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Risk assessment associated with Oil Storage Tanks. A case study: Buncefield accident

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ABSTRACT

The rapid expansion of the global economy has led to an increased focus on energy reserve strategies and production necessities within the petrochemical industry. As a result, the scale of petrochemical storage tank farms has expanded significantly, leading to increased capacity and more intensive development efforts. In recent years, several severe incidents—such as oil spills, explosions, and fires linked to storage tanks—have underscored the urgent need for a comprehensive investigation into the combustion and explosion dynamics of these facilities. This paper examines the mechanisms of explosive combustion in environments involving crude oil tanks, offering an extensive review of both domestic and international research advancements in the areas of crude oil explosions and combustion. Furthermore, it discusses several widely recognized risk assessment methodologies relevant to managing storage tank risks. Both qualitative and quantitative evaluations, complemented by simulations of accident consequences, can provide vital technical support for safety management and emergency response initiatives. To mitigate the risk of future incidents, it is crucial to draw lessons from previous accidents, enhance theoretical research, and implement effective safety protocols. This strategy will not only improve the safety of national energy reserves but also promote the overall integrity of the petrochemical industry.

Keywords: *crude oil, explosions, combustion, risk assessment, Storage Tanks*

1. Introduction

Safety in process industries is crucial for protecting against potential hazards. Therefore, it is essential to identify and acknowledge the possible risks that may arise within complex industrial and chemical processes. This recognition is vital for implementing effective risk mitigation strategies and ensuring the safety of future operations [1-6] .

In Chemical Process Industries, substantial incidents frequently arise from above-ground or "atmospheric" storage tanks vulnerable to containment breaches due to multiple factors. Some of the main contributors to tank failures include insufficient maintenance, operational mistakes, intentional sabotage, equipment malfunctions, the formation of cracks and ruptures, the buildup of static electricity, leaks, piping system failures, exposure to open flames, as well as natural disasters like earthquakes and hurricanes, and the occurrence of uncontrolled chemical reactions[7]. Furthermore, storage tanks are susceptible to damage and can easily be influenced by minor instances of overpressure or vacuum conditions[8]. In addition, the extensive global processing of crude oil, gasoline, various liquid fuels, and pressure-liquefied hydrocarbons has resulted in approximately 97% of all storage tank failures involving flammable substances. Accidental releases of these volatile liquids may occur due to operational errors, such as overfilling, as well as equipment malfunctions, including situations like the jamming of a discharge valve reported at Feyzin, or the development of cracks or ruptures in tanks or their connected pipelines [9-14].

Numerous catastrophic incidents over the decades, highlighting systemic weaknesses informing contemporary safety practices. Investigations into significant disasters, including the Flixborough, Bhopal, and Chernobyl incidents, reveal that the root causes of these industrial calamities frequently stem from critical oversights or failures in organizational structure and management practices[15]. Efforts to integrate non-hardware-related issues into hazard evaluations have primarily concentrated on minimizing human error at the operational level and enhancing the interactions between humans and machines [16] .

Before the 2005 Buncefield disaster, notable events such as the Flixborough explosion in the UK in 1974 and the Seveso chemical release in Italy in 1976 brought to light critical deficiencies in hazard management [17-19]. The Flixborough disaster, which resulted in the deaths of 28 workers and injuries to 36 others, was caused by an inadequately designed temporary pipe repair at a chemical facility, leading to an explosion with a force equivalent to 15 tons of TNT [20,21]. This tragic event served as a foundational moment for the development of process safety standards in the United Kingdom, underscoring the necessity for engineered safety measures and effective operational supervision. Similarly, the Seveso disaster, characterized by the release of toxic dioxin from a chemical plant in Italy, prompted the establishment of the Seveso Directive [19-22]. This directive requires comprehensive risk assessments and the establishment of emergency response plans for hazardous sites across Europe. Design and operational errors are frequently repeated, leading to the recurrence of similar accidents. This inability to draw lessons from earlier occurrences is not a conscious choice by designers or operators. It is broadly acknowledged that the chemical industry, as a collective entity, often fails to learn from previous incidents [23-27]. However, the Buncefield explosion demonstrated that complacency, fragmented safety systems, and human error can compromise the effectiveness of even the most robust regulations[28].

According to various reports, the vapor cloud generated by the overfilling incident at the Buncefield facility was extensive and was discharged over an extended duration [28,29,30]. However, these reforms seemingly neglected the crucial interconnections between technical and organizational safety measures. For example, the malfunctioning overfills protection systems at Buncefield, which were the result of insufficient maintenance, echoed similar shortcomings witnessed in prior disasters, such as the 2001 explosion at the Toulouse AZF fertilizer plant. The majority of these tank accidents could have been prevented through the application of sound engineering principles in design, construction, maintenance, and operation, coupled with the implementation and execution of a comprehensive safety management program[31].

This paper explores the mechanisms underlying explosive combustion in settings involving crude oil storage tanks. It presents a comprehensive review of both domestic and international research advancements related to crude oil explosions and combustion phenomena. Additionally, the paper addresses several widely recognized risk assessment methodologies pertinent to managing risks associated with storage tanks. By incorporating both qualitative and quantitative evaluations alongside simulations of potential accident outcomes, this study aims to offer essential technical support for safety management and emergency response strategies. To reduce the likelihood of future incidents, it is imperative to learn from prior accidents, advance theoretical research, and establish robust safety protocols.

Such an approach will not only enhance the safety of national energy reserves but will also contribute to the overall integrity of the petrochemical industry.

1.2 Characteristics of substances contained within storage tanks

The characteristics of the material being stored and processed, the inventory, and the procedures that it undergoes—such as high pressure, oxidation, hydrogenation, etc.—all influence the degree of chemical hazards[32]. However, basic physicochemical principles are essential to the chemical engineering activities, material movement, and reaction processes involved. These principles govern how materials will behave, such as flow, phase change, reaction or breakdown, pressure exertion, heat release or absorption, mixing or stratification, and expansion or contraction, and they must be predicted well enough to be used in the design and operation of equipment. These phenomena are greatly influenced by operating variables including agitation, turbulent flow, or increased interfacial area [33]. By using the same ideas, it is possible to identify the risks associated with fire, different kinds of "explosions," the discharge of corrosive or toxic substances, or exposure to the atmosphere that contains harmful contaminants.

1.3 Failure of Storage Tanks in Chemical Processing Plants

Storage tanks play a crucial role in chemical processing, functioning as essential vessels for the storage of raw materials, intermediates, and finished products. However, they continually face operational, environmental, and design challenges that threaten their structural integrity [34]. Failures within storage tanks, regardless of whether they are small shop-fabricated units or large structures compliant with API-650 standards, can result in severe repercussions such as environmental contamination, significant financial losses, and risks to public safety [32]. Historical incidents have highlighted the inherent vulnerability of these systems, even when adhering to stringent design criteria. Trevor Kletz, a pioneer in process safety, emphasized that "no piece of equipment is associated with more accidents than the storage tank," underscoring the susceptibility of these tanks to significant risks arising from seemingly minor operational errors [35].

While large storage tanks, such as those constructed in accordance with API-650 standards and exceeding 30 meters in diameter, are often regarded as structurally strong, their substantial dimensions intensify the associated risks. Even a minor pressure imbalance across an extensive surface area can result in significant forces, potentially culminating in catastrophic failures such as collapses or ruptures. On the other hand, smaller tanks, despite their less formidable appearance, encounter distinct challenges[35]. These include accelerated corrosion attributed to thinner walls and potentially insufficient maintenance intervals. An example of this is the collapse of a fiberglass acid tank, which might occur due to an unnoticed blind flange in its vent line during the filling process. This incident underscores how even minor oversights can lead to devastating consequences for smaller systems.

Yet, the challenges associated with the failure of storage tanks in chemical processing are complex, involving a blend of engineering principles, human dynamics, and environmental considerations [32-43]. Although improvements in materials and automation technology have enhanced the reliability of these systems, historical incidents serve as a stark reminder that complacency can lead to catastrophic outcomes. To effectively reduce risks and protect both infrastructure and surrounding communities, the industry must learn from previous failures, comply with continually evolving safety standards, and promote a culture of proactive maintenance. As safety consultant Roy E. Sanders aptly cautions, "Tanks should never be taken for granted—their fragility demands relentless vigilance" [35].

1.4 Potential Hazards Related to Combustible Materials

The leakage of liquids from the tank enhances the risk of a fire incident [44] .

The majority of leaks happen close to the tank's base for a variety of reasons, including corrosion, increased internal pressure, or the presence of additional fitting pumps that can disrupt the flow [45,46]. "Major dangers" arise when a significant amount of combustible substance spills into the open air [47]. Early or immediate ignition can produce a big flame, or "fireball," whose heat is the main source of risk. Clouds that are involved in open structures that provide partial containment and generate turbulence are more likely to produce explosion (pressure) and heat effects when ignited after mixing has had time to occur. There are several risks associated with combustible materials.[48] However, the following are some possible acute consequence pathways for a flammable gas leak [49]:

• Fireball: a cloud of burning fuel and air that primarily emits radiant heat as its energy. The outside layer of the cloud, where ignition first takes place, is made up of a combustible fuel-air mixture, whereas the inner core is virtually entirely made of fuel. The burning cloud tends to rise, expand, and take on a spherical shape as the buoyancy forces of hot gases grow.

• Vapour Cloud Explosion: an explosion that happens when a cloud of flammable gas, mist, or vapor ignites, and the flames accelerate to high enough speeds to create a substantial overpressure.

• Flash Fire: The burning of a mixture of flammable gas or vapor and air in which the flame spreads across the mixture with little to no harmful overpressure.

• Boiling Liquid Expanding Vapour Explosion (BLEVE): When a liquid, flammable or not, is abruptly released from containment at a temperature higher than its atmospheric boiling point and at a pressure greater than atmospheric, it vaporizes explosively quickly and releases energy in tandem. If the quickly depressurized liquid is flammable and the vessel failure due to an external fire causes its release, a BLEVE is sometimes accompanied by a fireball. A shock wave could result from the energy produced during flashing vaporization.

BLEVE is the most outstanding hazard for liquefied gas [50]. It will expand quickly as the liquid converts to vapor due to the abrupt discharge of liquefied gas from storage. The cloud spreads into a fireball when it ignites, engulfing adjacent buildings and people and causing injuries from secondary fires and heat radiation [16]. The shape, nature, and extent of the fire, as well as the atmospheric transmissivity between the fire and the receiver, all affect the amount of thermal radiation that is incident on the area surrounding the ignited release. It can also fluctuate with time after rupture and distance from the release point.

1.4.1 Elimination of all potential ignition sources.

In hazardous areas surrounding storage tanks, it is imperative to eliminate any potential sources of ignition for flammable vapors. This encompasses the prohibition of portable devices, including welders and hand lamps. The enforcement of a strict no-smoking policy is crucial, and 'No Smoking' signage must be prominently displayed. Any hot work activities should be conducted exclusively by trained professionals following a designated safe work protocol. When hot work is anticipated on tanks, it is essential to implement rigorous precautions to mitigate the risk of igniting flammable materials contained within the tanks. Figure 1 illustrates the hazardous areas associated with electrical equipment, classified into distinct hazard zones according to [51]:

◎ Zone 0: an area where an explosive mixture of vapor and air is consistently present or exists for extended durations.

◎ Zone 1: an area where an explosive mixture of vapor and air is expected to be present during normal operations.

◎ Zone 2: This zone is characterized by a low likelihood of an explosive vapor-air mixture occurring during normal operations. Should such a mixture arise, it is expected to exist only for a brief period.

Regions beyond these designated zones are classified as non-hazardous.

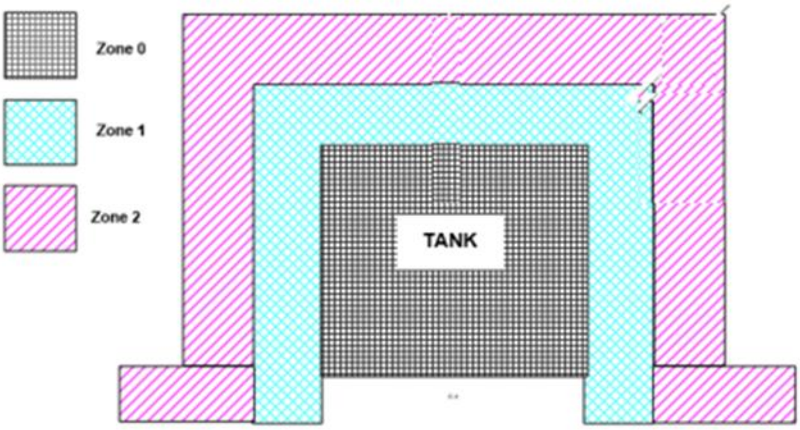

Figure 1: Hazard classification zones for the storage tank

1.5 Evaluation of potential hazards

A risk assessment is fundamental to any effective risk management strategy. Risk is typically defined as a product of the likelihood of an event occurring and the consequences of that event, expressed as follows [52]: Risk = (Probability of Event) * (Impact of Event)

A comprehensive risk assessment should encompass estimating the frequency and potential consequences of various hazardous scenarios, along with analysing both individual and societal risks. A key aspect of this assessment is reviewing sources that could lead to a release of hazards. Additionally, it is crucial to identify vulnerable targets, which may include both individuals and property [53]. For each potential hazard release, a specific scenario should be developed, outlining the nature of the release and the resulting chain of consequences. Given the vast number of potential releases, it is essential to categorize them into a limited number of groups that share similar characteristics. Factors that may influence these scenarios include the overall scale and duration of the event, which could be affected by the implementation of emergency shutoff measures the Buncefield disaster of 2005 underscores critical shortcomings in safety protocols, particularly with respect to inadequate training and reliance on faulty automation systems. This incident aligns with evaluations performed by the Centre for Chemical Process Safety (CCPS), which identifies factors such as overfilling and venting failures as prevalent contributors to tank-related incidents [35]. Additionally, the collapse of a railcar during its painting process, due to blocked vents, further illustrates the urgent necessity for effective management-of-change (MOC) protocols.

2 The Buncefield Oil Depot Accident

2.1 Incident Overview

The inquiry into the explosions and fires that occurred at the Buncefield oil storage and transfer depot in Hemel Hempstead on December 11, 2005, was overseen by the Health and Safety Commission. Evidence suggests that the principal explosion may have been caused by the ignition of a vapor cloud originating from Tank 912 in Bund A of the Hertfordshire Oil Storage Limited West site, likely due to an overfilling of unleaded petrol [23,54]> The Buncefield oil and transfer depot functions as an extensive tank farm managed by three distinct companies: Hertfordshire Oil Storage Limited, a collaborative enterprise between Total UK Limited and Chevron Limited; United Kingdom Oil Pipelines Limited; and West London Pipeline and Storage Limited, which operates under the management of British Pipeline Agency Limited; along with British Petroleum Oil UK Limited. All facilities within this site fall under the designation of 'top-tier' locations in accordance with the Major Accident Hazards (COMAH) Regulations of 1999 [55].

Figure 2 illustrates the configuration of the Buncefield depot along with its adjacent areas. The Buncefield depot is an integral component of a national network comprising petroleum refining, transportation pipelines, and storage facilities. Fuel products are delivered to Buncefield via three distinct pipeline systems, which are as follows:

- A 10-inch pipeline, known as FinaLine, runs from the Lindsey Oil Refinery located in Humberside and concludes at the West site of Hertfordshire Oil Storage Limited.
- A 10-inch pipeline extends from Merseyside to Buncefield, known as the M/B pipeline, concluding at the Cherry Tree Farm site, which is operated by the British Pipeline Agency Limited.
- A 14-inch pipeline extends from Thames (Coryton) to Kingsbury, Warwickshire, featuring a spur line that connects to Buncefield (T/K pipeline) and terminates at the main site operated by the British Pipeline Agency Limited.

All fuel products are transported in distinct batches through three pipelines, with each batch separated by an interface or buffer consisting of mixed products. At the terminal, operators oversee the arrival of various fuel types and segregate them into dedicated tanks based on their classifications. During standard operations, the mixed fuel interface is redirected to specialized small tanks, where it may be reinjected into the main large storage tanks if the fuel specifications permit. Alternatively, it can be transported back to the refinery as 'slops' for re-refining. The segregated products departed from the depot using either road tankers or, predominantly for aviation fuel, through two dedicated pipelines owned by the British Pipeline Agency Limited. These pipelines connect the main site to the West London Pipeline system, which serves Heathrow and Gatwick Airports. Tankers utilized at Buncefield had capacities of 44 or 18 tonnes and were increasingly managed by specialized transport companies.

2.2 Key Details Concerning the Event

The Buncefield Investigation Report outlines the timeline as follows [23], [56-59] :

December 10, 2005

- At approximately 19:00 on December 11, 2005, Tank 912 located in Bund A at the Hertfordshire Oil Storage Limited West site commenced the reception of unleaded motor fuel via the T/K pipeline, with a pumping rate of approximately 550 m3/hour.

- At approximately midnight (00:00), the terminal ceased operations for tankers, and a comprehensive inventory assessment of the products was conducted. This inventory process was completed by around 01:30, with no irregularities reported. Beginning at approximately 03:00, the level gauge for Tank 912 indicated a stable reading. Despite this stable measurement, the filling of Tank 912 proceeded at an approximate rate of 550 m^3 per hour.

- Calculations indicate that by approximately 05:20, Tank 912 would have reached its maximum capacity and begun to overflow. Evidence implies that the safety system designed to halt the petrol supply to the tank to prevent overfilling failed to function as intended. Following this moment, the ongoing pumping resulted in fuel spilling down the exterior of the tank and dispersing into the air, which rapidly generated a concentrated fuel/air mixture that accumulated in Bund A.

- At 05:38, CCTV footage from a camera positioned to observe the western edge of Bund A captures the initial visibility of vapor emanating from the leaking fuel. This vapor is seen drifting from the northwest corner of Bund A and moving westward.

- At 05:46, the vapor cloud had intensified, reaching a thickness of approximately 2 meters, and was dispersing in all directions from Boundary A.
- At 05:50, the vapor cloud began to drift off the site near the intersection of Cherry Tree Lane and Buncefield Lane, following the contours of the ground. It extended westward into the Northgate House and Fuji car parks and continued toward Catherine House.
- Between 05:50 and 06:00, the pumping rate along the T/k pipeline to Hertfordshire Oil Storage Limited West, and subsequently to Tank 912, progressively increased to approximately 890,550 m^3 per hour.
- By 06.01 the vapor cloud had expanded to the west, reaching nearly to Boundary Way between the three buildings: 3Com, Northgate, and Fuji. To the northwest, its reach extended to the closest corner of Catherine House.
- At 06:01, the initial explosion took place, which was subsequently followed by additional explosions and a significant fire that consumed more than 20 large storage tanks. The primary explosion seems to have originated from the parking area situated between the Hertfordshire Oil Storage Limited West site and the Fuji and Northgate buildings.
- At 06:08, a significant incident was declared by emergency services and operational command was established near the incident site within just a few minutes.
- At 09.00 Strategic Coordinating Group (‘Gold’ command’) convened for the first time.
- A significant plume of smoke originating from the burning fuel spread across southern England, visibly extending for several kilometers. This plume was not only discernible to the naked eye from a distance but was also distinctly captured in satellite imagery.

December 12, 2005

- At noon, the fire reached its apex, with 25 firefighting units from Hertfordshire deployed to the scene, supported by 20 auxiliary vehicles and a team of 180 firefighters.

- There was a partial failure of secondary containment, as the bunds could not completely hold back the fuel and firefighting water—referred to as "firewater"—which overflowed the bund walls.

December 14, 2005

- The Health and Safety Executive (HSE) took over the investigation from Hertfordshire Constabulary.
- The intense heat generated by the fire resulted in substantial damage to bunds, leading to a notable reduction in secondary containment measures at the Hertfordshire Oil Storage Limited facilities. Additionally, there was considerable degradation of tertiary containment at the site peripheries, allowing substantial quantities of contaminated liquids to escape off-site. Although the fire service managed to recover a significant portion of the contaminated runoff, they were ultimately unable to avert the contamination of both groundwater and surface water.

December 15, 2005

- 'Fire all out' declared by the fire Service.
- A total of 786,000 liters of foam concentrates and 68 million liters of water—comprising 53 million liters of 'clean' water and 15 million liters of recycled water—were utilized in the effort to manage the incident throughout the firefighting operations.
- The Strategic Coordinating Group, commonly referred to as the 'Gold' command, held its final meeting.

December 16, 2005

- The on-site investigation commenced, prompting the Health and Safety Executive (HSE) to issue directives aimed at securing the location. This ensured the preservation of evidence while facilitating the safe execution of clean-up operations.

December 18, 2005

- Hertfordshire Oil Storage Limited commenced its survey of the roads and structures located on the site.

December 20, 2005

- The HSC officially instructed the HSE and the Environment Agency to conduct an inquiry into the incident and prepare a detailed report. In response, the

HSE designated Taf Powell, the Director of its Offshore Division, to serve as the Investigation Manager. Additionally, the HSE disclosed the establishment of an independent board to oversee the investigation process.

- The control room at the Hertfordshire Oil Storage Limited West site exhibited adequate structural integrity, permitting access for the collection of records and additional evidence.

December 23, 2005

- The investigative team, in collaboration with Hertfordshire Constabulary and Hertfordshire Fire and Rescue Service, retrieved computers from the compromised offices and secured them in safe storage.

January 5, 2006

- The Hertfordshire Fire and Rescue Service transferred oversight of the site to the Investigation team. Both Hertfordshire Constabulary and the Hertfordshire Fire and Rescue Service continued to provide critical assistance to the Investigation team as they worked to gather and secure evidence.
- All flammable liquids had been cleared from the site and securely stored in preparation for proper disposal. The vicinity surrounding the loading gantry was rendered safe for access, and the tankers that were on-site during the incident were subsequently removed.
- Investigators gained access to Bound A for the first time.
- Internal roadways have been cleared, and preliminary efforts have commenced to remove debris from Bund A. Prior to the safe disposal of the material, fuel samples were collected from the pipeline. Due to the presence of residual fuel in the interconnecting pipework and damaged tanks, routine monitoring for flammable vapors was conducted.

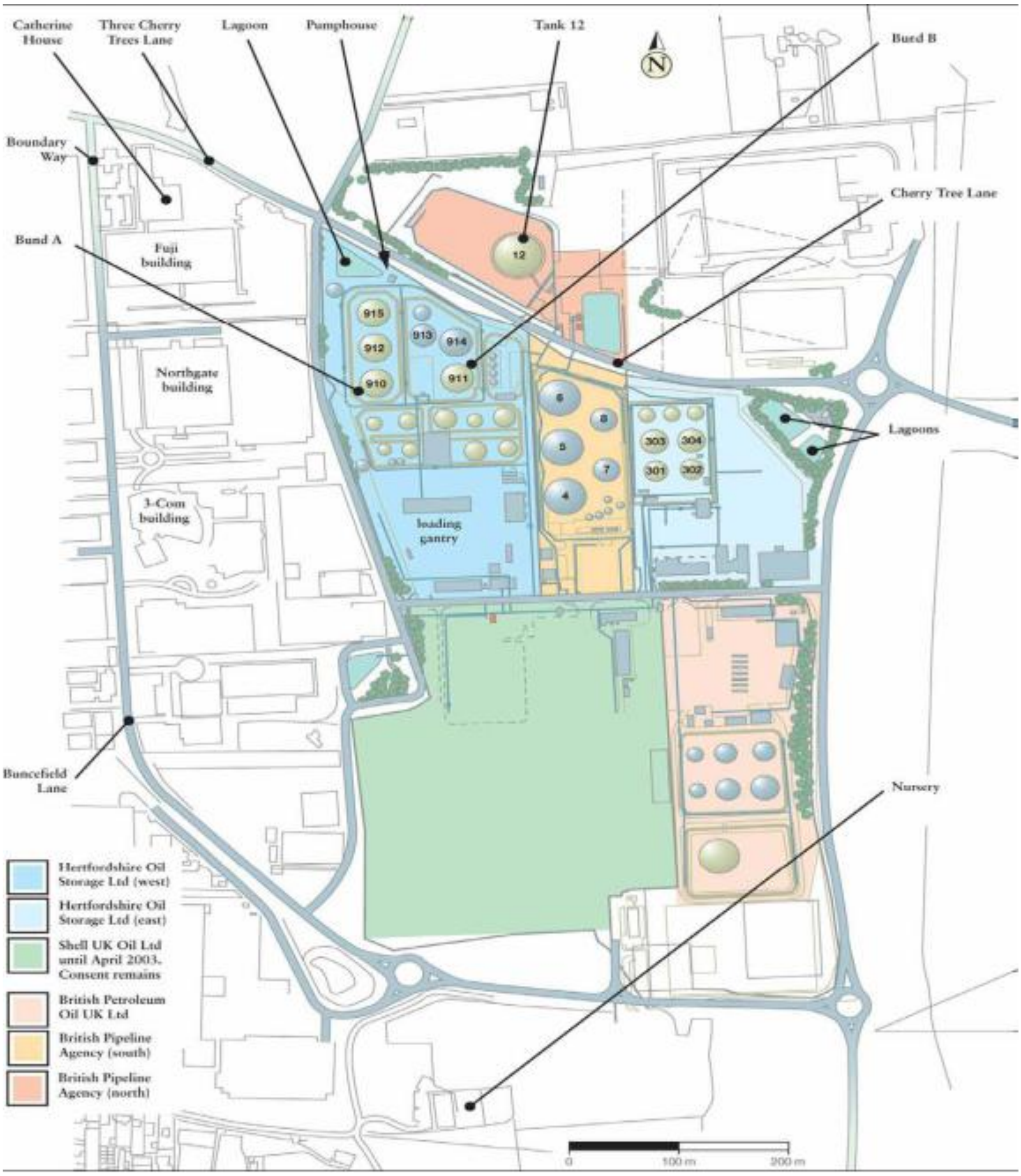

Figure 2: presents the layout of the Buncefield site. (adapted from: http://www.buncefieldinvestigation.gov.uk/images/index.htm)

2.3 The Most Likely Scenario of the Incident

The most widely accepted scenario begins with the **overflow of Tank 912 (Figure 3)**, which released approximately 300 tons of petrol into its bund. A critical failure of the Automatic Tank Gauging (ATG) system led to undetected overfilling, allowing a large flammable vapor cloud to form and spread across the site.[60] [30] An analysis of the pumping records associated with a pipeline delivering fuel to the storage depot at the time of the incident revealed that one of the substantial tanks (Tank 912) designated for the storage of unleaded petrol had been overfilled shortly prior to the explosion[44]. Between the moment the tank began to overflow and the explosion at 06:01, approximately 260 cubic meters, equivalent to 180 tonnes, of petrol was discharged from the tank.

Meteorological conditions, including low wind speeds and temperature inversions, likely contributed to the cloud's persistence and expansion, creating a fuel-rich environment spanning nearly the entire depot[61]. The Mechanism of explosion defied traditional models of confined vapor cloud explosions. Evidence from damage patterns, directional impulse indicators, and pressure decay analysis suggests a deflagration-to-detonation transition (DDT) as the most plausible mechanism[62]. The Key observations supporting this include [62-64]:

High Overpressures (200+ kPa): Damage to vehicles, steel drums, and buildings indicated pressures exceeding typical deflagration limits, consistent with detonation-like effects.

Directional Propagation: Flame acceleration through congested areas, such as tree lines and pipelines, created turbulence that facilitated DDT near the junction of Buncefield Lane and Three Cherry Trees Lane.

Lack of Confinement: Unlike classic detonation scenarios, most of the vapor cloud was unconfined, necessitating a hybrid model combining flame acceleration in partially obstructed zones and subsequent detonation

Other researchers have suggested that the ignition likely originated in the Emergency Pump House, where electrical equipment or mechanical sparks triggered a confined explosion[65]. This initial event vented into the external vapor cloud, propagating flames northward into congested zones. The transition to detonation occurred within seconds, generating shockwaves that amplified damage across the site. Notably, the absence of hearing damage among witnesses aligns with rapid pressure rises characteristic of DDT rather than pure detonation. J.E.S. Venart has proposed an alternative mechanism to elucidate the causes of the Buncefield explosion [29]. Based on the analysis of the available data (CCTV and photos), the dispersion of the vapour cloud, and possible blast reactions to vehicles, it has been concluded that ignitions with DDT-induced detonation started at least two places in the vapour cloud: the sensitive lean turbulent edges that touched west along the Northgate building's N and S sides. These virtually simultaneous ignitions are thought to have been caused by remote keyless entry/anti-theft alarms on vehicles.

They were started by a pressure wave from a flame that initially started from a vented explosion with a nearby pump house.

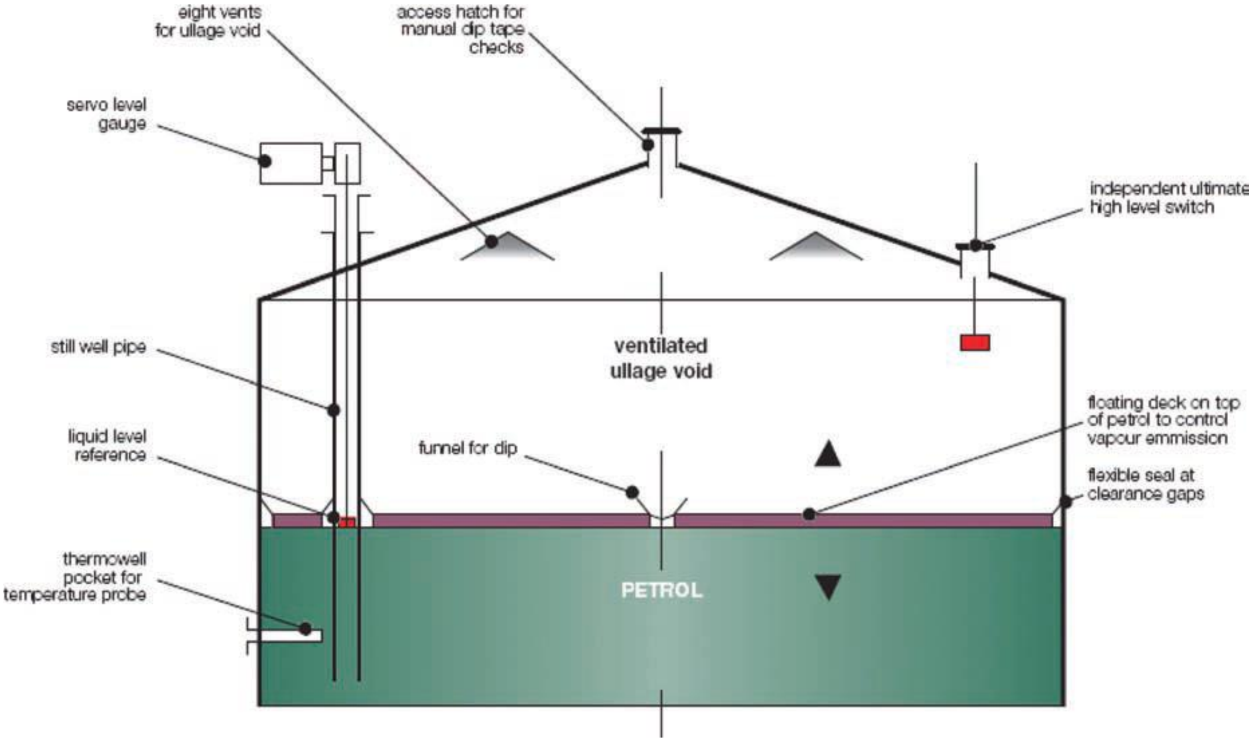

Figure 3: presents a schematic representation of Tank 912, which experienced overflow from its eight breather holes. (adapted from: http://www.buncefieldinvestigation.gov.uk/images/index.htm)

2.4 Vapor Cloud Formation and Characteristics

Flammable vapor clouds develop when volatile substances, such as hydrocarbons, are discharged into the atmosphere. Critical factors influencing this phenomenon include the rate of release, atmospheric conditions, and vapour density [66,67]. The vapor cloud generated during the overfilling operation at the Buncefield site was substantial and dispersed over an extended duration [44]. The dimensions of this cloud significantly influence various factors, making it a crucial element in assessing the potential repercussions of an explosion. A larger vapor cloud encompasses a greater quantity of fuel, which translates to an increased amount of energy available for conversion into explosive energy.

Furthermore, an enlarged cloud is more likely to encounter confinement or congestion, both of which can intensify the severity of an explosion. Congestion arises from the presence of obstacles and their proximity to one another. Moreover, the geometric configuration of these obstacles significantly influences the level of congestion. In the event of a gas explosion, these obstructions impede the propagation of the flame front, resulting in turbulence. Turbulence significantly contributes to the generation of substantial overpressures. Its influence is evident at two distinct stages: first, during the mixing of air with vapor, and second, in the propagation of high flame speeds. Each of these factors can affect the extent of overpressure. In contrast to congestion, confinement refers to the phenomenon where the released gas becomes entirely or partially contained within a restricted space[67]. Research indicates that both turbulence and confinement can significantly increase the severity of potential explosions[68] .

Three things to note from the prior information of the explosions as well as the most recent research findings are the mechanisms of the explosion, the release and formation of a substantial vapor cloud, and the prolonged length of the release. These can help to improve future hazard identification and risk assessment processes. Not enough attention has been paid to the possibility of flammable vapor clouds combusting in environments [49,69]. Improving the identification of overpressure-generating elements particularly those emphasized by the Buncefield disaster, requires a deeper comprehension of the factors driving explosions [70]. This involves a heightened awareness of possible deflagration intensities brought on by inter-area interactions that may result in overpressure. In the case of "bang boxes," for example, where a deflagration occurs in a restricted space and then releases energy into a nearby vapor cloud. This can serve as a crucial source of ignition for that cloud, increasing its energy output [71].

2.5 Evaluation of Explosion Overpressures via Damage Analysis

A dedicated team of explosion specialists was formed to conduct an in-depth investigation of the incident. The primary objective of the Buncefield Explosion Investigation Team was to collect potential pressure indicators necessary for a comprehensive damage analysis. This analysis utilized a range of methodologies, such as static pressure testing, gas explosion testing, detonation testing of high explosives, and finite element analysis. The overarching goal was to assess the overpressures generated by the Buncefield explosion [72].

3. Learnings from the Buncefield Accident and Improvements to Tank Safety Preventive

3.1 Operating and safety procedure

Maintaining current safety procedures presents considerable challenges, highlighting the fact that even well-established companies may struggle with compliance. To ensure superior safety standards, the following measures should be adopted [73]: - Develop operating procedures for every unit within the facility. - Create protocols for both start-up and shut-down operations. - Maintain a complete set of emergency procedures. - Regularly revise all procedures, prioritizing updates before implementing any new modifications to the facility. - Keep an accurate and up-to-date piping and instrumentation diagram readily available at all times. - Assess non-functional instruments for safety, clearly marking them as inoperable on the control panel, and provide documentation if the failure is considered permanent. - Provide a dedicated logbook for each unit to record production activities, disturbances, and repairs. - Establish a systematic shift handover protocol. - Ensure that all procedures are thoroughly read, comprehended, and strictly followed by operators. - Incorporate the practical experience of operators into the procedure development process. - Guarantee that operators possess a comprehensive understanding of both the design features and the operational steps involved.

As previously discussed, the measures outlined represent the current limits of what can be accomplished. The challenges associated with updating protocols and enhancing operator awareness are particularly formidable and will almost certainly necessitate the development of innovative techniques, such as more automated updating processes and the implementation of simulator training programs [74]. These advancements are essential for keeping pace with the frequent changes in operator errors. By focusing on this aspect, it is often possible to reduce the incidence of accidents in specific areas of the plant. During normal operations, plants may encounter various operational difficulties that prevent the realization of an ideal safety environment. In more severe cases, a shutdown may become necessary. However, when issues are less critical, efforts should be devoted to rectifying the situation to maintain safe operations.

It is crucial to classify and distinctly identify both major and minor issues [4]. The following areas illustrate where these criteria may be relevant: - Inadequate staffing levels - Malfunctioning safety systems - Insufficient supplies of firefighting water or foam – Poor quality of raw materials that present safety hazards - Lack of documentation and quality control protocols for raw materials - Unfavourable weather conditions.

3.2 Inspection and Safety Practice

Cracking is typically confined to the welded regions of vessels that have not undergone post-weld heat treatment [75]. Utilizing steel with low impurity levels can help mitigate the risk of internal cracking. Additionally, the application of surface coatings and effective inhibitors can further prevent such cracking [76]. Heat treatment is essential for eliminating absorbed substances, such as hydrogen, which can compromise the integrity of the material [77]. To protect against the detrimental effects of high temperatures on materials, careful selection must be employed; for example, low and high alloy chromium-molybdenum steels, certain copper alloys, and non-ferrous materials should be considered. Establishing an appropriate safety level is critical to ensure optimal safety standards are met. Magnetic particle inspection (MPI) should be employed to detect cracking at welded joints and in areas prone to environmental cracking and creep cracking [78]. It is apparent that conducting internal inspections poses significant challenges, as they typically require confined space entry, necessitating the vessel to be taken out of service, cleaned, and organized. Furthermore, internal inspections can uncover issues such as stress corrosion cracking, pitting, and other defects that may compromise the vessel's integrity [79]. Operators must give due consideration to the start-up and shutdown processes, as any potential process disturbances or unusual conditions could lead to overpressure scenarios. The risk associated with higher operating pressures and larger vessels is proportional to the energy released in the event of a rupture, which can result in severe consequences. It is important to highlight that, even if the vessel's contents are non-flammable, explosiveness and reactivity pose significant hazards. To identify subsurface cracks, routine X-ray examinations should be conducted. Additionally, a risk analysis should be performed for new materials to assess their vulnerability to cracking.

3.3 Corrosion and corrosion monitoring

Corrosion is widely acknowledged as a significant source of hazards, frequently arising from the use of inadequate or inferior construction materials during the design phase, as well as alterations in operational conditions. Prompt detection of corrosion is essential for preventing unnecessary losses and ensuring safe operational conditions. Therefore, it is essential to comprehend the principles of corrosion to effectively choose materials and to design, fabricate, and employ metal structures, ensuring both optimal economic longevity of facilities and safety.[80] The adverse impacts of corrosion can lead to the degradation of equipment, piping systems, fasteners, and structural steel supports. Such deterioration may cause structural vulnerabilities, ultimately increasing the risk of failures under conditions of pressure, impact, or load. This phenomenon has been extensively documented in the academic literature. [81-84] Certain corrosion monitoring methods are designed to identify the corrosion regime, while others specifically measure the extent of corrosion taking place [85]. However, monitoring corrosion poses considerable challenges due to its intricate nature.

Corrosion often results in significant repercussions for supporting structures and components, including bursting discs, gaskets, non-return valves, pipes, and storage or transport vessels. Notably, external corrosion of steel concealed beneath thermal insulation has led to various serious incidents, often due to the abrupt failure of high-pressure containment systems [1]. Therefore, it is essential to implement rigorous corrosion monitoring practices. Corrosion refers to the gradual degradation of metallic materials, which occurs because of chemical or electrochemical interactions with environmental elements, including atmospheric conditions, moisture, and various chemical substances. Electrochemical methods are commonly utilized to monitor corrosion, enabling the analysis of corrosion behaviour through various techniques. These techniques include: - Chemical analysis - Measurement of corrosion potential - Assessment of linear polarization resistance (LPR) - Electrochemical impedance spectroscopy - Potentiodynamic scanning - Measurement of electrochemical noise [86]. In addition, the presence of both mechanical stress and corrosive agents can lead to specific failure mechanisms, such as stress corrosion cracking and corrosion fatigue. Further, the corrosion coupons represent a cost-effective and efficient approach for assessing the corrosion rate within various systems or structures. This testing method, known as corrosion coupon testing, facilitates in-line monitoring, whereby the coupons are situated directly within the process stream and subsequently retrieved for analysis. This technique offers a direct quantification of metal loss, enabling the calculation of the overall corrosion rate [87,88]. An alternative method has been also used for evaluating the corrosion rate involving the application of radioactivity. This approach consists of inducing a slight radioactivity in the surface susceptible to corrosion and subsequently observing the variations in its radioactivity levels. A significant advantage of this technique is its impressive measurement sensitivity, combined with the relatively low levels of radioactivity, which negate the need for specialized safety measures [89].

Furthermore, Visual inspection requires physical access to the equipment and is primarily conducted during periods of shutdown. [90].

3.4 Avoiding storage tanks overfills

Ensuring the prevention of containment loss should consistently be regarded as the top priority. Several recommendations have been proposed concerning enhancements to the prevention of overfilling in storage tanks and regulation of societal risks associated with significant hazard locations. [91-93]. Implement redundant independent high-level switches (HLS) alongside primary-level gauges to ensure overfill detection even if one system fails. The Buncefield Major Incident Investigation Board emphasized the need for "independent layers of protection" to mitigate single-point failures [23]. Overfill protection should not be limited to monitoring high and high-high levels in storage tanks. It is essential to implement a system of "accountancy monitoring," which involves verifying actual level changes against expected outcomes during transfer operations through mass or volume balance analyses. This monitoring could be conducted by operators but could also be integrated into the logic of modern control systems. Recommendations have been proposed regarding the development of reports focused on the design of post-release mitigation measures [94]. The primary enhancements pertain to the design and functionality of tank bunds. Historically, the main design consideration for bunds involved ensuring they were adequately sized to contain the full capacity of any tank, typically 110% of the largest tank's volume. However, the Buncefield incident has underscored the importance of additional design elements, including the sealing of bund walls, the management of pipe penetrations within bunds, and the proper procedures for emptying bunds [95]. Moreover, Bunds must be constructed to incorporate foam layers for effective firefighting. In addition, it is essential to engineer overflow systems from the bunds to direct excess resources to secure locations, such as site drainage systems, rather than to nearby roadways, gravel areas, or similar environments. When managing extensive inventories, especially in pipeline systems, it is crucial to implement high-level trip mechanisms. This process involves thorough review, careful design, proper installation, and rigorous testing. In particular, in systems where the design of the tank isolation trip is implemented, it is crucial to account for the speed of the isolation action [55]. This design should ensure that, under the most extreme filling rates, there is adequate ullage above the high-high set point to allow sufficient time for the closure of the isolation valve. These functional considerations are equally significant as the reliability of the instrument loop.

3.5 Pressure testing

Pressure testing should be done on equipment and pipe work by using liquid, most often water. [96] However, gas or air can be used for the same purpose. Hydrostatic testing is preferable because at low pressure, e.g. < 20 bar, the stored energy is at least 3 orders of magnitude less than with gas [97]. The Flixborough disaster might have been averted if the 50-cm pipe had undergone testing in line with BS 3351, a standard procedure that would have revealed any potential deficiencies. Additionally, following the guidelines provided by the bellows manufacturer could have significantly reduced the associated risks. While the pipe was subjected to pneumatic leak testing, this method carries inherent dangers if adequate safety protocols are not enforced. Ideally, hydrostatic testing should have been performed at 1.3 times the design pressure to verify the pipe's structural integrity [98].

It is imperative to exercise caution when conducting hydrostatic testing at high pressures. Hydrostatic testing has been the subject of extensive research across multiple disciplines due to the progressive structural issues that pressure vessels encounter over time [99-101]. These vessels are particularly susceptible to a range of damages, including wear, scratches, impact-related injuries, and the effects of aging. Such deterioration can significantly diminish both the load-bearing capacity and the fatigue performance of pressure vessels [98]. Numerous accidents frequently arise during hydrostatic testing, and an analysis has been conducted to identify the underlying causes of these incidents[102] [103]. Incident reports highlight that the assessment of hydrostatic tests should extend beyond the pressure vessels themselves. For instance, an accident involving a spherical LPG tank revealed issues with the supporting structure of the tank. During the hydrostatic testing, water was introduced to 80% of the tank's height without any immediate complications. However, the supporting member had deteriorated over time, ultimately failing to bear the weight of the tank as it filled with water, resulting in a structural collapse. This underscores the importance of evaluating not just the integrity of the pressure vessel, but also the overall condition of the supporting structure during hydrostatic testing [104].

It is crucial to evaluate all components of the plant in their entirety rather than assessing individual elements in isolation. This is exemplified by the Flixborough incident, which demonstrated that while a specific component may meet standards, the overall installation of the section may be flawed. Furthermore, hydrostatic testing may not be feasible in certain circumstances, such as [33]:

The inability of supportive structures or foundations to bear the weight of equipment when filled with water. - Situations where water contamination is deemed unacceptable. - Scenarios where only mains water is available for testing stainless steel equipment, potentially leading to assisted stress corrosion cracking issues.

Before performing on-site tests, it is necessary to remove all plastic plugs intended for sealing ports or pipe connections, which are frequently utilized during transport and may occasionally be painted over. There have been instances where significant spills of flammable liquids have occurred due to the displacement or loss of these shipping plugs. To reduce risks associated with this process, the following routine safety measures should be implemented [97]. Ensure the removal of trapped air from the equipment by installing suitable vents or bleed valves. - Avoid making any adjustments, such as tightening bolts, while the system remains under pressure. - Limit the use of temporary threaded joints whenever feasible. - Refrain from conducting tests at elevated water temperatures.

3.6 Ventilation

It is advisable to implement open construction techniques in any situation where flammable liquids or gases are being processed, whenever feasible. This approach not only enhances general ventilation, aiding in the dispersion of gas or vapor leaks, but it also maximizes the available area for explosion venting. Furthermore, open construction contributes to improved firefighting efforts[33]. The dust collection equipment and filters should be situated in an open area that is devoid of any other processes. This location must remain clear of external activities to ensure optimal functioning.

The minimum advisable ventilation standard for any enclosed space where flammable liquids or gases are managed is six air changes per hour, equating to a flow rate of 1 meter of air per minute for each square meter of floor area[105]. To illustrate the stringent precautions necessary in scenarios where the failure of containment could lead to significant losses, current best practices for compressor houses managing flammable gases now encompass the following measures[106]: * Positioning compressors within an open-sided structure. * Implementing gas detection systems. * Installing remotely operated valves to allow for the isolation of leaking compressors and safe depressurization from a distance. * Surrounding compressors and associated equipment with a water curtain to inhibit the dispersion of vapor towards potential ignition sources.

To ensure the effective utilization of the system, it is essential to prioritize both thoughtful design and regular maintenance. The system will comprise several components, including a hood, which may take the form of a custom-built enclosure, canopy, or slotted duct. This ducting will facilitate the movement of exhaust air and contaminants, while a fan will be employed for airflow management. Additionally, there will be equipment dedicated to the collection and removal of contaminants, along with a stack designed for the safe dispersion of purified air [33].

3.7 Identification and prevention of ignition sources

The Buncefield incident involved a petrol spill from an overfilled storage tank, forming a vapor cloud that ignited. Investigations identified multiple failures, including faulty level sensors and inadequate overflow safeguards. The ignition source, though debated, was likely a diesel generator or nearby fire [1]. The explosion caused extensive damage, highlighting the interplay between vapor dispersion and ignition probability. In each case prior to ignition, there was a complete lack of detection. This delay in identifying hazardous conditions is exacerbated in contemporary settings due to two specific site "improvements": enhanced control over potential ignition sources and the implementation of increased automation. This analysis extends to the range of potential equipment malfunctions linked to electrical devices, which encompass the production of ignition sources due to both static electricity and mechanical ignition source generation. The ignition energy and its placement are critical factors influencing the overpressure resulting from a vapor cloud explosion (VCE). Existing literature suggests that positioning the ignition source in a more optimal location can reduce the overpressure by an order of magnitude [107,108]. Hence, the likelihood of small and medium-scale events encountering an ignition source within the facility can be reduced. In the case where detection systems are absent, this scenario heightens the probability of extended delayed ignition, primarily stemming from sources located outside the traditional hazardous areas. In addition, locations managing extensive inventories that have the potential to generate hazardous vapor clouds, especially substantial neutrally or dense vapor formations, must implement leak detection systems and incorporate methods for the remote isolation of fluid flows [93]. This requirement should be factored into any processing facility that enhances remote automated control while diminishing on-site staffing levels. Furthermore, such considerations should be integral to any organizational restructuring or workforce downsizing assessments.

3.8 Maintenance and safety procedures:

Establishing a comprehensive set of maintenance and safety procedures is essential for any organization [109]. For top-tier facilities, such a complete set of procedures may occupy an entire ring binder. For instance, the protocol for tank entry is typically encapsulated in a single page of clear instructions. Key topics that should be addressed within these procedures include [41]: - A list of instruments and equipment that require routine testing, alongside the corresponding test protocols. - Standard quality control measures for materials and products. - Requirements for proper labelling. - Procedures for preparing electrical equipment for repairs and safely shutting it down. - Guidelines for hot work activities and the associated permit requirements. - Scheduled inspections of vessels and assessments for corrosion. - Maintenance protocols for various apparatus. - Safe sampling techniques. - Guidelines for crane utilization. - Protocols for using breathing apparatus, gas masks, and personal protective clothing. - Procedures for filling and emptying tanks containing hazardous materials. - Regular replacement of hoses and crane slings. - Safe handling procedures for various substances. - Storage and warehousing safety practices. - Replacement protocols for gaskets and seals. - Special precautions regarding the selection of materials for repairs. - Authorization processes for repairs and modifications. - Procedures for de-blocking pipes. - Guidelines for the safe use of compressed air equipment. - Establishing and maintaining clear escape routes. - Handling procedures for flammable and toxic substances. - First aid protocols for burns, acid burns, or poisoning incidents. - Regular testing of fire protection equipment, safety showers, and alarms. Safety procedures should be articulated clearly and maintained in a straightforward format [110]. Personnel are expected to be familiar with these regulations and adhere strictly to them.

3.9 Reapplying models to the event

Mathematical models are recognized as essential tools for conducting a quantitative assessment of the effects resulting from the accidental release of hazardous materials [111]. When modelling such releases, two critical scenarios must be considered: continuous emissions sustained over a protracted timeframe and intermittent "puff" releases that also occur over an extended duration. The latter category of "puff" releases may result from a catastrophic "blow-up" event [112]. Future risk assessments, specifically in the context of consequence modelling, should take into account scenarios involving heavy gas releases and weather conditions.

Numerous significant material releases during incidents in processing plants are associated with heavy gases, including methane, propane, butane, ethylene, and propylene [113]. These gases pose a considerable risk of cloud fires. Modelling heavy gas releases is primarily guided by two major categories of theories. The first category encompasses what are known as “Top Hat” models [114]. Within this framework, the concentration profile across the plume is assumed to be uniform. Initially, the dispersion of the gas is depicted as a gravitational flow. However, over time, as the cloud travels a certain distance, turbulence both within the cloud and at its leading edge leads to processes of entrainment and dilution, increasing the cloud's height while gravitational spreading persists. The second category is referred to as the "K theory model," which posits a relationship between the gas flux within the cloud and its interaction with the surrounding air, influenced by turbulence [115]. This model takes into account various factors, including the velocity, temperature, and concentration of gas within the cloud. Moreover, it is essential to consider a range of physical phenomena within these models. Furthermore, numerous empirical explosion methods exist for assessing the consequences of overpressure. The traditional approach to modelling vapor cloud explosions begins with defining the extent of the vapor cloud, followed by the identification of regions within the cloud that are constrained or congested, which may lead to the generation of overpressures. Among these, the Multi Energy Method (MEM) has become increasingly prevalent and is widely regarded as an advancement in the evaluation of overpressure. This method entails relatively simple calculations and does not necessitate the use of complex computer programs. The acceptance of MEM in the United Kingdom is exemplified by its inclusion in the Health and Safety Executive's (HSE) Safety Report Assessment Guide for Highly Flammable Liquids [56].

Wind speed conditions are expected to persist for durations that warrant classification of this weather scenario, during which extended releases may take place [116]. However, the accurate calculation of air entrainment poses significant challenges due to its high sensitivity to the spatial distribution and geometric configuration of vessels[117]. The majority of significant vapor cloud incidents transpired under conditions of negligible or very low wind conditions. [118,119]. The issue of nil or low-wind vapor transport, characterized by the build-up of a gas layer with minimal downward dispersion, is not well-known among many risk assessors. However, this phenomenon is typically more clearly defined and, in theory, more straightforward to address than the more commonly understood dispersion that occurs in windy conditions.

There are approximate methods available that are appropriate for relatively flat terrain [120]. Even at low wind speeds, the dispersion of the vapor cloud would still be considerable, leading to smaller flammable vapor clouds in comparison to conditions with calm or zero wind. Therefore, another critical element observed in numerous large-scale explosion incidents is the extended duration of the release [121]. The modelling of calm weather conditions likely necessitates additional research and the development of practical empirical dispersion models, as this particular weather condition falls outside the valid range of existing empirical dispersion frameworks. Moreover, most dense-gas dispersion models that are typically employed in risk assessments are inadequate for simulating the Buncefield Incident, which occurred in the absence of wind. Consequently, attention has turned to the development of a computational fluid dynamics (CFD) model to better understand the flow dynamics in this context [122,123]. An investigation into the explosion mechanism has been conducted utilizing Computational Fluid Dynamics (CFD) to analyse the dispersion of flammable vapours released from an overfilled storage tank [124]. This research aimed to elucidate the way the vapor cloud disperses over extensive areas and to generate data that can be applied in explosion modelling studies. Conducting CFD simulations to analyse the dispersion of the vapour cloud at Buncefield presents significant challenges due to the extensive area encompassed by the visible mist and the prolonged duration of the release [124]. In addition, weather data relevant to the Buncefield site is available in the second edition of "Loss Prevention in the Process Industries [17]. These should be designed to account for heavy or neutrally buoyant vapor clouds, particularly in scenarios where there is a potential for extended-release.

3.10 Housekeeping and safety practice

This method has the potential to eliminate workplace hazards and facilitate the safe completion of tasks. The benefits of effective housekeeping are numerous, including: - Reduced risk of fire hazards - Decreased exposure of workers to hazardous substances - Enhanced efficiency in equipment clean-up and maintenance While it is challenging to quantify the impact of good housekeeping and effective safety practices on risk levels, these elements represent a critical component of safety management and likely exert a significant influence on overall safety outcomes. According to Taylor [41], best practices in this context include: - Storing materials, tools, and equipment only in designated areas or organizing them neatly to avoid obstruction during abnormal operations. - Marking escape and transport routes. - Erecting barriers or fencing around areas undergoing abnormal operations. –

Exercising oversight of contractor personnel. - Maintaining tidiness and clear markings in new construction zones. - Ensuring that new construction equipment adheres to safety regulations. - Keeping ignition sources as far away as possible from hazardous areas. - Providing safety instructions specifically for contractor staff. - Implementing clear marking for equipment to aid identification. - Ensuring the proper marking and identification of safety equipment. - Controlling access to the site effectively. Failure to adhere to these principles can significantly increase the likelihood of ignition-related incidents, diminish the effectiveness of emergency procedures, and elevate the frequency of fire outbreaks.

4. Additional techniques and Prospective Research Directions

Hazard and Operability (HAZOP) analysis, Fault Tree Analysis, Event Tree Analysis, Failure Modes Effects and Criticality Analysis, and "What If" Analysis are more techniques to evaluate risk and enhance the detection of process risks. By using targeted keywords to encourage team participation, HAZOP is a recommended technique for identifying all possible failure modes [125]. According to a (HAZOP) study's fundamental principle, typical operating conditions are deemed safe, and dangers only occur when these normal parameters are deviated from. The purpose of the HAZOP approach is to detect these aberrations and assess the related risks, categorizing them according to their potential severity [12]. One organized method for evaluating risk is fault tree analysis. An organized method for evaluating risk is fault tree analysis. It focuses on using a top-down analysis to determine the root causes of adverse circumstances, such as dangerous incidents and equipment failures. Bell Telephone Laboratories initially used this method in 1962 as part of the safety evaluation process for the intercontinental Minuteman missile's launch system [9]. Event tree analysis is another way for identifying risk. This method is mainly used to investigate the possible outcomes of specific incidents. It starts with an identifiable initiating event, like a pipe burst or a power outage, and works its way up from the bottom up. It is understood that event tree analysis combines qualitative and quantitative methods [126]. Our future research will focus on evaluating the risk related to the Buncefield accident and enhancing process hazard identification through Hazard and Operability (HAZOP) analysis.

5. Recommendation

To ensure the safety of all personnel in chemical plants working with flammable and combustible liquids, the following measures should be implemented:

1. Acquire and review the Material Safety Data Sheets (MSDS) for all materials handled by operators.

2. Ensure that all operators are knowledgeable about the various hazards associated with their materials, including fire risks, explosion potential, health concerns, chemical interactions, and reactivity.

3. Equip operators with the ability to differentiate between flammable and combustible liquids in their work environment.

4. Minimize or eliminate ignition sources, such as sparks, smoking, open flames, and hot surfaces, while working with these hazardous liquids.

5. Conduct all storage and handling of flammable and combustible liquids in well-ventilated areas while avoiding ignition sources.

6. Utilize only approved equipment, such as properly labeled safety containers, when managing flammable and combustible liquids.

7. Provide comprehensive training for all operators to handle emergencies effectively, including fires, spills, and injuries related to the materials they manage.

8. Create and implement effective procedures for preparing equipment for maintenance tasks.

9. Encourage adherence to safety protocols by discussing past incidents that resulted from inadequate procedures. It is essential to communicate to foremen and lead operators that their primary role is not only to operate the plant but also to prioritize safety by following established protocols.

10. Conduct regular checks to ensure compliance with safety procedures. When management demonstrates an active interest in safety practices, it reinforces their importance to foremen and operators. Proactive communication about safety measures can prevent accidents more effectively than disciplinary actions taken after incidents occur. Managers should review the permit-to-work log daily and verify compliance with actual tasks several times a week to maintain a culture of safety readiness.

To effectively mitigate the risk of significant leaks, operators should prioritize detailed design specifications followed by comprehensive inspections post-construction. This approach surpasses previous practices by ensuring adherence to design intentions and sound engineering principles, particularly in cases where specifics were not provided. Over the operational lifespan of the facility, the inspection of piping infrastructure assumes greater significance than ongoing assessments. In the event of a leak, the following proactive measures are recommended: - Operators should adopt a preventive mindset and anticipate potential leaks, engaging in discussions regarding the appropriate response strategies. - Installation of remotely operated isolation valves are crucial for equipment that poses a leakage risk. - When implementing remotely operated isolation valves, it is imperative to position the control mechanism at least 30 feet away from the potential leak source. - The integration of gas detection systems for equipment susceptible to leaks is essential. - In instances of flammable gas or liquid leaks, it is critical to promptly contact the fire department for assistance. - It is vital to notify individuals who are not involved in the situation to evacuate the area in the event of a flammable or toxic gas or liquid leak. - For leaks of flammable liquids, applying high-pressure water injection can effectively contain the leak, and reducing pressure may also diminish its severity. Furthermore, routine safety inspections of the site should be conducted to identify any hazardous installations. These inspections should be performed by professionals with expertise in electrical safety standards to prevent issues such as improper installation or oversight of critical systems, including lighting infrastructure.

6. Conclusion

All tanks and vessels must be designed and constructed in accordance with recognized standards, such as those set forth by the American Petroleum Institute (API) [127]. The construction materials for these tanks should be steel or other materials capable of withstanding, for a limited duration, the impacts of direct flame impingement or radiant heat from nearby fires. The composite materials employed in their construction must adhere to precise specifications to ensure they fulfill their intended service life without experiencing cracking or other forms of structural degradation. Additional measures may be necessary for above-ground tanks to maintain their reliability in the event of a fire. The materials used in tank construction, including the tank lining when applicable, should be well-suited to the chemical and physical properties of the stored liquid. This compatibility is crucial to prevent any interactions that could lead to tank failure. All tanks, along with their associated fittings and piping, should be adequately painted or otherwise protected against corrosion.

Strength testing of all tanks must be conducted by the manufacturer in accordance with the appropriate design codes, with hydraulic testing generally preferred over pneumatic testing for safety reasons. Leak testing should be performed on installed tanks and pipelines prior to their use. While hydraulic testing is typically favored, air may also be employed to apply pressure to water-filled tanks and piping. It is essential that all system components, including pipelines and supports, are sufficiently robust to withstand the hydraulic load when utilizing water, considering any specific gravity differences between water and the liquid intended for storage. To prevent leaks or failures, thorough inspections should occur before tanks are put into operation. A site assessment should be conducted to verify that the ground can adequately support the intended load, and a concrete raft or alternative support may be necessary. For vertical tanks, the foundation must comply with relevant standards, while horizontal tanks should be positioned on fixed foundations and supported by concrete, masonry, or steel saddles. Steel supports should have a fire-resistant material with a two-hour rating, and their design must facilitate the drainage of water and accommodate thermal expansion and contraction of the tank. Horizontal tanks should be anchored at one end, allowing the other end to remain free for movement, with pipelines attached to the secured end. To prevent flotation due to floodwaters or spillage into the bund, tanks should be securely anchored or weighted down. Fixed fire detection and alarm systems, as well as fire protection and firefighting equipment that meet the relevant standards, should be installed for all tanks and vessels in the vicinity. Before any construction work begins, the area designated for the installation of tanks or vessels must be rendered safe for work activities.

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