies on entropy optimized radiative flow of Maxwell ternary nanofluids with heat generation [32], three-dimensional unsteady viscous flow with thermal radiation across rotating discs [33] and CFD analysis of heat-transfer enhancement in concentric tube heat exchangers [34]. Uncertainty in input data, like stored mass, separation distance and failure frequency, can also be addressed by data-driven approaches: machine-learning based prediction and optimization of exergy efficiency of a cumene plant under uncertainty [35], an improved grey-wolf-optimized artificial neural network for prediction [36], dual predator optimization for energy management in hybrid power systems [37] and complex fuzzy bipolar soft sets for decision making [38]. Hydrogen and fuel-cell systems [39] and hybrid microgrids providing electric-vehicle (EV) charging stations [40] will also be deployed in locations alongside, or increasingly replace, gas pumps; hydrogen production from algal biomass [41] and lithium–sulfur batteries [42] will all be co-located with gas pumps. This should be expanded to these new fuels and storage systems in the QRA approach used in this work.

2.3 Risk of Worker Exposure

Exposure to gasoline is evaluated by the Occupational Safety and Health Administration (OSHA) Permissible Exposure Limit (PEL), and Leaking Underground Storage Tank (LUST) sites were evaluated at the current PEL of 1 ppm. EPA has documented Reference Concentrations (RfCs) and Reference Doses for chronic oral exposures (RfDs) in the Integrated Risk Information System (IRIS); the latest inhalation reference concentration of benzene is 0.03 mg/m^3 [43]. A review of the relevant literature suggests absorption efficiencies of 50%

and 100% for inhalation and oral routes of exposure, respectively. Adverse effects of benzene on human health depend on its concentration and exposure time.

Other research papers presented the adverse effects of gasoline and the cancer risk induced by inhalation [44, 45].

Vapour inhalation is not the only type of occupational and environmental exposure that can be experienced at fuel stations. A significant leakage pathway is leakage from buried lines and tanks: experiments with micro-hole leaks in a buried underground natural gas pipeline demonstrated that leakage rate is related to the earth cover and compaction level [46] which are relevant to the underground gasoline storage tanks and LUST sites. Bioremediation of petroleum sludge by the effective microorganism (EM) technology is an effective approach for treating spilled hydrocarbons [47] and membranes that use membrane oscillation and the geometry of the pores to control oil–water separation are effective methods of treating oily wastewater [48]. A common approach to treat the wastewater generated by car-wash facilities that are often located with fuel stations is by coagulation–flocculation and sand and gravel filtration [49], a dedicated treatment-process design for local car-wash stations [50] and low-cost treatment units that decrease fresh-water consumption [51]. In case of acidic and lead contaminated effluents, such as automotive battery production, then appropriate neutralisers can be used [52, 53] and emerging contaminants and toxic metals like cadmium can be treated using myco-remediation [54] and conventional or emerging adsorbents [55]. The chronic exposure of workers and adjacent communities could also be decreased when these control measures are incorporated into station design, as well as the acute fire and explosion hazards mentioned in this work.

Forecourt workers have the highest exposures as detected by occupational studies. The findings of 150 gasoline station workers in Thailand, a gas station workers study in Brazil using passive sampling, and a diesel station workers study at a bus depot in South Africa are similar, with approximately 70% of the workers at the gasoline stations having a risk assessment greater than the acceptable risk [44, 45, 56, 57]. The International Agency for Research on Cancer (IARC) has classified benzene as a carcinogen group 1, which means it is definitely carcinogenic to humans [17]. A systematic review and meta-analysis has found that exposure to benzene at work is associated with an increased risk of leukaemia [18]; haematotoxicity is observed in workers exposed to benzene levels below 1 ppm [15]; and mechanisms and susceptibility factors are detailed which link benzene to leukaemia and other health effects [6, 7]. These findings prove the need to impose a more stringent exposure control for station attendants in the Northern Borders region.

3. Fireball Modelling

When a BLEVE occurs, a fireball forms with characteristics dependent on mass. Empirical correlations are commonly used to determine fireball radius (R), duration (t), height (h), heat flux (q), and thermal dose (k). Thermal dose can be determined as:

$$k = q^{4/3} \times t \quad (2)$$

The probit model is then applied to evaluate the fatality rate:

$$Y = a + b \ln(k) \quad (3)$$

where Y is the probit value, a and b are empirical constants, and k is the thermal dose.

The fireball correlations and probit functions used in this study have been published in the process-safety literature. The mechanism, consequence assessment and management of BLEVEs have been reviewed in detail [58, 59] and empirical correlations for the various aspects of fireballs that have been developed for releases of pressurised LPG have been analysed by Roberts [60] and quantitatively evaluated by Prugh [61], whilst thermal radiation from hydrocarbon pool fires was analysed by Mudan [62]. Real accidents like the LNG BLEVE of a road tanker in Zarzalico [63] and the LPG disaster in Mexico City [64] demonstrate the potential extent of damage such events can cause near populated areas, and the growing fire and explosion hazards of the increased usage of LPG in populated areas [65]. Overpressure and mechanical energy produced by a BLEVE can be estimated using a number of alternative methods [66]. Probit relationships for fatality from thermal radiation are based on the vulnerability model of Eisenberg et al. [67] and are commonly used in the TNO Green and Yellow Books [68, 69] as well as in references on the effects and consequences of major accidents [70].

To assess the risk associated with the gas released from gas stations, several scenarios were studied. To investigate the worst-case scenario, the scenarios were set up as follows.

3.1 First Scenario

Many refueling stations in the Northern region are installed within a short distance (15–50 m) from target objects such as buildings or populated areas. However, the potential impact radius of a BLEVE fireball may exceed 200 m in medium installations and 600 m in high-capacity facilities. However, there is limited quantitative assessment available for existing gasoline capacities, fatality rate, and thermal radiation exposure.

The purpose of the scenario is to evaluate BLEVE, including the characteristics of the fireball, heat flux, thermal dose, and estimation of fatality rate at selected gasoline refilling stations in the Northern region.

The station capacities ranged from small installations (5–50 units) to large storage systems of up to 5000–20000 units.

4. Research Methodology

The research methodology focuses on the application of Quantitative Risk Assessment (QRA) and the design of a model to determine the probability and consequences of such an event using Fault Tree Analysis and Event Tree Analysis.

4.1 Study Area and Data Collection

Refilling stations across Arar, Rafha, and Owygela were analyzed. The data collected include:

(a) Gasoline storage capacity (V)

(b) Estimated gasoline mass (M)

(c) Measured distance to the nearest target object (D)

(d) Station identification code

4.2 Quantitative Risk Assessment (QRA)

The QRA framework was applied to estimate both the probability and consequences of BLEVE scenarios at selected gasoline refilling stations. The QRA methodology applied the international standards of CCPS [71], the TNO Books [68, 69], and the HSE risk criteria guidelines [72]. Risk is defined as:

$$\text{Risk} = \text{Probability} \times \text{Consequences} \tag{4}$$

4.3 Failure Rate (FR)

A mathematical model was used to evaluate the failure rate of gasoline refilling stations:

$$FR = 1 / E_{MTBF} = [N / S]_{T\ unit} \tag{5}$$

Therefore, the total failure rate can be determined as:

$$FR_{total} = FR_{T\ unit\ A} + FR_{T\ unit\ B} + FR_{T\ unit\ C} \tag{6}$$

The BLEVE consequence calculations for the four selected stations (S1–S4) are summarised in Table 3.

Table 3. BLEVE consequence calculations for the four selected stations (S1–S4)

Parameter	S1	S2	S3	S4
Volume of storage tank, V (m^3)	60	100	10	15
Distance to target, D (m)	12	10	25	25
Mass of gasoline, M (kg)	3102	51700	5170	7755
Fireball radius, R_b (m)	93.3	110.26	52.1	39
Fireball duration, t (s)	12.52	14.32	7.8	8.4
Fireball lift height, H_{BLEVE} (m)	186.5	220.5	104.2	119
Distance X (m)	186.9	220.2	107.2	394.2
Surface emissive power, SEP (J/m^2)	2561397	203109.3	2561397	2213872
Heat flux, q ($J/m^2 \cdot s$)	469696	37096	469696	4186338
View factor, F_{view}	0.25	0.249	0.25	0.249
Thermal dose, k (kW/m^2)	437993330.3	1194551.8	437993330.3	1551780
Explosion energy, W × M (MJ)	4786.9	7971.32	4786.9	62243.3

Correlations: $R_b = C_g M^{0.325}$ with $C_g = 3.24$; $t = C_{10} M^{0.26}$ with $C_{10} = 0.852$. For S1, $M = 517 \times 60 = 3102$ kg and $R_b = 3.24 \times 28.82 = 93.3$ m.

4.4 Deductive Logic Structure

A top-down, deductive logic structure is used to evaluate how lower-level basic events combine through logic gates to cause a major system failure or undesirable top event. Qualitative

analysis evaluates the logical structure of the fault tree without using numerical probabilities. It focuses on how a system fails and identifies structural vulnerabilities.

4.4.1 Fault Tree Structure

Fault tree analysis is a deductive method used to determine the failure probability, often carried out in several steps:

1. Definition of the problem, system, and boundary conditions of the analysis
2. Construction of the fault tree
3. Identification of minimal cut sets
4. Qualitative analysis of the fault tree
5. Quantitative analysis of the fault tree

The study focuses on the qualitative and quantitative analyses of the fault tree and event tree.

Top event. The top event is the description of the critical system event.

Basic events. They are the lowest level of identified causes.

Logic gates. Symbols such as OR or AND are used to describe the gate, which gives the logical relationship between the TOP event and the basic events. Additional symbols are shown in the legends of Figures 1 and 2.

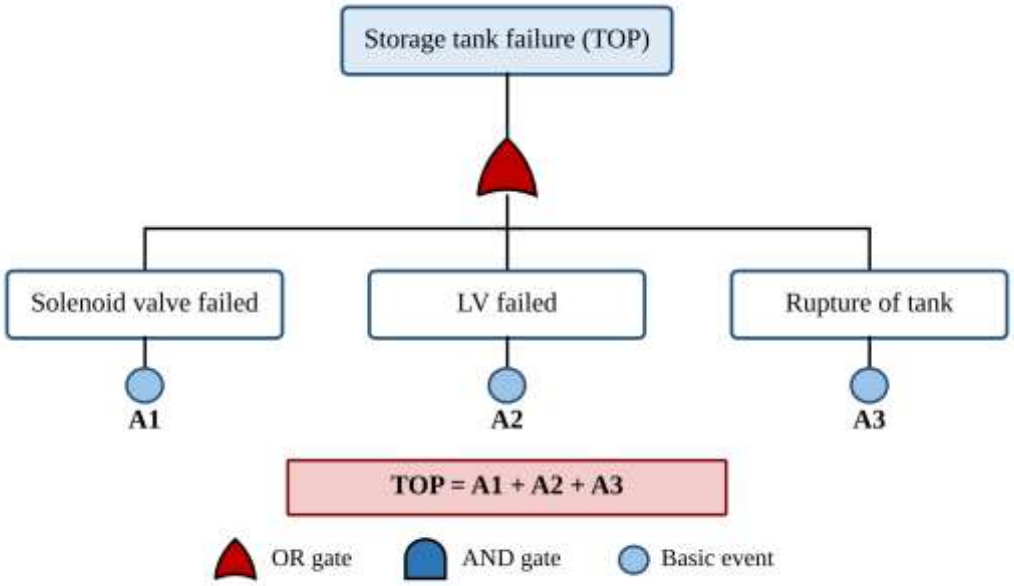


Figure 1. Fault tree of the storage tank.

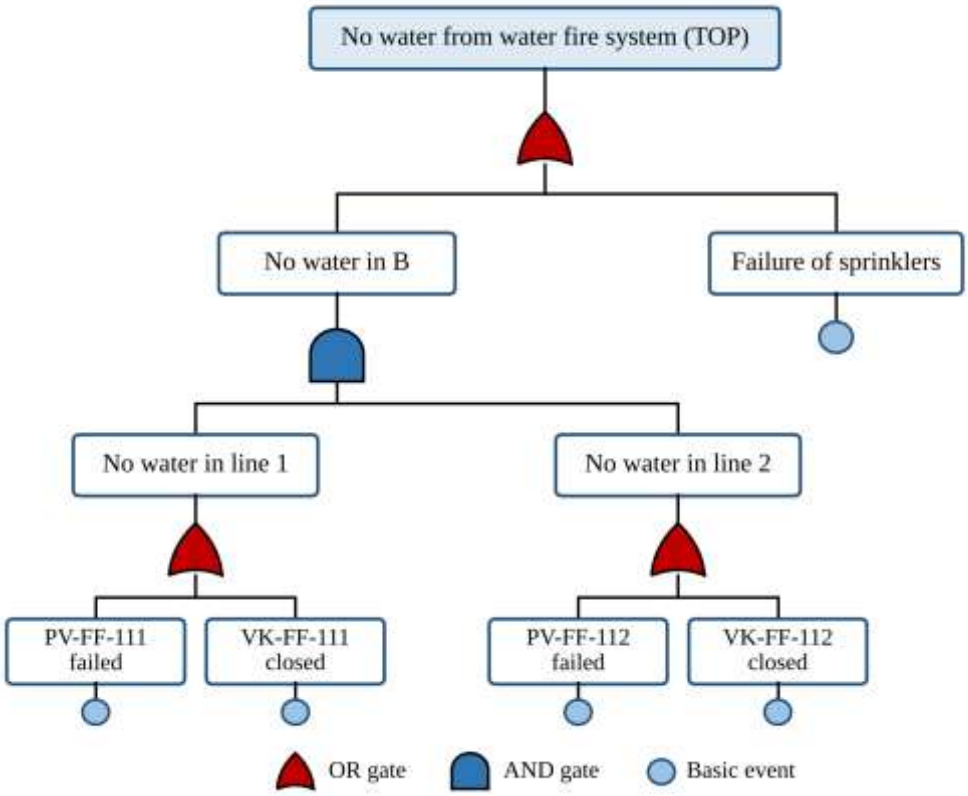


Figure 2. Fault tree of the water system.

4.4.2 Event Tree Structure

An event tree illustrates the probability of such an event happening. It is an inductive procedure which describes all possible outcome scenarios and consequences from a single initiating event. The structure involves several steps: identifying the initiating event, determining safety barriers, constructing the tree, assigning probabilities, and evaluating outcomes (Figure 3).

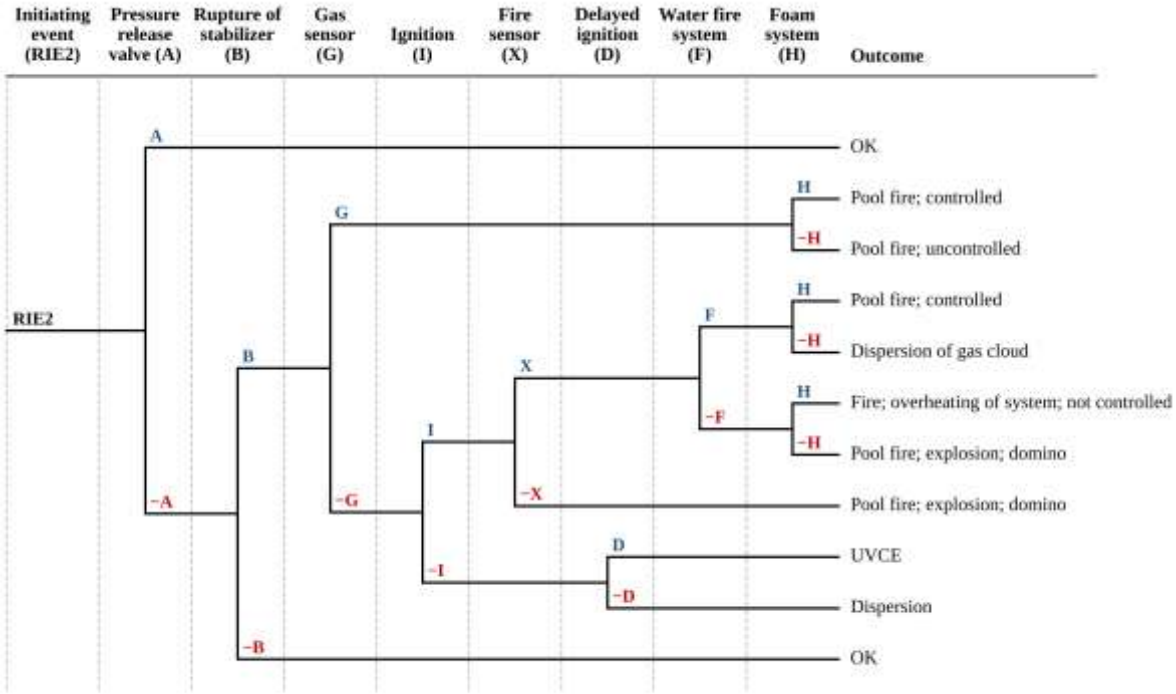


Figure 3. Event tree structure (initiating event RIE2).

The need for systematic risk analysis is underlined by accident statistics. Fires and explosions are the major outcome for major accidents in the process industries [73] and accidents in storage tanks [74] and domino effects, where one fire or explosion leads to other units, are a substantial proportion of chemical accidents [75–77]. The domino effect can be incorporated into a quantitative area risk analysis [78] and the damage probability of a station with multiple underground and above ground tanks can be estimated from a fire damage model of a single above ground tank [79]. The fault tree and event tree techniques used here are based on the Fault Tree Handbook [80] and recent studies have been published that discuss how uncertainty can be incorporated into the fault/ event tree analysis [81] and how the fault and event tree can be used in combination with a Bayesian network in process facilities [82] or fuzzy risk matrix for cases where limited failure data exists [83]. The HSE tolerability framework [72] can be used to frame risk-acceptance decisions, and separation distances and station layout can be assessed against codes of practice for motor fuel dispensing stations, such as NFPA 30A [84].

5. Results and Discussion

5.1 Results

The volume from refilling station to the target was determined across the regions to calculate the potential health and safety impacts in an event of explosion, i.e. BLEVE. The data are summarized in Table 3.

Station S1. Calculations for harm effects and loss prevention due to BLEVE illustrate catastrophic consequences, with fatality and injuries resulting from the high exposure to

thermal dose (Table 3). The damage resulting from the fireball is identical to economic loss. The expected distance of explosion is 186.8 m in 12.53 s.

Station S2. At station S2, there is an expectation of devastating explosion and critical injuries due to high exposure to thermal dose (Table 3). Damage from the fireball reaches the target since X is large. The expected distance of explosion is 220 m in 14.32 s.

Station S3. At station S3, there is an expected BLEVE with potential fatality and injuries due to high exposure to thermal dose (Table 3). The expected distance of explosion is 107.2 m in 7.8 s.

Station S4. At station S4, there is an expected BLEVE with a huge explosion resulting in devastating consequences, with fatality and injuries due to high exposure to thermal dose (Table 3). The expected distance is 394.2 m in 8.4 s.

In addition, economic loss can be determined by choosing a proper model such as the probit equation (Eq. 3).

5.2 Discussion

The results show that thermal radiation is the dominant hazard mechanism for the different scenarios. High-capacity installations generate extensive hazard zones, exceeding common urban setback distances.

Small installations may still pose local hazards when placed within 10 m of the nearest residential areas. Current siting practices in some regions appear inconsistent with the consequence modelling results. Assessment prior to licensing and strict compliance monitoring are highly recommended.

Loss-of-containment events caused by mechanical and climatic conditions should also be mitigated. It has been proven that a free vibration analysis can be used to identify damaged mechanical structures from undamaged structures [85] without causing any damage and can be used to identify deterioration in storage tanks and pipework and dispensers before failure. Two-stage evaporative coolers using an optimally sized air precooler [86] may be useful to reduce the equipment room and tank enclosure temperatures in the hot climate of the Northern Borders because of the high ambient temperature, which increases vapour pressure and evaporative losses. On the emissions front, the carbon dioxide emitted from gasoline combustion (Eq. 1) can be targeted with the implementation of poly(amide-b-ethylene) based membranes for CO_2 capture [87] and using nanomaterials based mixed matrix membranes for CO_2 capture [88] to reduce the amount of gasoline stored and dispensed, while bioethanol produced from waste banana peels [89] is an example of a renewable blending component that would help reduce the volume of gasoline stored and dispensed. These engineering and consequence-based siting measures would offer a more comprehensive approach to safety for the refuelling stations in the region.

6. Conclusion

The research illustrates explosion incidents at gasoline refueling stations in the Northern region of Saudi Arabia and presents substantial thermal radiation hazards. The study determines the

potential hazards and the consequences which lead to catastrophic results using qualitative and quantitative analysis methods.

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