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Modelling of Bleve Fireball and its Impact Assessment of Thermal Radiation Hazard in an Oil & Gas Industry

Anuj Kumar[1], Dr. Sandeep Yadav[2]
[1]*Master of Technology in Industrial Safety and Engineering, Vikrant University, Gwalior (M.P)*
[2]*Associate Professor, Department of Fire Technology & Safety Engineering, School of Engineering and Technology, Vikrant University, Gwalior (M.P)*

Abstract: The oil and gas industry, a linchpin of the global energy sector, faces significant safety challenges due to the handling and storage of flammable substances. Among the most perilous events within this industry is the Boiling Liquid Expanding Vapor Explosion (BLEVE), characterized by the rapid release of pressurized flammable materials, resulting in a fiery and potentially catastrophic explosion. This study delves into the modelling of BLEVE fireballs and the assessment of their thermal radiation hazard within the context of the oil and gas sector. The research comprehensively explores the intricate elements of BLEVE events, encompassing the fluid dynamics, thermodynamics, ignition mechanisms, and dispersion of vapor clouds. Accurate modelling is essential to simulate these events, considering factors such as the initial release rate of the fuel, vapor cloud dispersion, and the ignition source. Furthermore, the study scrutinizes the thermal radiation hazard emanating from BLEVE fireballs, quantifying heat flux, radiant energy exposure, and assessing potential impacts on humans, structures, and the environment. In doing so, it facilitates a deeper understanding of the potential consequences of BLEVE incidents and aids in the development of effective safety measures and emergency response plans. Regulatory compliance, safety systems, emergency response procedures, and asset protection strategies within the oil and gas industry are also evaluated to ensure the responsible management of BLEVE risks. The study, grounded in real-world data and best practices, strives to mitigate the hazards posed by BLEVE incidents, safeguard lives, assets, and the environment, and facilitate the industry's ongoing commitment to safety and sustainability. In a rapidly changing energy landscape, this research provides critical insights into managing the inherent risks while promoting the secure and efficient operation of the oil and gas sector.
Keywords: BLEVE, Fireball, Heat flux, ALOHA, Robert's method, TNO Method, Vapour Cloud Explosion.

I. INTRODUCTION

A. Introduction

The project, titled "Modelling of BLEVE Fireball and Its Impact Assessment of Thermal Radiation Hazard in an Oil & Gas Industry," aims to develop a comprehensive model that can predict the behaviour of BLEVE fireballs and assess the thermal radiation hazards associated with them. The model will take into account various factors, including the container's geometry, the properties of the flammable liquid, and the surrounding environment. After the industrial revolution of the nineteenth century, the world has experienced significant growth in new technologies embedded in the process industry such as gas processing, manufacture of transportation means, etc. In these installations, several fuel elements are present and require special attention in order to avoid accidents whose consequences have severe impacts on people, equipment, and environment. The most common accidents encountered in the chemical and petrochemical process industry are fires, explosions, and toxic releases. Considering the number of existing and future installations, the consequences of these types of accidents remain a major concern for decision-makers, industrial experts, and fire safety analyst. The oil and gas industry plays a pivotal role in powering modern civilization, providing essential energy resources to sustain economic growth and daily life. However, the handling and transportation of volatile hydrocarbons within this industry present inherent risks, particularly concerning catastrophic events like the Boiling Liquid Expanding Vapor Explosion (BLEVE). Understanding and mitigating the potential consequences of a BLEVE incident is a critical component of safety management within this sector. A BLEVE is an event characterized by the sudden rupture of a pressurized vessel containing flammable or combustible substances, often caused by external factors such as fire, impact, or mechanical failure. This rupture leads to the instantaneous release of a superheated vapor cloud, followed by ignition and the formation of a fireball.

The resulting fireball can have devastating consequences, including severe thermal radiation hazards, structural damage, and, in some cases, loss of life.

The consequences of major accidents with severe impacts on people, equipment and environment remain a primary concern for decision-makers and industrial experts. The three main most commonly encountered types of accidents in the chemical and petrochemical process industry are: fires, explosions and toxic releases. With the technological growth of existing and emerging facilities, it is necessary to enhance the safety of these facilities by optimizing and improving the risk analysis methods.

In the labyrinthine infrastructure of the oil and gas industry, where colossal tanks and pipelines intertwine to meet the world's energy demands, the spectre of catastrophic events looms ominously. Among these, the Boiling Liquid Expanding Vapor Explosion (BLEVE) stands as a sentinel of peril, capable of unleashing devastating fireballs with lethal thermal radiation hazards.

BLEVEs occur when the integrity of pressurized vessels containing volatile liquids is compromised, triggering a cataclysmic chain reaction of vaporization and ignition. The resultant fireballs, with their searing temperatures and billowing plumes, pose existential threats to personnel, infrastructure, and the environment within the oil and gas industry.

This study embarks on a journey through the turbulent seas of BLEVE phenomena and thermal radiation hazards, navigating the treacherous terrain where science intersects with industry. Drawing upon the latest advancements in computational modelling, risk assessment methodologies, and regulatory frameworks, we endeavour to chart a course toward safer shores.

But this voyage is not one of mere academic pursuit; it is a solemn obligation to safeguard lives and livelihoods in the face of an ever-present danger. As we delve into the intricacies of BLEVE dynamics and thermal radiation assessments, we illuminate pathways to resilience and fortification against the tempests that threaten to engulf us.

Through collaboration, innovation, and unwavering dedication to safety, we aspire to erect bulwarks of protection that shield our industry from the ravages of catastrophe. For in the crucible of adversity, it is our collective resolve that shall emerge unscathed, forging a future where the flames of progress burn bright, untainted by the shadows of calamity.

BLEVE events are highly dangerous and can have catastrophic consequences. It is crucial to engage with experts in process safety engineering and use advanced software tools to model and assess these events accurately. Additionally, proactive measures to prevent BLEVE incidents and effective emergency response planning are key to ensuring the safety of oil and gas industry operations. Here are some industries in India where BLEVE fireball modelling is of significant importance:

1) Oil and Gas Industry: This is perhaps the most critical sector where BLEVE modelling is of utmost importance. The industry involves the storage and transportation of large quantities of flammable hydrocarbons, making the risk of BLEVE events a serious concern. Chemical Industry: The chemical industry deals with various hazardous chemicals, many of which are flammable or combustible. Proper BLEVE modelling is crucial for risk assessment and safety measures.
2) Liquefied Petroleum Gas Storage and Distribution: The LPG industry, which supplies cooking gas to households and industries, handles large quantities of a highly flammable substance. BLEVE events can have severe consequences, making modelling essential.
3) Petroleum Refineries: Refineries process crude oil into various petroleum products. The presence of volatile and flammable materials necessitates accurate BLEVE modelling for safety and risk management.
4) Pharmaceutical Industry: This industry often deals with the production and storage of flammable solvents and chemicals, making BLEVE modelling crucial for safety.
5) Petrochemical Industry: The petrochemical sector produces a wide range of chemicals and plastics. It involves handling flammable materials that pose BLEVE risks.
6) Power Plants: Power plants, including thermal and gas-based power generation facilities, use large quantities of flammable fuels. Accurate BLEVE modelling is important for safety planning and risk mitigation.
7) Manufacturing and Warehousing: Industries involved in manufacturing, warehousing, and storage of flammable goods need to consider BLEVE modelling as part of their safety protocols.
8) Transportation and Logistics: The transportation of flammable materials, whether by road, rail, or pipelines, is another area where BLEVE modelling is vital. Accidents during transport can lead to BLEVE events.
9) Liquefied Natural Gas Terminals: Facilities that handle LNG for import or export require careful consideration of BLEVE risks due to the cryogenic nature of the fuel.
10) Ammunition and Explosives Manufacturing: Industries dealing with the production and storage of explosives and ammunition must assess BLEVE risks and plan for safety accordingly.
11) Agriculture and Fertilizer Storage: Certain agricultural chemicals and fertilizers can be flammable or reactive. Proper modelling helps in ensuring safety in agricultural operations.

12) Aviation Fuel Storage: Facilities that store aviation fuels and other flammable materials at airports must consider BLEVE risks to protect both property and human life.
13) Petrochemical Storage and Tank Farms: Large storage tank facilities, where various petrochemical products are stored, need to assess BLEVE hazards and develop safety strategies.
14) Bulk Chemical Storage and Handling: Industries that handle bulk chemicals, such as chlorine, ammonia, or other hazardous substances, should conduct BLEVE modelling for safety planning. These industries in India and worldwide must prioritize BLEVE modelling as part of their risk assessment and safety management strategies to minimize the potential for catastrophic incidents.

The project will involve extensive research and analysis of the relevant literature, as well as the development and testing of the model using real-world data. The model's accuracy and reliability will be validated through a series of experiments and simulations.

The project's findings will have significant implications for the oil and gas industry, as they will provide a better understanding of the risks associated with BLEVE fireballs and enable companies to implement more effective safety measures. The model can also be used to train emergency responders and develop evacuation plans, further enhancing the industry's safety and reducing the risk of accidents.

B. *Objective Of Project*

The objectives of studying and assessing BLEVE (Boiling Liquid Expanding Vapor Explosion) fireballs in the context of safety and risk management in the oil and gas industry include:

1) To identify the potential hazards associated with BLEVE events, which occur when pressurized containers containing flammable liquids rupture, release their contents, and form fireballs.
2) To assess the risks posed by BLEVE fireballs to personnel, equipment, and nearby communities, considering factors such as fireball size, thermal radiation levels, and blast effects.
3) To inform the design and engineering of safety measures and mitigation strategies aimed at preventing or minimizing the impact of BLEVE events, such as pressure relief systems and blast barriers.
4) To develop effective emergency response plans that include procedures for evacuating personnel, controlling fires, and mitigating the consequences of a BLEVE, ensuring the safety of responders and minimizing damage.
5) To prevent the accidents and minimize potential losses in terms of lives, property, and environmental damage by implementing proactive safety measures based on a thorough understanding of BLEVE fireball hazards.

C. *Scope Of The Project*

This project will explore the complexities of BLEVE events, from their initiation to the assessment of thermal radiation hazards, with a focus on their applicability in the oil and gas sector. By gaining a comprehensive understanding of BLEVE phenomena and the tools to model and assess them, industry professionals can proactively manage the risks associated with these potentially catastrophic incidents and promote the safety and sustainability of oil and gas operations.

II. REVIEW OF THE LITERATURE

A. *Introduction*

Literature survey for the project is related to the project title (Modelling of BLEVE fireball and its Impact Assessment of Thermal Radiation Hazard in an Oil & Gas Industry). All the research papers are from international journals, and of authors who were specialist in their field. These literatures help me to complete my project with more dedication and accuracy. The literature is arranged by year wise which show that research have been done previously year by year related to my project title and it justify that.

B. *Classification Of Literature*

1) *Lei Huo, Yawei He, Erping Ma, and Xing Liu (2023)*

In this research paper, CO2-oil recovery enhancement technology, the occurrence of a Boiling Liquid Expansion Vapor Explosion (BLEVE) can result in dangerous events that endanger the lives and health of workers, while also leading to significant economic losses. This happens when there is an excessive injection concentration and volume of CO2, coupled with container defects. To address the limited research on the mechanism and destruction of BLEVE, this study conducts experiments to explore these issues. The experimental results reveal that the bursting piece ruptures at a temperature of 36C, and the specimen explodes when the pressure intensity exceeds the residual strength of the specimen, reaching 69.97 MPa.

The findings indicate that parameters, such as initial pressure, initial temperature, and failure pressure, can impact the risk of CO2 BLEVE occurrence and the propagation of explosion shock waves. The pressure inside the container during the BLEVE process fluctuates due to the joint action of the leakage rate and gasification rate of liquid CO2. This research provides a framework for evaluating the risk of CO2 BLEVE during CO2 geological storage and enhanced oil recovery injection processes, offering theoretical support for BLEVE prevention and control.

2) Xing Zhou, Yongmei Hao, Jian Yang, Zhixiang Xing, Han Xue and Yong Huang (2023)

In this research paper, with the rapid development of high-pressure combustible gas pipelines, it brings convenience and also buries potential safety hazards. This paper presents an in-depth exploration of the thermal radiation hazards of fireball accidents caused by leakage and provides a reference for the prevention and control of this type of accident and on-site rescue. Based on the basic principle of fluid mechanics and the calculation model of the leakage rate, a three-dimensional pipeline model was constructed by FDS software to simulate the fireballs with different positions of low, middle and high. The simulation shows that the ground temperature field of the low and middle fireballs is quite different from that of the high fireball, and the temperature level is: low position > middle position > high position. On this basis, the observation elevation angle is introduced to improve the classical fireball thermal radiation model formula, the model calculation value is compared with the numerical simulation value and the optimal threshold is determined by combining the thermal radiation flux criterion. The results show that the numerical simulation is basically consistent with the calculation results of the improved model. The smaller the observation elevation angle, the closer the target receives the thermal radiation flux to the optimal threshold and the calculated hazard range is more reliable.

3) Shan Lyu a, Shuhao Zhang, Xiaomei Huang, Shini Peng, Jun Li (2022)

In this research paper, the liquefied petroleum gas (LPG) accident in Wenling, Zhejiang Province, China, on June 13, 2020, was analysed and simulated. An LPG tank truck overturned and collided with the concrete guardrail; the subsequent explosion of the tank released 25.36 t LPG. Shortly afterward, the LPG tank was shot into the air, and the gas cloud ignited, thereby triggering a fire and vapor cloud explosion (VCE). This accident killed 20 people, injured 175 people, and caused significant property loss. The accident timeline was established based on multiple accident images, and the accident process was discussed in detail. The distribution of tank debris, evaporation and spreading of the LPG pool, dispersion of the LPG gas cloud, and VCE were simulated with the EFFECTS and ALOHA software. The images of the accident scene helped to determine and analyse the accident process. In the particular case in which a tank is shot into the air with a continuous two-phase jet, the actual flight distance of the tank is much greater than the prediction of the debris distribution model. The gas cloud distribution simulated with the SLAB model approximately corresponds to a major part of the severely damaged zone. In this accident, the TNO multi-energy method and ALOHA provide relatively consistent predictions with the actual building damage distribution when models use a specific confined explosive mass.

4) Joseph M. Cabeza-Lainez, Francisco Salguero-Andújar and Inmaculada Rodríguez- Cunill (2022)

In this research paper, radiation fireballs are singular phenomena which involve severe thermal radiation and, consequently, they need to be duly assessed and prevented. Although the radiative heat transfer produced by a sphere is relatively well known, the shadowing measures implemented to control the fireball's devastating effects have frequently posed a difficult analytical instance, mainly due to its specific configuration.

The objective of this article is to develop a parametric algorithm that provides the exact radiative configuration factors for the most general case in which the fireball is located at any distance and height above the ground, partially hidden by a protective wall over an affected area at different positions with respect to the said fireball. To this aim we use methods based on Computational Geometry and Algorithm-Aided Design; tools that, departing from the projected solid-angle principle, provide exact configuration factors, in all cases, even if they do not present a definite analytical solution. This implies dealing with spatially curved radiative sources which had not been addressed formerly in the literature due to their mathematical difficulties. Adequate application of this method may improve the safety of a significant number of facilities and reduce the number casualties among persons exposed to such risks. As a similar radiative problem appears in volcanic explosions; we hope that further extensions of the method can be adapted to the issue with advantage.

5) *Dmitriy Makarov, Volodymyr Shentsov, Mike Kuznetsov and Vladimir Molkov (2021)*

In this research paper, the engineering correlations for assessment of hazard distance defined by a size of fireball after either liquid hydrogen spill combustion or high-pressure hydrogen tank rupture in a fire in the open atmosphere (both for stand-alone and under-vehicle tanks) are presented. The term “fireball size” is used for the maximum horizontal size of a fireball that is different from the term “fireball diameter” applied to spherical or semi-spherical shape fireballs. There are different reasons for a fireball to deviate from a spherical shape, e.g., in case of tank rupture under a vehicle, the non-instantaneous opening of tank walls, etc. Two conservative correlations are built using theoretical analysis, numerical simulations, and experimental data available in the literature. The theoretical model for hydrogen fireball size assumes complete isobaric combustion of hydrogen in air and presumes its hemispherical shape as observed in the experiments and the simulations for tank rupturing at the ground level. The dependence of the fireball size on hydrogen mass and fireball’s diameter-to-height ratio is discussed. The correlation for liquid hydrogen release fireball is based on the experiments by Zabetakis (1964). The correlations can be applied as engineering tools to access hazard distances for scenarios of liquid or gaseous hydrogen storage tank rupture in a fire in the open atmosphere.

6) *Federico Ustolin, Ernesto Salzano, Gabriele Landucci, Nicola Paltrinieri (2020)*

In this research paper, hydrogen is one of the best candidates in replacing traditional hydrocarbon fuels to decrease environmental pollution and global warming. Its consumption is expected to grow in the forthcoming years. Hence its liquefaction becomes necessary to store and transport large amounts of this fuel. However, a liquid hydrogen (LH2) boiling liquid expanding vapor explosion (BLEVE) is a potential accident scenario for these technologies, despite the fact it may be considered as atypical. A BLEVE is a physical explosion resulting from the catastrophic rupture of a tank of a liquid at a temperature above its boiling point at atmospheric pressure. Its consequences are the pressure wave, the missiles, which are the tank debris thrown away by the explosion, and a fireball if the substance is flammable and an ignition source is present. The aim of this paper is to estimate the consequences associated with BLEVEs from LH2 storage and transport systems by means of integral models. Both ideal and real gas behavior models were considered to calculate the explosion overpressure. The physical models were employed to analyse the consequences of analogous fuel BLEVEs, in order to provide a comparative assessment of the results. BLEVE experimental results for LH2 are not available in literature yet. For this reason, the developed models will be validated during the SH2IFT project in which LH2 BLEVE experimental tests will be conducted.

7) *Brady Manescau, Khaled Chetehouna, Ilyas Sellami, Rachid Nait-Said and Fatiha Zidani (2020)*

In this research paper, the numerical modeling of the BLEVE (Boiling Liquid Expanding Vapor Explosion) thermal effects. The goal is to highlight the possibility to use numerical data in order to estimate the potential damage that would be caused by the BLEVE, based on quantitative risk analysis (QRA). The numerical modeling is carried out using the computational fluid dynamics (CFD) code Fire Dynamics Simulator (FDS) version 6. The BLEVE is defined as a fireball, and in this work, its source is modeled as a vertical release of hot fuel in a short time. Moreover, the fireball dynamics is based on a single-step combustion using an eddy dissipation concept (EDC) model coupled with the default large eddy simulation (LES) turbulence model. Fireball characteristics (diameter, height, heat flux and lifetime) issued from a large-scale experiment are used to demonstrate the ability of FDS to simulate the various steps of the BLEVE phenomenon from ignition up to total burnout. A comparison between BAM (Bundesanstalt für Materialforschung und –prüfung, Allemagne) experiment data and predictions highlight the ability of FDS to model BLEVE effects. From this, a numerical study of the thermal effects of BLEVE in the largest gas field in Algeria was carried out.

8) *Yuanyuan Wang, Xiaochen Gu, Li Xia, Yong Pan, Yuqing Ni, Supan Wang, Wei Zhou (2020)*

In this research paper, the hydrocarbon fireball characteristic of LPG tanker Boiled Liquid Evaporate Vapor Explosion (BLEVE) under different conditions, computational fluid dynamics (CFD) simulations of the hydrocarbon fireballs from the LPG tanker BLEVE accidents were carried out. Several new different factors, such as the mass of fuel, inlet velocity and airflow velocity, were considered to analyse the influence on the evolution of the characteristics of the fireball and the development of the LPG tanker BLEVE accidents. Results indicate that the fireball with a greater mass of fuel radiates more heat but slower. The large longitudinal diameter of the fireball and high radiation heat flux are observed in case of a faster inlet velocity used for the same mass. The airflow was found to shorten the initial phase of the fireball effectively. Some suggestions were proposed to prevent the LPG BLEVE accidents. Analysis performed show that various parameters like fireball diameter, radiative heat flux and lifting speed of fireball can be predicted well using FDS code.

9) Jingde Li and Hong Hao (2020)

In this research paper, the prediction of blast wave generated from the Boiling Liquid Expanding Vapour Explosion (BLEVE) has been already broadly investigated. However, only a few validations of these blast wave prediction models have been made, and some well-established methods are available to predict BLEVE overpressure in the open space only. This paper presents numerical study on the estimation of the near-field and far-field blast waves from BLEVEs. The scale effect is taken into account by conducting two different scale BLEVE simulations. The expansion of pressurized vapour and evaporation of liquid in BLEVE are both modelled by using CFD method. Two approaches are proposed to determine the initial pressure of BLEVE source. The vapour evaporation and liquid flashing are simulated separately in these two approaches. Satisfactory agreement between the CFD simulation results and experimental data is achieved. With the validated CFD model, the results predicted by the proposed approaches can be used to predict explosion loads for better assessment of explosion effects on structures.

10) M. Anandhan, Dr. T. Prabaharan, M. Muhaidheen and S. Ragavendran (2019)

In this research paper, The Risk Assessment is an important legal requirement which should be carried out in industries in order to prevent any incident in future and manage emergencies better. In this article a typical LPG (Liquefied Petroleum Gas) storage bullet of capacity 14.7m 3 and truck tanker of capacity 18 m 3 were selected for the study. Risk assessment was carried out for various fire scenarios such as BLEVE, VCE, and Jet fire which can happen in LPG storage area. The inputs used in the estimation are collected from various articles and from a typical LPG handling and storing industry in the southern part of Tamil Nadu. The meteorological conditions for the assumed Madurai region are given as an input data in the ALOHA software for dispersion predictions of various scenarios. The accident situations are selected from various reports and literatures of LPG storages around the world. By using the ALOHA software, the dispersion models are used to estimate dispersion concentrations, Blast effects, Flammable effects, Thermal radiation and Toxic effects. The results are arrived from the predicted and user defined inputs in ALOHA software with the references and industrial investigations.

11) Yuan Chen (2018)

In this research paper, boiling liquid expanding vapour explosions (BLEVEs) are among the most dangerous accidents that can occur in the chemical process industry, particularly during the storage and transportation of liquefied gases. To better understand the hazards associated with BLEVEs during the transport of liquefied gases, historical cases involving transportation of Liquefied Petroleum Gas (LPG) from around the world were investigated. A literature review was conducted to identify available models and math models to estimate the characteristics of BLEVEs, and to determine if any prior research had been completed on the comparative analysis of observed and predicted BLEVE characteristics. Math models were found to be a useful tool in this regard and are summarized in a table that outlines the step-by-step calculation methodologies. Furthermore, seven different cases of BLEVE accidents are presented in the BLEVE case histories chapter, describing the effects and phenomena observed during such incidents. Data obtained from these case studies were analysed using different methodologies to estimate the fireball parameters (diameter, duration, and height), thermal radiation from the fireball at specific viewpoints, overpressure wave, and maximum missile distance after the accidents. The estimated results were then compared with the observed damage to assess the accuracy of the prediction models and to critically evaluate their validity. Finally, a discussion on the best model to use in different BLEVE consequences is proposed. The uncertainty associated with damage observed after the accidents and the calculation of the BLEVE consequences are also discussed in this study. By investigating the historical cases of BLEVEs and using different methodologies to estimate their hazards, this study provides valuable insights into the potential hazards associated with BLEVEs during the transportation of liquefied gases and highlights the importance of accurate and reliable prediction models to prevent such accidents.

12) André Laurent, Laurent Perrin, Olivier Dufaud (2018)

In this research paper, presently in France the control authority (DREAL) in charge of the inspection of the Seveso installations requires the examination of the scenario “cold BLEVE” of very flammable liquid storages (flash point < 273K; vapour pressure > 105 Pa at 308K). The proposed case study reports the consequence analysis of a 4,800 m3 spherical isopentane storage tank. The potential cold BLEVE is characterized by a ground level cloud fire associated with a weak fireball tangential to the ground level. Estimations of the explosion energy, blast overpressure and thermal radiation effects were examined with different models. Uncertainties are carefully studied. The prescribed calculation methodology constitutes a basis for administrative decision with important consequences for the safety of population, industry and Land Use Planning.

13) Ilyas Sellami, Brady Manescau, Khaled Chetechouna, Charles de Izarra, Rachid Nair- Said, Fatiha Zidani (2018)

In this research paper, BLEVE is one of major accidents observed in gas industry causing severe damage to people and environment. Its effects are manifested in three ways: shock wave propagation, fireball radiation and fragments projection. To assess these effects, risk decision-makers often use Quantitative Risk Analysis (QRA). In most cases, QRA data are obtained from empirical correlations. However, these correlations are not very satisfactory because they generally overestimate BLEVE effects and do not take into account geometry effects. In order to overcome the limitations of these empirical approaches, CFD modeling appears as a powerful tool able to provide more ac- curate data to better realize QRA. In this paper, the objective is to develop a CFD methodology in order to predict BLEVE thermal effects. Numerical simulations are carried out using the CFD code FDS. A sensitivity analysis of numerical models is performed in order to choose the right parameters allowing to model the fireball dynamics. The models retained are based on a single-step combustion using EDC model coupled with a LES turbulence model. Predictions show good agreement in comparison with results issued from three large-scale experiments. Furthermore, a case study on a propane accumulator in an Algerian gas processing unit is carried out.

14) Behrouz Hemmatian, Joaquim Casal, Eulàlia Planas (2017)

In this research paper, huge amounts of hazardous materials are transported by rail and road, being from time to time involved in traffic accidents. In these cases, flammable materials such as, for example, LPG, can originate a severe accident if a loss of containment takes place: a BLEVE explosion usually followed by a fireball. This type of accident, which often follows the domino effect sequence of fire□explosion, has caused the death of many people, including firefighters and spectators, the mechanical and thermal effects reaching significant distances. A historical survey has been performed on 167 accidents obtained from diverse databases. The results thus obtained have been used, together with the adequate mathematical models, to analyse the time to failure that can be expected and to estimate the lethality reach of the diverse effects –overpressure, ejected fragments, thermal radiation. Finally, a set of considerations concerning the safety and emergency measures that should be adopted in these accidents are commented.

15) Paul Blankenhagel, Kirti Bhushan Mishra, Klaus-Dieter Wehrstedt, Jörg Steinbach (2016)

In this research paper, the burning behaviour and thermal radiation of pool fires of organic peroxides (OP) have been studied by several authors in the past. It was shown that mass burning rates, flame temperatures and thus the Surface Emissive Power (SEP) of OP exceed to that of hydrocarbons considerably. These facts lead to further investigations of even dangerous worst-case scenarios i.e. related to storage and transportation. A metal drum containing 200 l of DTBP (Di-tert-butyl peroxide) is investigated under a surrounding wood fire. Due to a higher heat flux to the substance, the mass burning rate reaches multiples of an equivalent pool fire and results in several fireballs. The analyses of thermographic camera images and radiometer measurements show higher flame lengths, higher temperatures and therefore increased thermal radiation compared to OP pool fires. The resulting greater safety distances for a DTBP fireball event are discussed.

16) Alfonso Ibarreta, Hubert Biteau, and Jason Sutula (2016)

In this research paper, the storage of flammable liquids and vapours in closed vessels can lead to a catastrophic failure of the vessel during a fire. When a vessel explosion involves a flammable substance, it is usually followed by a fireball. If the flammable material is stored as a pressure liquefied gas, a sudden failure of the storage vessel may result in a Boiling Liquid Expanding Vapor Explosion (BLEVE). A BLEVE event will result in a sudden conversion of stored thermal energy into mechanical energy in the form of a pressure wave. Additionally, the rupture of a compressed gas storage vessel may also result in a pressure wave. A sudden energy release from a compressed vessel failure will result in damage associated with the pressure wave and the impact of missiles displaced by the explosion. In the case of a vessel filled with a flammable gas or liquid, the sudden ignition of the material can result in a fireball that travels upward while burning. This fireball may cause additional damage due to the associated flame radiation.

17) Kirti Bhushan Mishra (2016)

In this research paper, the scenarios of multiple BLEVEs (Boiling Liquid Expanding Vapor Explosions), characteristics of multiple explosions and fireballs of flammable gas bottles are investigated within the context of a recent Russian road carrier accident. The applicability of available semi-empirical equations (models) to estimate the explosion overpressure and fireball characteristics e.g. diameter, elevation, Surface Emissive Power, irradiances, thermal safety distances and missile/projectile distances are evaluated. It is shown that the existing models are valid only for a scenario of single event of BLEVE and fireball.

Hence, characterization of multiple BLEVEs and fireballs require appropriate estimation of an equivalent mass that actually contributes in the overall hazard. Such an equivalent mass helps to use the existing models and establish the safety distances that match the observed reality on the site very well.

18) Mohammad Kamaei, Seyed Shams Aldin Alizadeh, Abdolrahman Keshvari, Zeynab Kheyrkhah, Parisa Moshashaei (2016)

In this research paper, although human industrial activities are as a part of efforts to achieve greater prosperity, the risks related to these activities are also expanding. Hazard identification and risk assessment in the oil and gas industries are essential to reduce the frequency and severity of accidents and minimize damage to people and property before their occurrence. The aim of this study was to evaluate the liquefied and pressurized petroleum gas spherical tanks in a refinery and assessing the risks of Boiling Liquid Expanding Vapor Explosion (BLEVE) phenomenon.

19) Nilambar Bariha, Indra Mani Mishra, Vimal Chandra Srivastava (2016)

In this research paper, an analysis and simulation of an accident involving a liquefied petroleum gas (LPG) truck tanker in Kannur, Kerala, India. During the accident, a truck tanker hit a divider and overturned. A crack in the bottom pipe caused leakage of LPG for about 20 min forming a large vapor cloud, which got ignited, creating a fireball and a boiling liquid expanding vapor explosion (BLEVE) situation in the LPG tank with subsequent fire and explosion. Many fatalities and injuries were reported along with burning of trees, houses, shops, vehicles, etc. In the present study, ALOHA (Area Locations of Hazardous Atmo- spheres) and PHAST (Process Hazard Analysis Software Tool) software have been used to model and simulate the accident scenario. Modeling and simulation results of the fireball, jet flame radiation and explosion overpressure agree well with the actual loss reported from the site. The effects of the fireball scenario were more significant in comparison to that of the jet fire scenario.

20) Xinrui Li a, Hiroshi Koseki b, M. Sam Mannan (2015)

In this research paper, after the 2011 Tohoku earthquakes, several chemical and oil complexes on the Pacific Ocean shoreline of northeast Japan experienced massive losses. In Chiba, a refinery operated by Cosmo Oil lost 17 LPG storage vessels which were either heavily damaged or totally destroyed by fires and explosions in the refinery. These large vessels ranged in size from 1000 to 5000 m3. The estimated volume of LPG at the time of the incident was between 400 and 5000 m3 for each vessel. Five boiling liquid expanding vapor explosions (BLEVEs) of LPG occurred, resulting in huge fire balls measuring about 500 m in diameter.

A BLEVE is defined as the explosive release of expanding vapor and boiling liquid when a container holding a pressure-liquefied gas fails catastrophically. It is thus important to estimate the physical properties of superheated liquids: the thermodynamic and transport properties, the intrinsic limits to superheating and depressurization, and the nature of thermodynamic paths. Also, it is hoped to provide better understanding of the vessels designed, manufactured, installed, and operated to reduce or eliminate the probability that a sequence of events will result in BLEVE or loss of primary containment. Knowledge of these matters is still incomplete. The objective of this research is to estimate the significant BLEVE phenomenon in very large-scale spherical vessels based on published information in Japan. There are some models predicting BLEVEs. However, it is essential to know if this is true for very large scales such as spheres since validation is usually rare to provide confidence in estimating the superheated liquids behaviors. To this end, comparing with the information on this event, the conditions in the five LPG vessels at the time of the BLEVE were determined in terms of: duration of vessel failure (time to BLEVE); mass fraction in the vessel with time; temperature distribution in the liquid and vapor region and pressure within the vessel (e.g. initial pressure and internal high-speed transient pressure during failure), by means of a computer program AFFTAC Analysis of Fire Effects on Tank Cars, which solves heat conduction, stress and a failure model of the tank, a thermodynamic model of its fluid contents, and a flow model for the lading flowing through the safety relief device. Subsequently, the consequences from the sphere BLEVE, such as the expected fireball diameter and duration and the expected blast overpressure produced by the BLEVE failures, are also subjects of active research. Here the blast using the methods of PHAST and SFPE Handbook of Fire Protection Engineering was calculated.

Results suggest that methodologies here used gave reasonable estimations for such real and huge BLEVEs in a validated way, which may provide valuable guidance for risk mitigation strategy with regard to LPG facility in design, emergency planning, resiliency, operations, and risk management.

21) Bhisham K. Dhurandher, Ravi Kumar and Amit Dhiman (2015)

In this research paper, failure of the pressure vessel containing pressure liquefied petroleum gas leads to Boiling Liquid Expanding Vapour Explosion (BLEVE). Further, ignition of released gas results in the formation of fireballs.

In the present paper the semi-empirical equations are presented that represent the impact assessment of thermal radiation hazards from the liquefied petroleum gas fireball. Also, an attempt has been made to determine the safe separation distance.

22) ZHANG Qian-Xia and LIANG Donga (2013)

Correlations are presented that represent consensus views on the influence of mass of LNG in the release on BLEVE fireball diameter, duration, and radiation output. And when the BLEVE fireball accidents of different load of LNG road tankers occurred, the corresponding safety distances of thermal radiation influence are calculated.

23) SHAO Hui and DUAN Guoning (2012)

In this research paper, to study gas leakage accident risk in Natural Gas Power Generation Co., Ltd. and its impact on the surrounding residents, we analysis the accident scenes of natural gas power plant and accident scenes which may occur in the key hazardous areas. By taking the pipeline leakage accident in the last branch lines station as example, the diffusion statuses were simulated by using ALOHA after the natural gas leak. The frequency of pipeline leakage accident and the consequences in the power plant were analysed. Then individual risk and social risk were obtained. The results show that social risk of the plant is related to the population distribution near natural gas pipelines and the factors of death probability. Assuming three kinds of leak conditions that leakage apertures are respectively 100mm, 200mm and 1200mm, the individual risk and social risk are beyond the acceptable range. When pipeline leakage aperture is 100mm, rescue and evacuation shall be promptly carried out in the power plant and the leakage accident has no effect on the town. When pipeline leakage aperture is 200mm, people should immediately control the leak and make the explosion-proof measures from 55m to 92m of the power plant downwind which is in the range of natural gas explosion limits. When pipeline leakage aperture is 1200mm, emergency evacuation measures should be taken and prevent accidents expanding in most of the town which is in the range of natural gas explosion limits. The results of the quantitative risk calculations and ALOHA simulations provide bases and decisions for the pipelines plan, construction of natural gas power plant and the spatial location of the town.

C. Literature Contribution to Project Work

Total 23 different BLEVE fireball modelling research paper for the different scenario has been reviewed by me during my dissertation. Areal Locations of Hazardous Atmospheres (ALOHA) software is my base methodology. With the help of this methodology different aspect were calculated like, thermal radiation threat zone, flammable threat zone, burn rate, release rate, toxic threat zone, overpressure threat zone.

III. AREA OF STUDY

A. Industrial Introduction

The oil and gas industry are a cornerstone of the global economy, providing the essential energy resources that fuel our modern way of life. It encompasses a vast and intricate network of activities, from the exploration and extraction of hydrocarbons deep beneath the Earth's surface to their refinement into various petroleum products and their distribution to end-users. This industry has played a pivotal role in shaping geopolitics, economies, and technological advancements over the past century. However, as concerns about environmental sustainability and the transition to cleaner energy sources gain momentum, the sector is also at the forefront of transformative changes. It faces the dual challenge of meeting the world's energy needs while reducing its environmental impact. As such, the oil and gas industry are undergoing a profound shift toward innovation, diversification, and the development of greener technologies to ensure a sustainable energy future for our planet.

B. Description On Material, Process And Operation

The operations and processes in the oil and gas industry are diverse and complex, involving a series of steps from exploration to distribution. Here's a detailed overview of how operations and processes are carried out in each stage:

1) Exploration

- Geological and Geophysical Surveys: Oil and gas exploration begins with geological surveys to identify areas with potential hydrocarbon reserves. Geophysical surveys, including seismic imaging, are conducted to further assess subsurface structures.
- Exploratory Drilling: Once prospective areas are identified, exploratory wells are drilled to confirm the presence of oil or gas deposits. This involves the use of drilling rigs and specialized equipment to penetrate the earth's crust and collect rock samples.

2) Drilling and Production (Upstream)

- Well Planning: Engineers and geologists develop well plans based on geological data to optimize drilling locations and target reservoirs.
- Drilling Operations: Drilling rigs are used to drill wells into the earth's crust. Various drilling techniques, including rotary drilling and directional drilling, are employed to reach target depths and formations.
- Well Completion: Once a well is drilled, it undergoes completion, which involves installing casing, tubing, and wellhead equipment to facilitate production.
- Production Operations: Oil and gas are extracted from reservoirs through production wells. Primary, secondary, and tertiary recovery techniques are employed to maximize production rates and recoverable reserves.

3) Processing and Refining (Midstream)

- Separation: Raw crude oil and natural gas are separated from impurities such as water and solids using separation equipment.
- Refining: Crude oil is transported to refineries, where it undergoes various refining processes to produce refined petroleum products such as gasoline, diesel, jet fuel, and lubricants.

4) Transportation and Storage (Midstream)

- Pipeline Transportation: Oil and gas are transported over long distances via pipelines. Pipelines are a cost-effective and efficient means of transportation.
- Tanker Transport: Crude oil and liquefied natural gas (LNG) are transported across oceans via tankers. These large vessels carry large quantities of oil and gas to refineries, terminals, and export markets.
- Storage: Facilities such as storage tanks and terminals are used to store crude oil, refined products, and natural gas.

5) Distribution and Marketing (Downstream)

- Distribution: Refined petroleum products are distributed to end-users through various channels such as trucking, rail, and pipelines.
- Marketing: Oil and gas companies engage in marketing and branding activities to promote their products to consumers.

6) Environmental and Regulatory Compliance:

- Environmental Regulations: Oil and gas companies must comply with environmental regulations governing theiroperations, including emissions monitoring and pollution control.
- Health and Safety Regulations: Regulations ensure the safety of workers and communities near oil and gas operations.

7) Research and Development

- Companies invest in research and development to improve extraction techniques, enhance refining processes, and develop cleaner technologies.
- This includes innovations in drilling technology, enhanced oil recovery methods, and renewable energy initiatives.

These operations and processes collectively form the value chain of the oil and gas industry, from exploration and production to refining, transportation, distribution, and marketing. Each step requires careful planning, execution, and management to ensure the efficient and safe extraction, processing, and delivery of oil and gas resources to consumers.

C. Statement of Problem For Which Project is Proposed

The exploration, extraction, and processing of hydrocarbons in the oil and gas industry constitute a vital component of global energy supply. However, alongside its indispensable role, this industry also contends with inherent risks and hazards, among which the Boiling Liquid Expanding Vapor Explosion (BLEVE) stands out as a formidable threat. The BLEVE phenomenon, characterized by the sudden release of pressurized liquefied gas, can trigger catastrophic fireballs with devastating consequences for personnel, infrastructure, and the environment.

This monumental project embarks on a journey into the intricate realm of BLEVE fireball modelling and its profound impact assessment concerning thermal radiation hazards within the oil and gas industry. Spanning an extensive body of research and computational analysis, this endeavour seeks to unravel the complexities surrounding BLEVE events, offering invaluable insights into their dynamics, propagation, and aftermath. This project represents an exhaustive exploration of BLEVE phenomena, meticulously examining every facet and nuance. Through sophisticated modelling techniques and advanced computational simulations, it endeavours to elucidate the multifaceted nature of BLEVE fireballs, unravelling the intricate interplay of factors influencing their formation, size, and thermal radiation emission. At its core, this project endeavours to go beyond mere observation, aiming to comprehensively analyse the implications of BLEVE incidents on personnel safety, infrastructure integrity, and environmental sustainability within the oil and gas sector. By meticulously assessing the thermal radiation hazards associated with BLEVE fireballs, it seeks to provide industry stakeholders, regulatory bodies, and safety professionals with invaluable data-driven insights essential for enhancing safety protocols and emergency response strategies. Furthermore, this monumental endeavour aspires to contribute significantly to the broader scientific community, enriching the collective understanding of BLEVE phenomena and advancing the frontier of knowledge in hazard assessment and risk management. Through its exhaustive exploration and meticulous analysis, this project endeavours to serve as a cornerstone in the ongoing pursuit of safety excellence and operational resilience within the oil and gas industry. In the oil and gas industry, the occurrence of a Boiling Liquid Expanding Vapor Explosion (BLEVE) represents a severe and potentially catastrophic hazard. A BLEVE event can lead to the rapid release of flammable or combustible substances from pressurized vessels, resulting in the formation of a fireball with a significant thermal radiation hazard. The problem at hand involves a comprehensive study to address the following aspects:

1) Modelling the BLEVE Fireball: Develop an accurate and reliable modelling approach for simulating the initiation and progression of a BLEVE event in an oil and gas industry setting. This involves understanding the fluid dynamics, thermodynamics, and ignition mechanisms associated with BLEVEs.
2) Thermal Radiation Hazard Assessment: Assess the thermal radiation hazard posed by the BLEVE fireball, including the calculation of heat flux, radiant energy exposure, and understanding its impact on personnel, structures, and the environment.
3) Data Collection and Analysis: Gather and analyse relevant data pertaining to the specific scenario under investigation, including information about the storage vessel, contents, operating conditions, and environmental factors.
4) Safety Measures and Regulatory Compliance: Evaluate existing safety measures, emergency response plans, and compliance with local, national, and international regulations and standards to mitigate the risk of BLEVE incidents.
5) Emergency Response Planning: Develop and refine emergency response plans to manage BLEVE incidents, including evacuation procedures, protective actions, and coordination with response teams.
6) Mitigation Strategies: Explore methods to prevent or minimize the occurrence of BLEVE events, such as improved vessel maintenance, enhanced safety systems, and updated operating procedures.
7) Asset Protection: Consider strategies for safeguarding valuable assets, including infrastructure, equipment, and facilities, from damage caused by BLEVE incidents.
8) Accounting for Environmental Factors: Consideration of environmental factors such as weather conditions, terrain features, and proximity to populated areas is essential for assessing the potential consequences of BLEVE events. Understanding how these factors influence fireball dynamics and thermal radiation dispersion can help in developing targeted mitigation strategies and emergency response plans tailored to specific environmental contexts.
9) Incorporating Uncertainty and Variability: Acknowledging and addressing uncertainty and variability in BLEVE scenarios is crucial for robust risk assessment and mitigation planning. This involves conducting sensitivity analyses to evaluate the impact of uncertain parameters on the outcomes of thermal radiation hazard assessments and developing strategies to mitigate uncertainty through scenario planning and probabilistic modelling.
10) Considering Regulatory Compliance and Liability: Compliance with regulatory requirements and liability considerations play a significant role in shaping mitigation strategies and risk management practices within the oil and gas industry. Understanding regulatory obligations related to safety standards, emergency preparedness, and environmental protection is essential for ensuring legal compliance and minimizing liability risks associated with BLEVE events.
11) Integrating Technological Solutions: Leveraging technological advancements, such as remote sensing technologies, real-time monitoring systems, and predictive analytics, can enhance the detection, prediction, and mitigation of BLEVE events and their associated thermal radiation hazards. Integrating these technologies into existing infrastructure and emergency response protocols can improve situational awareness and enable proactive risk management strategies.

12) Addressing Human Factors and Behavioural Aspects: Recognizing the role of human factors and behavioural aspects in influencing the likelihood and consequences of BLEVE events is critical for developing effective risk mitigation strategies. This involves implementing training programs, emergency drills, and safety culture initiatives aimed at enhancing personnel awareness, decision-making skills, and response capabilities in the event of a BLEVE incident.
13) Assessing Economic Impacts and Cost-Benefit Analysis: Evaluating the economic impacts of BLEVE events and the associated thermal radiation hazards is essential for prioritizing mitigation measures and allocating resources effectively. Conducting cost-benefit analyses to assess the potential costs of implementing mitigation strategies against the expected benefits in terms of risk reduction, safety improvements, and operational continuity can inform decision-making and resource allocation processes.
14) Engaging Stakeholders and Communities: Engaging stakeholders, including industry partners, regulatory agencies, local communities, and emergency responders, in the development and implementation of BLEVE mitigation strategies fosters collaboration, transparency, and trust. Building relationships with stakeholders and proactively communicating risk information and mitigation plans can enhance preparedness, resilience, and community acceptance of risk management efforts.
15) Continuous Improvement: Establish a framework for regular review and updates of safety measures and emergency response plans to adapt to evolving risks and industry best practices.
16) Training and Education: Develop training programs and awareness campaigns to ensure that personnel are well-prepared to respond to BLEVE incidents.

In essence, this project represents a monumental undertaking, driven by a relentless commitment to unravelling the mysteries of BLEVE fireballs and their thermal radiation hazards, with the overarching goal of fostering a safer, more resilient future for the oil and gas industry and the communities it serves.

IV. ANALYSIS OF DATA AND RESEARCH FINDINGS

A. Introduction

BLEVE is described as a violent explosive vaporization resulting from the rupture of a tank containing a liquid at a temperature significantly above its boiling point at atmospheric pressure. BLEVE can occur with any liquid, flammable or not, when heated and pressurized into a closed container. Two types of BLEVE can be distinguished, cold BLEVE and hot BLEVE, depending on the temperature at which the rupture of the enclosure occurs.

Modeling a BLEVE (Boiling Liquid Expanding Vapor Explosion) fireball and assessing its thermal radiation hazard in the oil and gas industry is a complex and critical task. Here are the key steps and considerations involved in this process:

1) Data Collection: Gather data on the specific chemicals, equipment, and conditions in the oil and gas facility. This includes information on the type of fuel, storage tanks, ambient temperatures, and pressure relief systems.
2) BLEVE Modeling: Use specialized software or models to simulate the BLEVE event. These models should consider factors like the initial temperature and pressure, rupture point, and release rates of flammable gases.
3) Thermal Radiation Modeling: Utilize thermal radiation modeling software to calculate the radiation levels at various distances from the BLEVE. This involves taking into account factors such as flame temperature, fireball size, and atmospheric conditions.
4) Safety Zones: Define safety zones based on the calculated thermal radiation levels. These zones indicate areas where personnel should not be present during a BLEVE event.

B. Solutions

Designing a solution to mitigate the risks associated with a BLEVE (Boiling Liquid Expanding Vapor Explosion) fireball is critical for ensuring the safety of personnel and facilities in the oil and gas industry. Here's a comprehensive solution:

1) Risk Assessment

- Conduct a thorough risk assessment to identify areas with a potential risk of BLEVE events.
- Prioritize equipment and processes that handle flammable substances.

2) Engineering Controls

Install Pressure Relief Systems

- Ensure that pressure relief valves and systems are properly designed, regularly inspected, and well-maintained to prevent over pressurization of containers.

Use Blast-Resistant Equipment

- Replace or retrofit vulnerable structures with blast-resistant designs.
- Protect control rooms and critical infrastructure.

3) Process Safety Management

Implement a robust process safety management program:

- Conduct hazard assessments.
- Establish operating procedures.
- Provide operator training.
- Perform management of change reviews.

4) Emergency Shutdown Systems

- Install automated emergency shutdown systems triggered by abnormal conditions to prevent escalation.

5) Monitoring and Detection

Implement advanced monitoring and detection systems:

- Gas and flame detectors for early warning.
- Process control systems to monitor pressure, temperature, and substance levels.
- Real-time data analytics for anomaly detection.

C. Methods

1) Robert's Method

The Roberts Method, also known as the Roberts BLEVE (Boiling Liquid Expanding Vapor Explosion) Model, is a widely used approach for modeling the consequences of a BLEVE event, which is a catastrophic failure of a vessel containing a pressurized liquefied gas. BLEVE events can result in explosions and fires, posing significant risks to both life and property.

The Roberts Method was developed by Dr. Philip H. Roberts and is primarily used to estimate the blast overpressure and thermal radiation levels produced by a BLEVE. The method takes into account various parameters, including the characteristics of the vessel, the properties of the liquid, and the ambient conditions. Here are the key steps involved in the Roberts Method for BLEVE fire modeling:

a) Determine Initial Conditions: Collect data on the following initial conditions:

- Pressure inside the vessel (P).
- Temperature of the liquid (T).
- Volume of the liquid (V).
- Mass of the liquid (M).
- Vessel dimensions (Diameter, Length).
- Ambient temperature and pressure.
- Properties of the surrounding environment (e.g., wind speed, terrain).

b) Calculate Vaporization Rate: Determine the rate at which the liquid is vaporizing. This is typically done using the Ideal Gas Law or a more complex equation of state for the specific gas.

c) Calculate Critical Temperature and Pressure: Determine the critical temperature (Tc) and critical pressure (Pc) of the substance being stored. These values are important for estimating the behavior of the expanding vapor.

d) Calculate Vapor Superheat: Calculate the difference between the liquid temperature (T) and the critical temperature (Tc) to determine the degree of superheat.

e) Estimate Vessel Failure Time: Estimate the time it takes for the vessel to fail due to overpressure or thermal weakening. This may involve calculating the stress rupture time or other failure criteria.

f) Calculate Blast Overpressure: Estimate the blast overpressure resulting from the BLEVE. This can be done using equations that consider the expanding vapor volume and the release of energy during the rupture.

g) Calculate Thermal Radiation: Estimate the thermal radiation levels produced by the BLEVE event, taking into account factors such as flame size, duration, and radiative heat transfer.

h) Evaluate Protective Measures: Assess the potential impact on people, structures, and the environment based on the calculated blast overpressure and thermal radiation levels. Evaluate the effectiveness of protective measures and evacuation plans.

2) TNO Method

The TNO (Netherlands Organization for Applied Scientific Research) method for BLEVE fireball modeling is a widely recognized approach used to predict the characteristics of fireballs resulting from Boiling Liquid Expanding Vapor Explosions (BLEVEs). BLEVEs occur when a pressurized vessel containing a liquefied gas rupture, leading to the rapid release of the gas, its expansion, and subsequent ignition. These events can result in the formation of fireballs that pose significant hazards to safety.

The TNO method was developed by TNO, a Dutch research organization, and is based on empirical data and observations. It provides estimates for key parameters such as fireball dimensions, duration, and thermal radiation levels. Here are the main steps involved in the TNO method for BLEVE fireball modeling:

a) Determine Initial Conditions: Gather data on the following initial conditions:
- Pressure inside the vessel (P).
- Temperature of the liquefied gas (T).
- Volume of the gas (V).
- Mass of the gas (M).
- Vessel dimensions (Diameter, Length).
- Ambient temperature and pressure.
- Properties of the surrounding environment (e.g., wind speed, terrain).

b) Calculate Vaporization Rate: Estimate the rate at which the liquid in the vessel is vaporizing. This rate is typically determined using the Ideal Gas Law or other relevant equations.

c) Determine BLEVE Type: Identify whether the BLEVE is of the "gas-driven" or "liquid-driven" type. This classification is based on the proportion of gas and liquid released during the event.

d) Calculate Fireball Parameters: Depending on the BLEVE type, use empirical correlations provided by the TNO method to calculate the following fireball parameters:
- Fireball diameter.
- Fireball duration.
- Fireball rise height.
- Thermal radiation levels at various distances from the fireball.

e) Evaluate Protective Measures: Assess the potential impact of the fireball on people, structures, and the environment based on the calculated parameters. Consider safety distances and protective measures to mitigate the hazards.

f) Consider BLEVE Mitigation: Explore strategies to prevent or mitigate BLEVE events, such as improving vessel design, implementing safety systems, or establishing evacuation plans.

3) Areal Location of Hazardous Atmospheres (ALOHA)

ALOHA (Areal Location of Hazardous Atmospheres) is a widely used software tool developed by the U.S. Environmental Protection Agency (EPA) for modelling the dispersion of hazardous chemicals and assessing the potential impact of accidental releases. ALOHA is valuable for emergency responders and industrial safety professionals. Here are various steps included in ALOHA:

a) Data Entry and Setup: Define the source of the chemical release, including its type (liquid, gas, etc.), release rate, duration, and location. Specify environmental conditions like wind speed, temperature, and atmospheric stability.

b) Chemical Database: Access a comprehensive database of chemicals, including physical and chemical properties, toxicity data, and response parameters.

c) Atmospheric Dispersion Modelling: ALOHA calculates the dispersion of the released chemical based on the source characteristics and environmental conditions. It uses various models, including the Gaussian dispersion model for heavier-than-air gases and the surface roughness dispersion model for lighter-than-air gases.

d) Results Visualization: ALOHA provides graphical outputs that show the dispersion of the chemical plume and its potential impact area. It displays contour maps and hazard zone estimates, which help assess the extent of the hazardous area.

e) Toxicity Assessment: The software calculates the potential toxic effects of the released chemical based on its concentration and exposure duration. It provides information on the types of health effects that might occur within the affected area.

f) Protective Action Recommendations: ALOHA suggests protective actions that should be taken in response to the chemical release. These actions may include sheltering in place, evacuation, or the use of personal protective equipment.
g) Emergency Response Information: ALOHA offers guidance on initial response actions, including recommended distances for evacuation or sheltering.
h) Plume Modelling: The software predicts the path and behaviour of the chemical plume, taking into account wind direction, terrain, and building effects.
i) Real-Time Da ta Integration: ALOHA can incorporate real-time weather and sensor data to improve the accuracy of its modelling during an ongoing incident.
j) What-If Scenarios: Users can input various scenarios to assess the potential impact of different release scenarios and response strategies.
k) Printing and Reporting: ALOHA allows users to generate and print reports of the modelling results for documentation and communication with response teams and stakeholders.
l) Sensitivity Analysis: The software enables sensitivity analysis to understand how changes in input parameters, such as release rate or wind speed, affect the modelling results.
m) GIS Integration: ALOHA can be integrated with Geographic Information Systems (GIS) to visualize and analyse hazardous material releases in a geospatial context.
n) Historical Weather Data: Users can input historical weather data to analyse past incidents and improve preparedness for future events.

ALOHA is a versatile tool for assessing and managing hazardous material incidents, making it valuable for emergency responders, environmental agencies, and industries dealing with hazardous materials. It aids in understanding the potential consequences of chemical releases and developing effective response plans.

V. CONCLUSIONS AND RECOMMENDATIONS

A. Observations

1) Data Used For Risk Estimation

a) Case 1: Propane

The ALOHA modelling of dispersion is carried out by considering a single storied building located at Madurai (9.9 0N 78.1 0E) with the elevation of 131 m, Tamilnadu, India. The atmospheric condition for the wind was chosen as North-North East direction above 3m from the ground at the speed of 1.38 m/s. The ground roughness was taken as open country and partly cloudy.

Propane Storage Details

The chemical used was assumed to be Propane of Molecular Weight: 44.10 g/mol, Ambient boiling point: -42.4 ^{0}C and Freezing point: -188 ^{0}C. The temperature of air and internal storage temperature was taken as 37.2 ^{0}C with 50% of relative humidity. The Table-1 shows the dimensions of bullet used in the risk estimation. Assuming bullet as cylindrical shapes, volume of bullet have been arrived.

Description	Bullet
Diameter (m)	2.2
Length (m)	3.87
Volume (m^3)	14.7

Table 1 Dimensions of Bullet of Propane

The Propane storage tank data used in this study was referred from the various articles and Propane storages from manufacturing industries. For the study the storage chosen was bullets of capacity 14.7 m^3. Propane stored in the bullet was assumed to be filled up to 97% of its capacity and was assumed to be above ground level. The bullet pressure was around 2kg/cm^2 (28.4467 psi).

b) Case 2: Butane

The ALOHA modelling of dispersion is carried out by considering a single storied building located at Madurai (9.9 0N 78.1 0E) with the elevation of 131 m, Tamilnadu, India. The atmospheric condition for the wind was chosen as North-North East direction above 3m from the ground at the speed of 1.38 m/s. The ground roughness was taken as open country and partly cloudy.

Butane Storage Details

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The chemical used was assumed to be Butane of Molecular Weight: 58.12 g/mol, Ambient boiling point: -0.9 ^{0}C and Freezing point: -138 ^{0}C. The temperature of air and internal storage temperature was taken as 37.2 ^{0}C with 50% of relative humidity. The Table-1 shows the dimensions of bullet used in the risk estimation. Assuming bullet as cylindrical shapes, volume of bullet have been arrived.

Description	Bullet
Diameter (m)	2.2
Length (m)	3.87
Volume (m^3)	14.7

Table 2 Dimensions of Bullet of Butane

For the study the storage chosen was bullets of capacity 14.7 m^3. Butane stored in the bullet was assumed to be filled up to 97% of its capacity and was assumed to be above ground level. The bullet pressure was around 2kg/cm^2 (28.4467 psi).

B. Results And Discussion

Results Obtained From Aloha

a) Case 1: Propane

Thermal Radiation of BLEVE

Boiling Liquid Expanding Vapour Explosion abbreviated as BLEVE is a physical explosion which occurs when storage vessels are exposed to external and lasts for a few seconds, and could be of an accident of very high intensity. The effects caused due to bullet BLEVE was shown in Figure-1. Table-3 shows the outputs arrived for the Bullet BLEVE.

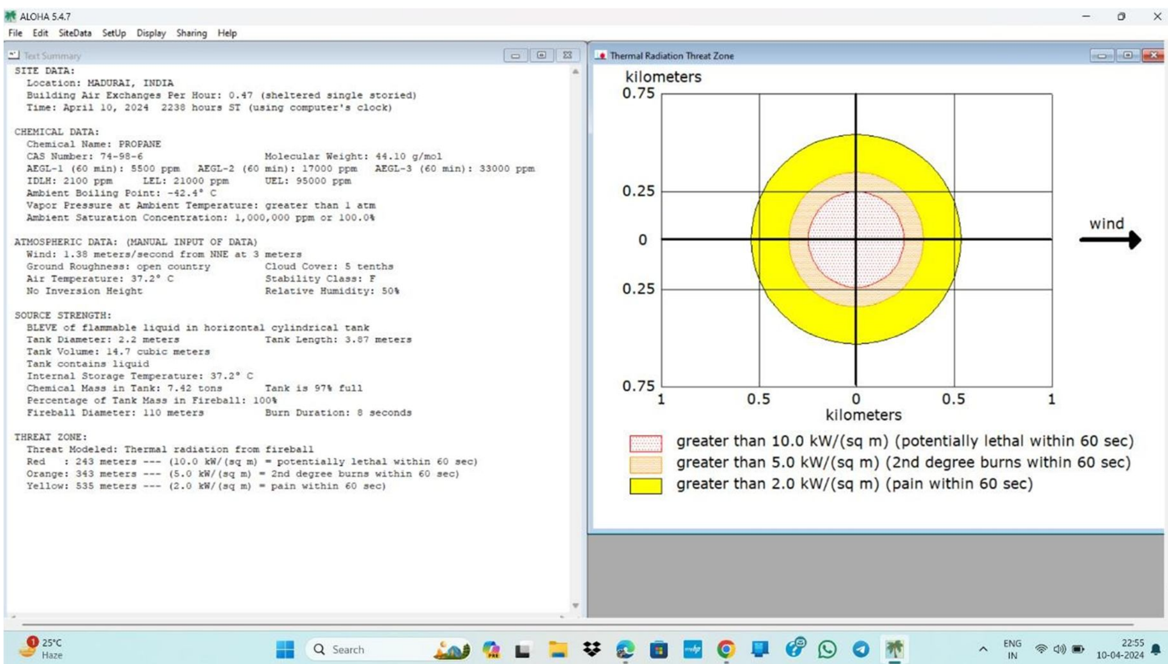

Figure 1 Bullet BLEVE (Propane)

Source	Volume (m^3)	Fireball Duration (sec)	Fireball Diameter (m)	Thermal Radiation levels		
				10 (kw/m^2) for radius of	5 (kw/m^2) for radius of	2 (kw/m^2) for radius of
Bullet	14.7	8	109	243m	343m	535m

Table 3 Thermal Radiation due to BLEVE (Propane)

Jet Fire

The other cases of fires include jet fires that generally create localized effects. This can happen due to the release of flammable liquids confined or spread in the form of a liquid jet. After catching fire by the external forces, this burns as a jet and radiates heat around. The Figure – 2 represents the bullet jet fire heat radiation levels considering short pipe/valve opening of rectangular shape having length 15 cm and width of 5 cm at the middle of the tank. The jet is assumed to be ignited by external sources.

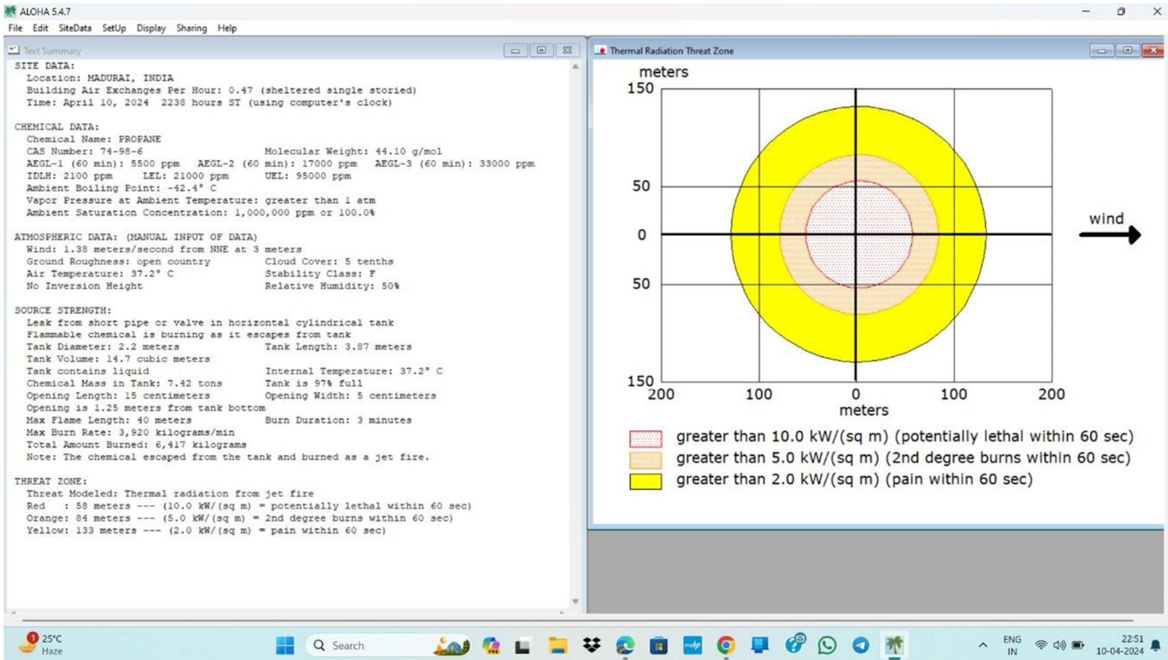

Figure 2 Bullet Jet fire (Propane)

Source	Maximum Burn rate (kg/min)	Flame Length (m)	Duration (sec)	Thermal Radiation levels		
				10 (kw/m^2) for radius of	5 (kw/m^2) for radius of	5 (kw/m^2) for radius of
Bullet	3920	40	120	58m	84m	133m

Table 4 Thermal Radiation due to Jet Fires (Propane)

Dispersion and Flammable Effects

Vapour cloud explosions (VCE) are capable of creating great impact on the plant and surroundings. Vapour cloud explosions produce pressure waves. The effect of VCE depends on the peak incident over pressure due to pressure waves and the duration of the maximum overpressure. The vapour cloud can travel with the wind flow if it was not ignited. So, the Vapour clouds are also hazardous once they reach the neighbourhood. Table-5 provides the damage criteria for vapour cloud explosions (from ALOHA). The flammable threat zones caused due to Vapour Cloud explosion for Bullet is shown in Figure-5.

Peak Overpressure (bars)	Extent of Damage
0.02	10% of glasses broken
0.10	Shatters glass
0.20	Shattering of concrete block walls; distortion of steel frames and others pulling away from foundations
0.24	Serious injury
0.56	Destruction to buildings
0.68	Heavy machinery movement and bad damage

Table 5 Damage Criteria for Vapour Cloud Explosions (Propane)

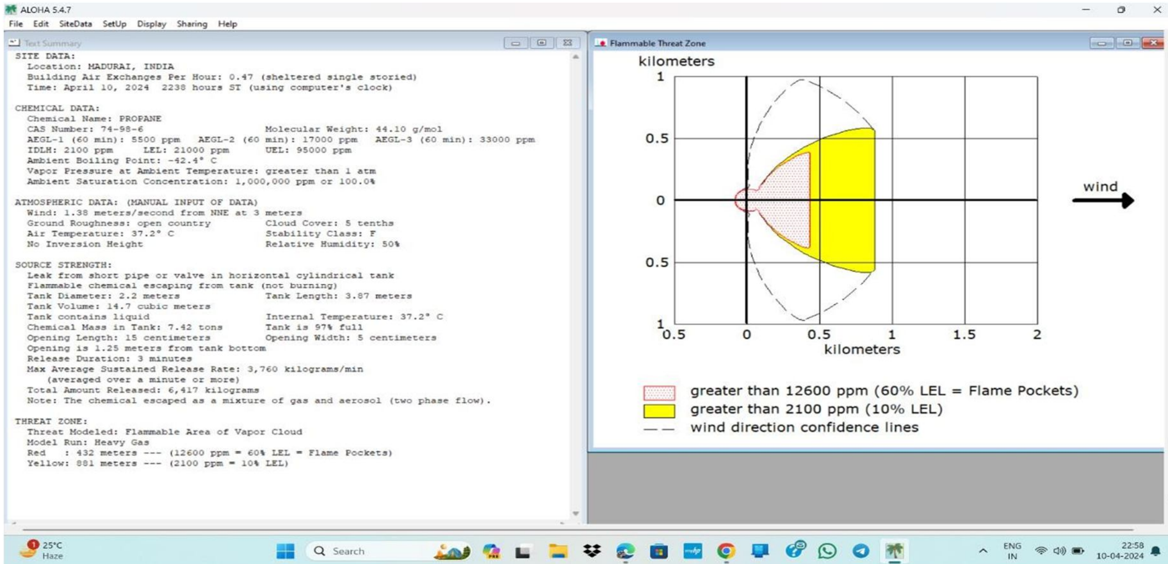

Figure 3 Bullet Flammable Threat Zone (Propane)

Source	Volume (m3)	Maximum Avg. Release rate (kg/min)	Duration (Sec)	Flammable		
				100% LEL up to the distance of	60% LEL up to the distance of	10% LEL up to the distance of
Bullet	14.3	3810	180	---	432m	881m

Table 6 Flammable threat Zone of Vapour Cloud (Propane)

Dispersion and Toxic Effects

In case of dispersion, if the chemical is toxic instead of flammable the effects of dispersion are far reaching. Therefore, it will be equally damaging as the persons exposed to various levels of concentrations depending upon the toxic characteristics of the chemical. The degree of toxic hazard depends on the factors of exposure duration, cloud concentration and gas toxicity. The Figure-4 shows the toxic vapour concentrations around the area of bullet. The below Table-7 shows the outputs arrived for the bullet toxic Vapour Cloud.

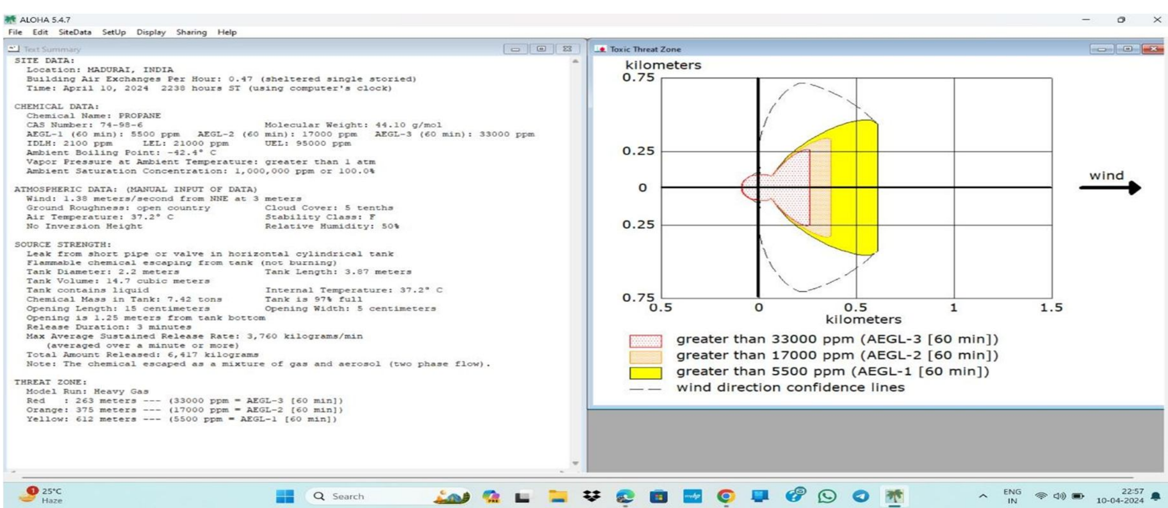

Figure 4 Bullet Toxic area of Vapour Cloud (Propane)

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Source	Volume (m3)	Duration (sec)	Toxic level distance		
			AEGL-1 up to the distance of	AEGL-2 up to the distance of	AEGL-3 up to the distance of
Bullet	14.7	180	612m	375m	263m

Table 7 Toxic Effects due to Vapour Clouds (Propane)

Dispersion and Blast Effects

The leakage due to a small opening was assumed for the bullet vapour cloud blasts. The rectangular opening was considered in this case. The area for the opening was taken as 15 cm length and 5 cm width. The leakage through the opening was assumed to be happened in a short pipe/ valve. The ignition was assumed to be happened after 2 minutes of leakage by a spark or flame. The blast area of overpressure was modelled in the Figure-5 for bullet VCE. The Table-8 shows the blast over pressure zone arrived for the bullet Vapour Cloud Explosions.

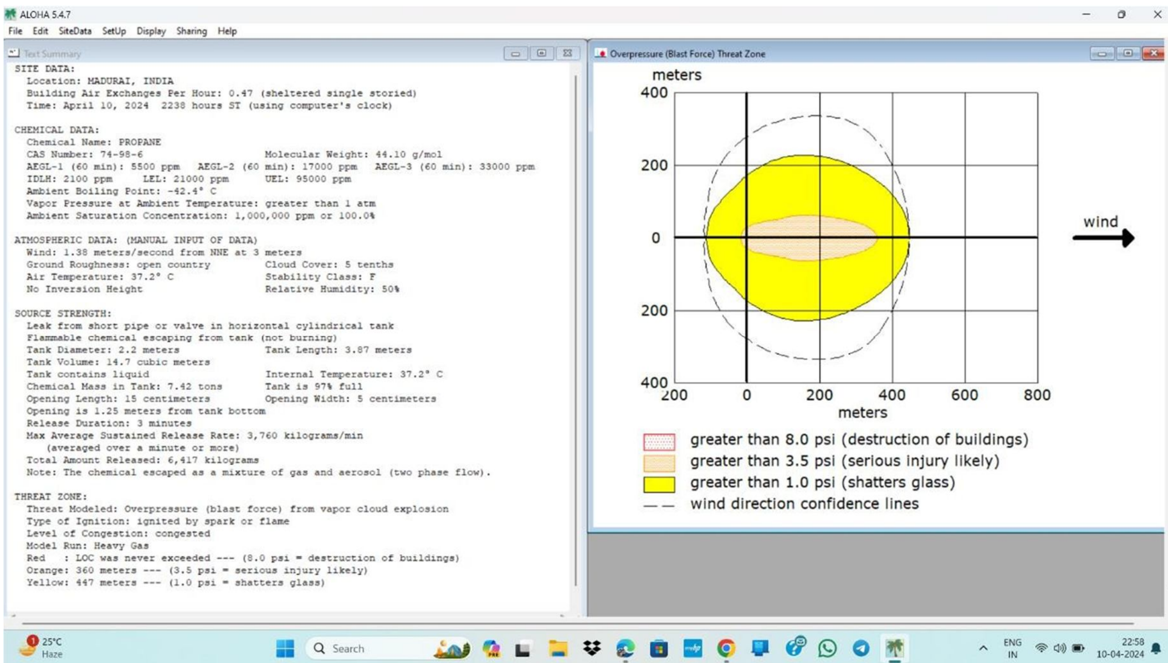

Figure 5 Bullet Vapour Cloud Explosion (Propane)

Source	Volume (m3)	Time of ignition after release (sec)	Blast Over pressure zone		
			8.0 psi up to the radius of	3.5 psi up to the radius of	1.0 psi up to the radius of
Bullet	14.7	120	---	360m	447m

Table 8 Blast over pressure zone due to Vapour Cloud Explosion (Propane)

b) CASE 2: Butane

Thermal Radiation of BLEVE

Boiling Liquid Expanding Vapour Explosion abbreviated as BLEVE is a physical explosion which occurs when storage vessels are exposed to external and lasts for a few seconds, and could be of an accident of very high intensity. The effects caused due to bullet BLEVE was shown in Figure-1. Table-3 shows the outputs arrived for the Bullet BLEVE.

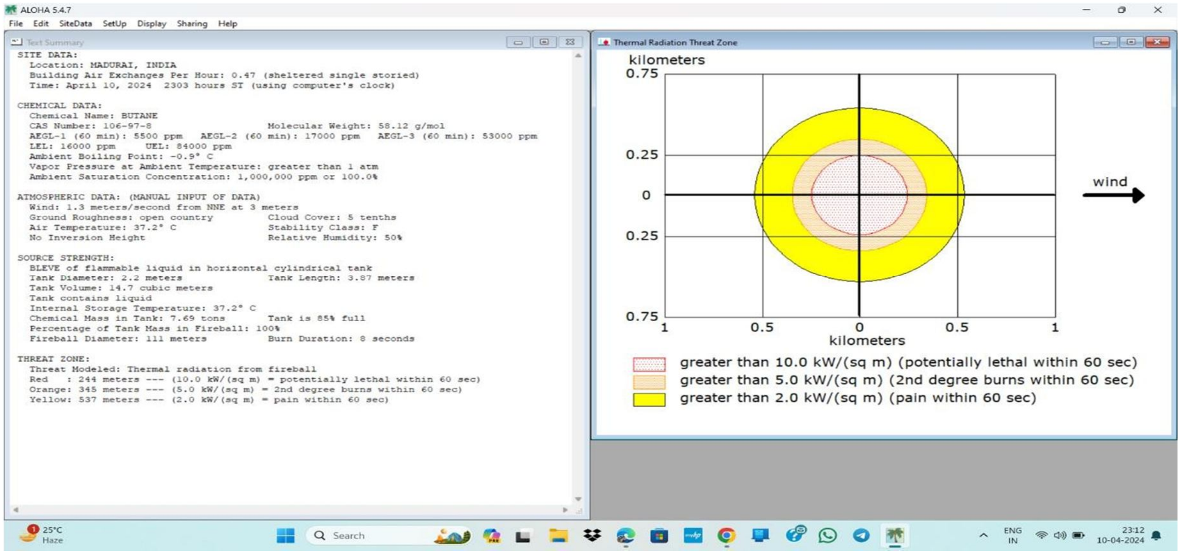

Figure 6 Bullet BLEVE (Butane)

Source	Volume (m^3)	Fireball Duration (sec)	Fireball Diameter (m)	Thermal Radiation levels		
				10 (kw/m^2) for radius of	5 (kw/m^2) for radius of	2 (kw/m^2) for radius of
Bullet	14.7	8	109	244m	345m	537m

Table 9 Thermal Radiation due to BLEVE (Butane)

Jet Fire

The other cases of fires include jet fires that generally create localized effects. This can happen due to the release of flammable liquids confined or spread in the form of a liquid jet. After catching fire by the external forces, this burns as a jet and radiates heat around. The Figure – 2 represents the bullet jet fire heat radiation levels considering short pipe/valve opening of rectangular shape having length 15 cm and width of 5 cm at the middle of the tank. The jet is assumed to be ignited by external sources.

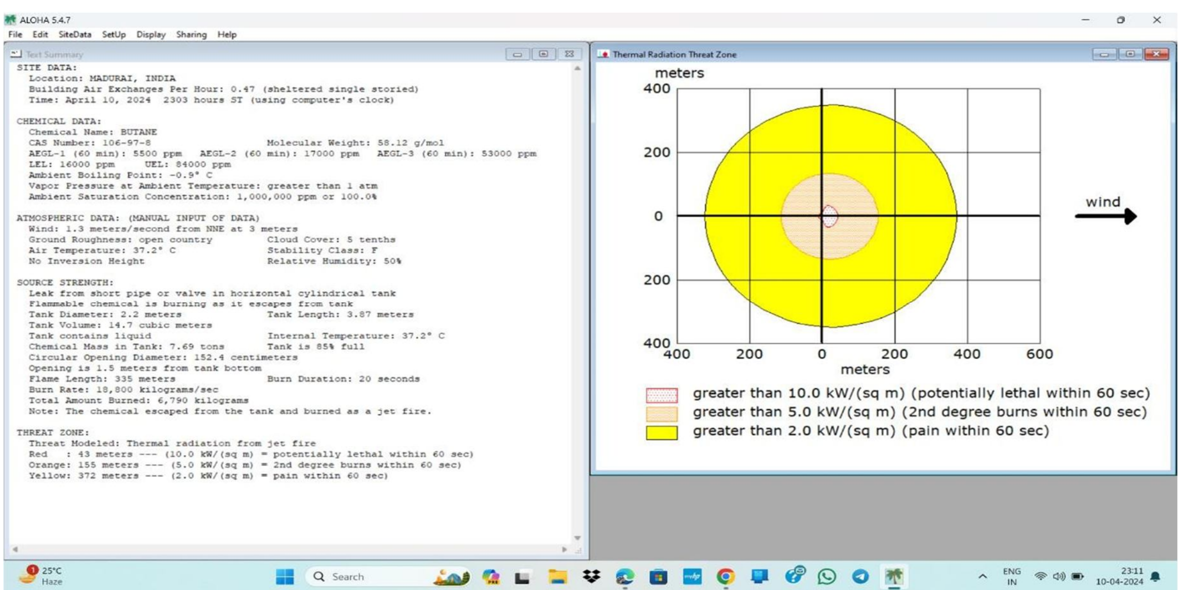

Figure 7 Bullet Jet fire (Butane)

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Source	Maximum Burn rate (kg/min)	Flame Length (m)	Duration (sec)	Thermal Radiation levels		
				10 (kw/m^2) for radius of	5 (kw/m^2) for radius of	5 (kw/m^2) for radius of
Bullet	3920	40	120	43m	155m	372m

Table 10 Thermal Radiation due to Jet Fires (Butane)

Dispersion and Flammable Effects

Vapour cloud explosions (VCE) are capable of creating great impact on the plant and surroundings. Vapour cloud explosions produce pressure waves. The effect of VCE depends on the peak incident over pressure due to pressure waves and the duration of the maximum overpressure. The vapour cloud can travel with the wind flow if it was not ignited. So, the Vapour clouds are also hazardous once they reach the neighbourhood. Table-5 provides the damage criteria for vapour cloud explosions (from ALOHA). The flammable threat zones caused due to Vapour Cloud explosion for Bullet is shown in Figure-5.

Peak Overpressure (bars)	Extent of Damage
0.02	10% of glasses broken
0.10	Shatters glass
0.20	Shattering of concrete block walls; distortion of steel frames and others pulling away from foundations
0.24	Serious injury
0.56	Destruction to buildings
0.68	Heavy machinery movement and bad damage

Table 11 Damage Criteria for Vapour Cloud Explosions (Butane)

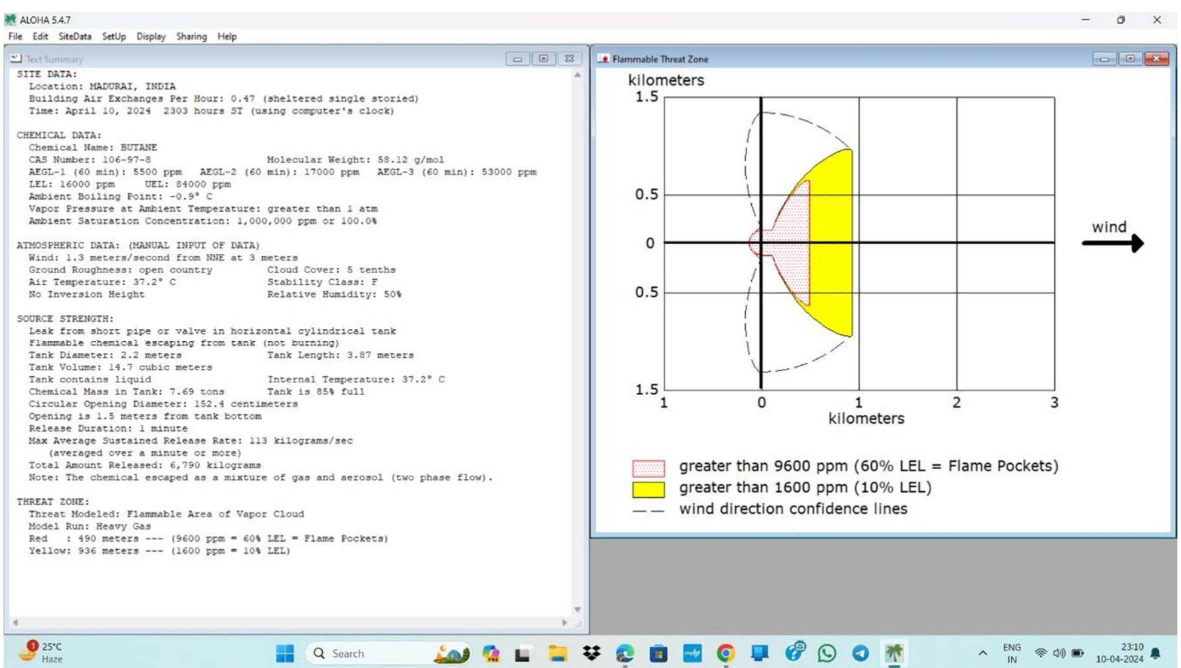

Figure 8 Bullet Flammable Threat Zone (Butane)

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Source	Volume (m3)	Maximum Avg. Release rate (kg/min)	Duration (Sec)	Flammable		
				100% LEL up to the distance of	60% LEL up to the distance of	10% LEL up to the distance of
Bullet	14.3	3810	180	---	490m	936m

Table 12 Flammable threat Zone of Vapour Cloud (Butane)

Dispersion and Toxic Effects

In case of dispersion, if the chemical is toxic instead of flammable the effects of dispersion are far reaching. Therefore, it will be equally damaging as the persons exposed to various levels of concentrations depending upon the toxic characteristics of the chemical. The degree of toxic hazard depends on the factors of exposure duration, cloud concentration and gas toxicity. The Figure-4 shows the toxic vapour concentrations around the area of bullet. The below Table-7 shows the outputs arrived for the bullet toxic Vapour Cloud.

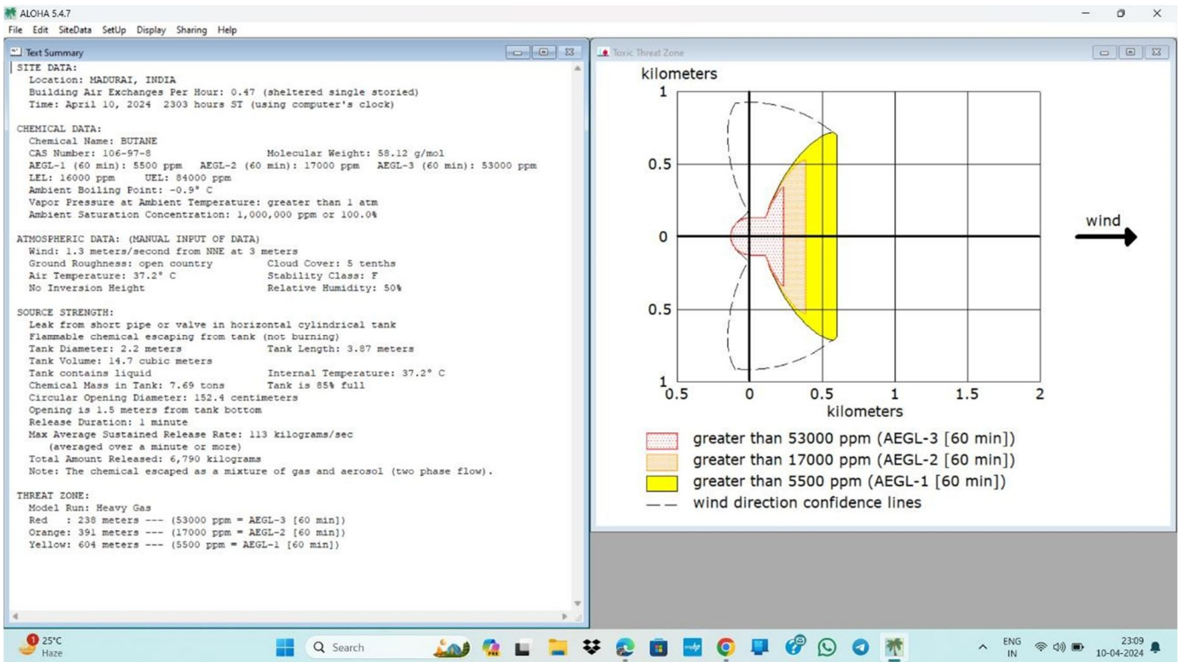

Figure 9 Bullet Toxic area of Vapour Cloud (Butane)

Source	Volume (m3)	Duration (sec)	Toxic level distance		
			AEGL-1 up to the distance of	AEGL-2 up to the distance of	AEGL-3 up to the distance of
Bullet	14.7	180	604m	391m	238m

Table 13 Toxic Effects due to Vapour Clouds (Butane)

Dispersion and Blast Effects

The leakage due to a small opening was assumed for the bullet vapour cloud blasts. The rectangular opening was considered in this case. The area for the opening was taken as 15 cm length and 5 cm width. The leakage through the opening was assumed to be happened in a short pipe/ valve. The ignition was assumed to be happened after 2 minutes of leakage by a spark or flame. The blast area of overpressure was modelled in the Figure-5 for bullet VCE. The Table-8 shows the blast over pressure zone arrived for the bullet Vapour Cloud Explosions.

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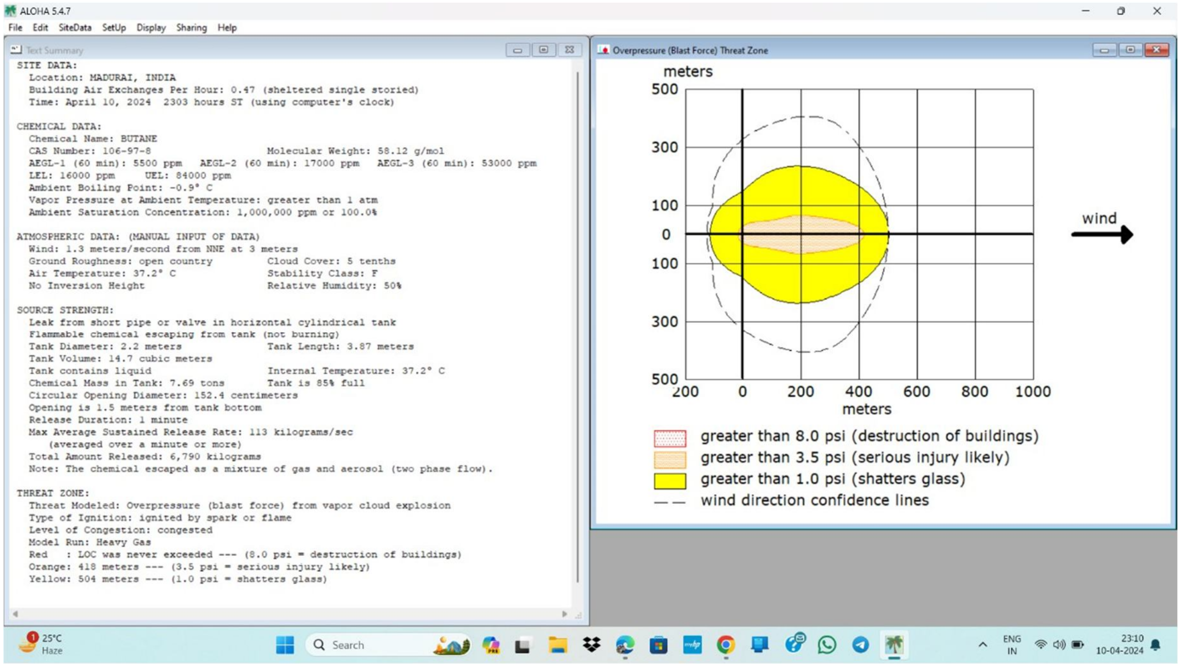

Figure 10 Bullet Vapour Cloud Explosion (Butane)

Source	Volume (m3)	Time of ignition after release (sec)	Blast Over pressure zone		
			8.0 psi up to the radius of	3.5 psi up to the radius of	1.0 psi up to the radius of
Bullet	14.7	120	---	418m	504m

Table 14 Blast over pressure zone due to Vapour Cloud Explosion (Butane)

C. Results Obtained From Robert's Method And Tno Method

1) Case 1: Propane

Robert's Method

According to Roberts [Roberts 1982], the maximum diameter D_{max} (m), and the total time duration t_{max} (m) of the fire ball sphere are calculated from the following empirical expressions:

$$D_{max} = c_2\ M^{1/3}$$

$$t_{max} = c_3\ M^{1/3} \quad \text{where, } c_2 = 5.8mkg^{-1/3} \text{ and } c_3 = 0.45skg^{-1/3}$$

As we know mass of propane is 7690 kg, by using this

$D_{max} = c_2\ M^{1/3}$

$D_{max} = 5.8\times(7690)^{1/3}$ m

$D_{max} = 115.46$ m $t_{max} = c_3\ M^{1/3}$

$t_{max} = 0.45\times(7690)^{1/3}$ s $t_{max} = 8.95$ sec

TNO Method

TNO proposed that the maximum diameter D_{max} (m), and the total time duration t_{max} (s), of the fire ball must be calculated from the following empirical expressions:

$$D_{max} = c_4\ M^{0.325} \quad t_{max} = c_5\ M^{0.26}$$

where, $c_4 = 6.48 mkg^{-0.325}$ and $c_5 = 0.852 skg^{-0.26}$

As we know mass of propane is 7690 kg, by using this $D_{max} = c_4 M^{0.325}$
$D_{max} = 6.48 \times (7690)^{1/3}$
$D_{max} = 58.05$ m $t_{max} = c_5 M^{0.26}$
$t_{max} = 0.852 \times (7690)^{1/3}$ s
$t_{max} = 7.63$ sec.

2) Case 2: Butane

Robert's Method

According to Roberts [Roberts 1982], the maximum diameter D_{max} (m), and the total time duration t_{max} (m) of the fire ball sphere are calculated from the following empirical expressions:

$$D_{max} = c_2 M^{1/3} \quad t_{max} = c_3 M^{1/3}$$

where, $c_2 = 5.8 mkg^{-1/3}$ and $c_3 = 0.45 skg^{-1/3}$

As we know mass of butane is 7690 kg, by using this $D_{max} = c_2 M^{1/3}$
$D_{max} = 5.8 \times (7690)^{1/3}$ m
$D_{max} = 115.46$ m $t_{max} = c_3 M^{1/3}$
$t_{max} = 0.45 \times (7690)^{1/3}$ s $t_{max} = 8.95$ sec

TNO Method

TNO proposed that the maximum diameter D max (m), and the total time duration t max (s), of the fire ball must be calculated from the following empirical expressions:

$$D_{max} = c_4 M^{0.325} \quad t_{max} = c_5 M^{0.26}$$

where, $c_4 = 6.48 mkg^{-0.325}$ and $c_5 = 0.852 skg^{-0.26}$

As we know mass of butane is 7690 kg, by using this $D_{max} = c_4 M^{0.325}$
$D_{max} = 6.48 \times (7690)^{1/3}$
$D_{max} = 58.05$ m $t_{max} = c_5 M^{0.26}$
$t_{max} = 0.852 \times (7690)^{1/3}$ s
$t_{max} = 7.63$ sec.

D. Comparison Table

The results obtained from various methods are compared in the table given below:

S. No.	Chemical Name	Diameter (Meters)			Time (Seconds)		
		ALOHA	Robert's Method	TNO Method	ALOHA	Robert's Method	TNO Method
1.	Propane	109	115.46	58.05	8	8.95	7.63
2.	Butane	109	115.46	58.05	8	8.95	7.63

Table 15 Comparison Table

E. Conclusion Of The Project

The modelling of a BLEVE fireball and the assessment of its thermal radiation hazard within an oil and gas industry setting are critical steps toward enhancing safety protocols and minimizing risks associated with such catastrophic events.

Through the comprehensive review of literature and the utilization of advanced modelling techniques, several key conclusions can be drawn:5

1) Understanding the BLEVE Phenomenon.
2) Importance of accurate modelling.
3) Identification of hazard zones.
4) Risk management strategies.
5) Continued research and development.

The project underscores the importance of proactive measures in mitigating the risks associated with BLEVE incidents in the oil and gas industry. By leveraging advanced modelling techniques and adopting a comprehensive risk management approach, stakeholders can work towards ensuring the safety and well-being of personnel and safeguarding critical infrastructure against the potentially devasting efforts of such events.

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REFRENCES

[1] Brady Manescau, Khaled Chetehouna, Ilyas Sellami, Rachid Nait-Said and Fatiha Zidani (2020), “BLEVE Fireball Effects in a Gas Industry: A Numerical Modelling Applied to the Case of an Algeria Gas Industry.”
[2] Yuanyuan Wang, Xiaochen Gu, Li Xia, Yong Pan, Yuqing Ni, Supan Wang, Wei Zhou (2020), “Hazard analysis on LPG fireball of road tanker BLEVE based on CFD simulation.”
[3] Jingde Li and Hong Hao (2020), “Numerical study of medium to large scale BLEVE for blast wave prediction.”
[4] M. Anandhan, Dr. T. Prabaharan, M. Muhaidheen and S. Ragavendran (2019), “Quantitative Risk Assessment in LPG Storage Area for different fire scenarios.”
[5] Ilyas Sellami, Brady Manescau, Khaled Chetechouna, Charles de Izarra, Rachid Nair Said, Fatiha Zidani (2018), “BLEVE fireball modelling using Fire Dynamics Simulator (FDS) in an Algerian gas industry.”
[6] Nilambar Bariha, Indra Mani Mishra, Vimal Chandra Srivastava (2016), “Fire and explosion hazard analysis during surface transport of liquified petroleum gas (LPG): A case study of LPG truck tanker accident in Kannur, Kerala, India.”
[7] Bhisham K. Dhurandher, Ravi Kumar and Amit Dhiman (2015), “Impact Assessment of Thermal Radiation Hazard from LPG Fireball.”
[8] SHAO Hui and DUAN Guoning (2012), “Risk quantitative calculation and ALOHA simulation on the leakage accident of natural gas power plant.”
[9] Zhang Qian-xi, Liang Dong, “Thermal radiation and impact assessment of LNG BLEVE fireball.”
[10] Dmitriy Makarov, Volodymyr Shentsov, Mike Kuznetsov and Vladimir Molkov (2021), “Hydrogen Tank Rupture in fire in the open atmosphere: hazard distance by fireball.”
[11] Federico Ustolin, Ernesto Salzano, Gabriele Landucci (2020), “Modelling liquid hydrogen BLEVEs: a comparative assessment with hydrocarbon fuels.”
[12] Lei Huo, Yawai He, Erping Ma and Xing Liu (2023), “Mechanisms and destruction status of CO2 BLEVE during CO2 geological storage and enhanced oil recovery injection process.”
[13] Andre Laurent, Laurent Perrin, Olivier Dufaud (2016), “Consequence assessments of a cold BLEVE. Can we do it better?”
[14] Mohammad Kamaei, Seyed shams Aldin Alizadeh, Abdolrahman Keshvari (2016), “Risk assessment and consequence modelling of BLEVE explosion wave phenomenon of LPG spherical tank in a refinery.”
[15] Behrouz Hemmatian, Joaquim casal, Eulalia planas (2017), “Essential points in the emergency managements in transport accidents which can lead to a BLEVE- fireball.”
[16] Alfonso Ibarreta, Hubert Biteau, and Jason sutula (2016), “BLEVE and fireballs.” [17.] Joseph M. Cabeza-Lainez, Francisco Salguero-Andujar and Inmaculada Rodriguez cunill (2022), “Prevention of hazards induced by radiation fireball through computational geometry and parametric design.”
[17] Paul Blankenhagel, Kirti Bhushan Mishra, Klaus-Dieter Wehrstedt, Jorg Steinbach (2016), “Thermal radiation impact of DTBP fireballs.
[18] Xing Zhou, Yongmei Hao, Jian Yang, Zhixiang Xing and Yong Huang (2023), “Study of the thermal radiation hazard from a combustible gas fireball resulting from a high-pressure gas pipeline accident”.
[19] Yuan Chen (2018), “Process safety implications of boiling liquid expanding vapour explosions (BLEVEs): A comprehensive analysis of BLEVE during road/rail transportation of LPG accidents and BLEVE.”