IJARSCT

International Journal of Advanced Research in Science, Communication and Technology

International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal

ISSN: 2581-9429

Volume 6, Issue 2, August 2026

Impact Factor: 8.2

Quantitative Risk Assessment (QRA) of Major Accident Hazards in a Petrochemical Refinery Using Fault Tree and Consequence Analysis

Devesh Dixit[1] and Dr Neeta Banger[2]

Research Scholar[1] and Professor[2]

Department of Industrial Safety Engineering

Shiv Kumar Singh Institute of Technology & Science, Indore

Rajiv Gandhi Proudyogiki Vishwavidyalaya (RGPV), Bhopal, MP, India

Abstract: *The relentless expansion of the Chemical Process Industry (CPI) necessitates the implementation of rigorous and comprehensive safety evaluations. This research manuscript presents an extensive Quantitative Risk Assessment (QRA) conducted on a major petrochemical refinery, specifically targeting the hazards associated with the storage and processing of highly volatile and toxic substances. Integrating Hazard Identification and Risk Assessment (HIRA), Failure Mode and Effects Analysis (FMEA), and Fault Tree Analysis (FTA), this study establishes a robust methodological framework for assessing industrial risk. A systematic screening process utilizing IPO (Inter Provinciaal Overleg) A-factor and S-factor metrics was deployed to isolate the most severe major accident hazard (MAH) installations, culminating in the selection of pressurized Liquefied Petroleum Gas (LPG) and Propylene Horton spheres, large-scale Naphtha storage tanks, and Hydrogen Sulphide (H2S) transfer pipelines. Advanced mathematical consequence modeling was executed, comprising TNT equivalency methods for Vapour Cloud Explosions (VCE), semi-empirical thermodynamic models for Boiling Liquid Expanding Vapour Explosions (BLEVE), and the Pasquill-Gifford dispersion model for toxic gas plumes. The consequence analysis revealed that a catastrophic failure of a 1,200 MT LPG Horton sphere generates a fireball 616.3 meters in diameter, emitting lethal horizontal thermal radiation fluxes (109 kW/m²) that extensively impinge upon vulnerable off-site residential boundaries. Furthermore, the synthesis of FTA-derived failure frequencies (3.6E-7 per year for Horton spheres) with local demographic data demonstrated that the societal risk (F-N curve) breaches the universally accepted ALARP (As Low As Reasonably Practicable) thresholds. The findings underscore the acute vulnerability of densely populated regions adjacent to legacy pressurized storage facilities. The manuscript concludes by presenting concrete, inherently safer design recommendations, advocating strongly for the phase-out of above-ground spheres in favor of mounded bullet technology, alongside the enhancement of Safety Instrumented Systems (SIS) and stringent land-use zoning.*

Keywords: Quantitative Risk Assessment (QRA), BLEVE, Hazard Identification and Risk Assessment (HIRA), Fault Tree Analysis (FTA), Failure Mode and Effects Analysis (FMEA), Petrochemical Refinery, Consequence Modeling

I. INTRODUCTION

In the contemporary era of rapid industrialization and escalating global energy demands, the Chemical Process Industry (CPI)—with petroleum refining at its vanguard—has undergone unprecedented expansion. To maximize throughput and efficiency, modern refineries deploy highly complex, integrated unit operations that process, transfer, and store vast

ISSN: 2581-9429
Volume 6, Issue 2, August 2026
Impact Factor: 8.2

inventories of hazardous, volatile, flammable, and acutely toxic chemicals. These operations frequently occur under extreme thermodynamic conditions, including highly elevated temperatures and pressures. Consequently, the intrinsic risk profile of these installations is magnified. Any accidental loss of containment—whether precipitated by metallurgical fatigue, mechanical failure, operational deviation, or exogenous perturbations—can precipitate catastrophic chains of events. Such incidents routinely manifest as major fires, massive explosions, or extensive toxic vapor dispersions, yielding devastating consequences for human life, capital infrastructure, and the surrounding ecosystem.

The historical record of the CPI is unfortunately punctuated by severe catastrophic accidents that serve as stark reminders of the destructive potential of uncontrolled chemical energy. Disasters such as the Bhopal Gas Tragedy in India (1984), the Flixborough explosion in the UK (1974), the Pasadena explosion in the USA (1989), and the Visakhapatnam refinery fire (1997) have irrevocably altered the global perspective on industrial safety. These tragedies highlighted a critical vulnerability: the progressive encroachment of civilian populations and residential developments toward industrial perimeters. As population densities in these 'buffer zones' increase, the probability that an on-site mechanical failure will translate into a mass-casualty societal disaster amplifies exponentially. This phenomenon necessitates a paradigm shift from reactive safety protocols to highly proactive, predictive, and mathematically rigorous risk management strategies.

In response to these challenges, Quantitative Risk Assessment (QRA) has emerged as the definitive analytical framework for evaluating and managing major accident hazards (MAH). Unlike traditional qualitative hazard spotting, QRA provides a structured, probabilistic methodology that quantifies both the likelihood of specific failure events and the physical magnitude of their ensuing consequences.

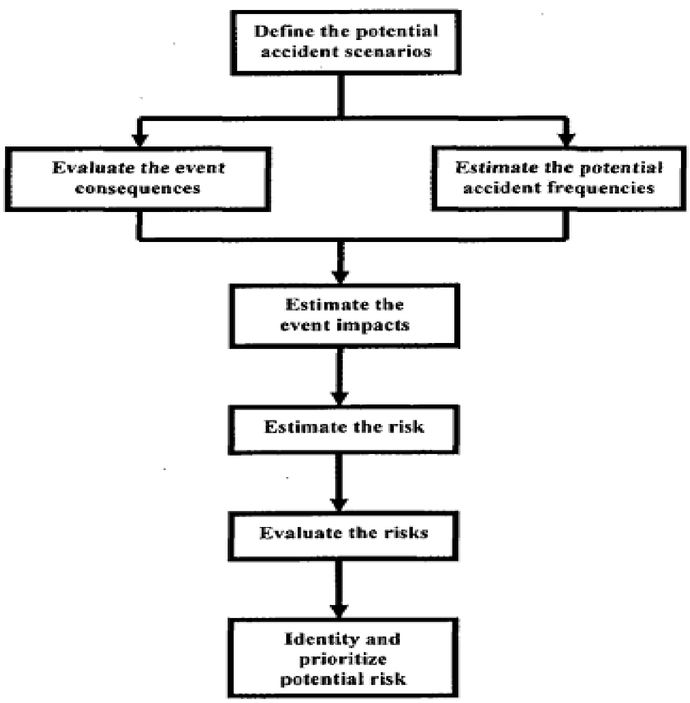

Figure 1.1: QRA Methodology

By systematically identifying failure modes and modeling the propagation of energy or toxic materials into the environment, QRA enables safety engineers and policymakers to objectively map risk contours and make informed, data-driven decisions regarding facility siting, emergency response planning, and capital safety investments. The core objective of this research paper is to present a comprehensive, multi-tiered QRA of a major petrochemical refinery. By integrating Hazard Identification and Risk Assessment (HIRA), Failure Mode and Effects Analysis (FMEA), and Fault Tree Analysis (FTA), this study delivers a granular evaluation of the risks posed by pressurized hydrocarbon storage (LPG and Propylene) and continuous toxic process streams.

II. LITERATURE REVIEW

The academic and industrial discourse surrounding risk assessment in the CPI has evolved significantly over the past three decades. Early safety methodologies were largely deterministic and heavily reliant on historical failure data and engineering heuristics. Arendt (1990) was instrumental in articulating the shift toward probabilistic QRA, emphasizing its capacity to synthesize component-level reliability data into predictive models for complex system failures. Pietersen et al. (1992) further advanced the discipline by establishing frameworks for mapping Individual Risk Contours (IRC) and societal risk, demonstrating how spatial consequence modeling could directly inform municipal land-use planning and zoning regulations.

The integration of specific safety engineering and reliability tools into the QRA matrix has been a focal point of recent research. Khan and Abbasi (1998, 1999) conducted exhaustive reviews of methodologies such as HIRA, FTA, and FMEA, positioning them as fundamental prerequisites for any robust risk analysis. Their extensive causal analysis of historical CPI accidents reaffirmed that Vapour Cloud Explosions (VCE) represent the highest volumetric damage potential among industrial hazards, necessitating the use of precise modeling techniques such as the TNT equivalency method and the TNO Multi-Energy model (Mercx et al., 2000; Alonso et al., 2006). These models allow for the accurate prediction of blast overpressures and impulse decays over specified geographical distances.

A significant portion of literature is dedicated to the study of the Boiling Liquid Expanding Vapour Explosion (BLEVE), recognized universally as one of the most devastating phenomena in chemical processing. Tasneem Abbasi and S.A. Abbasi (2007) provided profound insights into the complex thermodynamic mechanisms that precipitate a BLEVE. Their research consolidated various semi-empirical mathematical formulations required to accurately predict fireball geometry, combustion duration, and the attenuation of lethal thermal radiation fluxes through the atmosphere. Concurrently, accurate frequency analysis is paramount. Beerens et al. (2006) and Moosemiller (2006) underscored the critical necessity of maintaining robust, updated failure rate databases. They argued that the precision of any Fault Tree Analysis (FTA) is inherently bounded by the quality of the underlying component reliability metrics. This manuscript builds upon this extensive foundation by synthesizing HIRA, FMEA, and FTA into a unified, highly detailed QRA, applying these theoretical constructs directly to the assessment of high-risk Horton sphere storage networks.

Conclusions from the Literature Review

Following conclusions were derived from the above literature survey:

- Risk is a subjective concept which varies with respect to the context and the depth of study.
- Guidelines for QRA are available from such sources as AIChE/CCPS, British HSE, and NUREG etc provide a structure to be adopted for risk assessment but leave choice of methods and steps to the assessors.
- Cost benefit analysis is a crucial factor in risk assessment
- Risk assessment can be qualitative as well as quantitative. Quantitative methods are being given more stress since they allow for a better comparison of risk levels and reduce subjectivity in decision making process.
- The major accidents in the history of the petroleum refineries revealed that they originated from the inventories.
- To perform the frequency analysis we can go with plant specific data if available. If not we can trust the generic data from the sources like TNO, PERD, OREDA depending on the situation that matches to the conditions.
- The major problem in QRA is the presence of trustworthy data.
- There is no possibility of eliminating risk but we can put efforts to bring it under the acceptable region.

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 2, August 2026
Impact Factor: 8.2

III. REFINERY CONFIGURATION AND SITE CHARACTERISTICS

The facility under investigation is a high-capacity, fully integrated petrochemical refinery engineered to process a diverse slate of imported and indigenous bituminous and non-bituminous crude oils. The refinery spans a primary operational footprint of 515 acres, augmented by an Additional Tankage Project (ATP) covering an adjacent 215 acres. Geographically, the installation is situated near significant topographical features, located approximately 1 km northwest of a major hill range, which can influence local micro-meteorological dispersion patterns. Crucially, the facility is bordered by other heavy industrial complexes to the north, west, and east, and is flanked by densely populated civilian residential colonies to the south. This specific geographical orientation establishes a highly sensitive baseline for societal risk, as any significant off-site migration of thermal radiation or toxic plumes will directly impinge upon vulnerable populations.

The operational architecture of the refinery comprises multiple high-complexity process units, each presenting unique hazard profiles. Primary among these are three Crude Distillation Units (CDU), responsible for the initial thermal fractionation of crude oil into distinct hydrocarbon cuts including fuel gases, naphtha, kerosene, and heavy diesel. Downstream upgrading is facilitated by two Fluidized Catalytic Cracking Units (FCCU) that operate at elevated temperatures to convert heavy residual fractions into lighter, high-value olefins and gasoline blending components; these units also manage significant volumes of Carbon Monoxide (CO) via specialized boiler systems. Environmental compliance and fuel quality are ensured by the Diesel Hydro De-Sulphurisation (DHDS) unit, which processes high-sulfur streams under substantial hydrogen partial pressures, inherently involving the handling and continuous transfer of acutely toxic Hydrogen Sulphide (H2S).

The most concentrated energy inventories reside within the refinery’s extensive tank farm and storage infrastructure. This sector features a variety of containment systems tailored to the volatility of the stored media. Heavy, low-volatility products (Class C) are maintained in standard non-pressure fixed-roof tanks. Highly volatile liquid hydrocarbons (Class A and B), such as Naphtha and Motor Spirit, are stored in large-capacity external and internal floating-roof tanks designed to minimize vapor space and evaporative losses. However, the apex of hazard potential is located within the pressurized storage zone, which utilizes arrays of heavy-walled, spherical pressure vessels (Horton spheres) to contain massive inventories of liquefied gases—specifically Liquefied Petroleum Gas (LPG) and Propylene—at ambient temperatures and highly elevated equilibrium vapor pressures.

IV. INTEGRATED RISK ASSESSMENT METHODOLOGY

To ensure a comprehensive and mathematically rigorous evaluation of the facility's hazard profile, this study employs a multi-tiered, integrated risk assessment methodology. This framework systematically progresses from qualitative hazard identification to quantitative frequency and consequence modeling, culminating in spatial risk characterization.

4.1 Hazard Identification and Risk Assessment (HIRA)

Hazard Identification and Risk Assessment (HIRA) serves as the foundational analytical layer. This phase involves a systematic inventory and characterization of all chemical substances and physical conditions within the refinery capable of inducing harm. The analysis cataloged highly flammable inventories, notably LPG, Propylene, and Naphtha, assessing their respective Lower and Upper Explosive Limits (LEL/UEL), flash points, and auto-ignition temperatures. Simultaneously, acutely toxic substances, primarily Hydrogen Sulphide (H2S), Ammonia (NH3), and Chlorine (Cl2), were evaluated against critical physiological thresholds including Immediately Dangerous to Life and Health (IDLH) concentrations and Lethal Concentration (LC50) metrics. This comprehensive mapping ensured that no potential source of catastrophic energy release or toxic exposure was omitted from the subsequent screening phases.

4.2 Scenario Selection (A-Factor and S-Factor Matrix)

Given the vast number of individual components and storage vessels within a modern refinery, modeling every conceivable failure scenario is computationally prohibitive and analytically inefficient. Therefore, a systematic screening methodology, based on the internationally recognized IPO (Inter Provinciaal Overleg) guidelines, was

DOI: 10.48175/IJARSCT-38129

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429 Volume 6, Issue 2, August 2026 Impact Factor: 8.2

applied to isolate the subset of installations capable of generating significant off-site consequences. This process involves the calculation of two distinct indices: the Notification Factor (A-factor) and the Selection Factor (S-factor).

The A-factor provides a semi-quantitative measure of the intrinsic hazard potential of a specific inventory, calculated as:

$$A = (Q \times O\_total) / G$$

Where 'Q' represents the total mass of the hazardous material in kilograms, 'O_total' is a composite circumstance factor reflecting the physical state, operational temperature, and pressure of the substance, and 'G' denotes the specific threshold quantity (in kg) above which the substance is deemed a major hazard.

Subsequently, the S-factor scales the A-factor against the geographical distance ('L', in meters) from the containment unit to the facility's perimeter, differentiating between toxic and flammable propagation mechanics:

For Toxic Materials: $S\_toxic = (100 / L)^2 \times A$

For Flammable Materials: $S\_flammable = (100 / L)^3 \times A$

According to the IPO criteria, only those installations yielding an S-factor greater than or equal to 1.0 are designated as critical MAH sources requiring detailed, quantitative consequence modeling.

4.3 Failure Mode and Effects Analysis (FMEA)

To bridge the gap between hazard identification and probabilistic frequency analysis, Failure Mode and Effects Analysis (FMEA) was utilized. FMEA is a structured, inductive methodology that systematically evaluates discrete equipment components to identify all potential failure modes, their immediate local effects on the subsystem, and their ultimate systemic consequences on the facility. For the pressurized storage systems, FMEA evaluated mechanisms such as metallurgical fatigue in the shell plates, micro-cracking at weld seams, catastrophic failure of bottom drain valves due to shear stress, and the failure of pressure relief valves (PRVs) upon demand. The qualitative insights generated by the FMEA provided the structural logic required to construct the Fault Tree Analysis.

V. IDENTIFICATION OF CRITICAL SCENARIOS

The rigorous application of the A-factor and S-factor screening matrix to the refinery's extensive inventory database successfully filtered the installations down to a critical subset. The calculations confirmed that while the majority of process units and small-scale intermediate storages yielded S-factors well below 1.0 (indicating that their hazard footprints remain confined within the facility boundaries), several massive bulk storage and transfer systems significantly breached the threshold.

The following distinct release sources were definitively identified as possessing the potential to inflict severe off-site consequences:

1. DHDS Unit Transfer Lines: The high-pressure acid gas pipeline transferring concentrated Hydrogen Sulphide (H2S) from the Amine Regeneration Unit to the Sulphur Recovery Unit.
2. Bulk Naphtha Storage: Large-capacity (35,430 KL) non-pressure storage tanks (120-T-7A) containing highly volatile Naphtha.
3. Pressurized LPG Storage: A battery of five identical Horton spheres (e.g., 120-T-12A), each holding 1,200 Metric Tons of LPG under high pressure.
4. Pressurized Propylene Storage: Twin Horton spheres (e.g., 120-T-180A), each containing 750 Metric Tons of highly reactive Propylene.

VI. CONSEQUENCE MODELING AND RESULTS ANALYSIS

With the critical scenarios isolated, advanced mathematical modeling was deployed to quantify the physical magnitudes of the potential energy releases and toxic dispersions. This phase translates hypothetical loss-of-containment events into tangible metrics: blast overpressures, thermal radiation fluxes, and toxic concentration gradients.

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 2, August 2026
Impact Factor: 8.2

6.1 Vapour Cloud Explosion (VCE) Modeling: Naphtha Storage Tank

The postulated scenario for the Naphtha storage tank involves a catastrophic mechanical failure of the largest bottom nozzle (6-inch equivalent diameter). Given the lack of immediate isolation capabilities for this specific failure mode, a continuous release duration of 300 seconds is assumed, resulting in a massive unconfined liquid pool. Rapid evaporation from this pool, driven by ambient heat transfer, generates a substantial heavier-than-air vapor cloud. Upon encountering a delayed ignition source, the cloud undergoes deflagration, generating a Vapour Cloud Explosion (VCE). To estimate the spatial distribution of the resulting blast wave, the TNT Equivalency Method was employed. The total mass of Naphtha released was calculated at 39,300 kg. Utilizing an empirical explosion yield factor (η) of 5%, the equivalent mass of TNT (W) was determined to be 19,683.8 kg. The scaled distance (Z), defined as $Z = R / W^{(1/3)}$ (where R is the distance from the explosion center), was calculated for various radii to derive the peak incident overpressure (psig) and impulse (Pas).

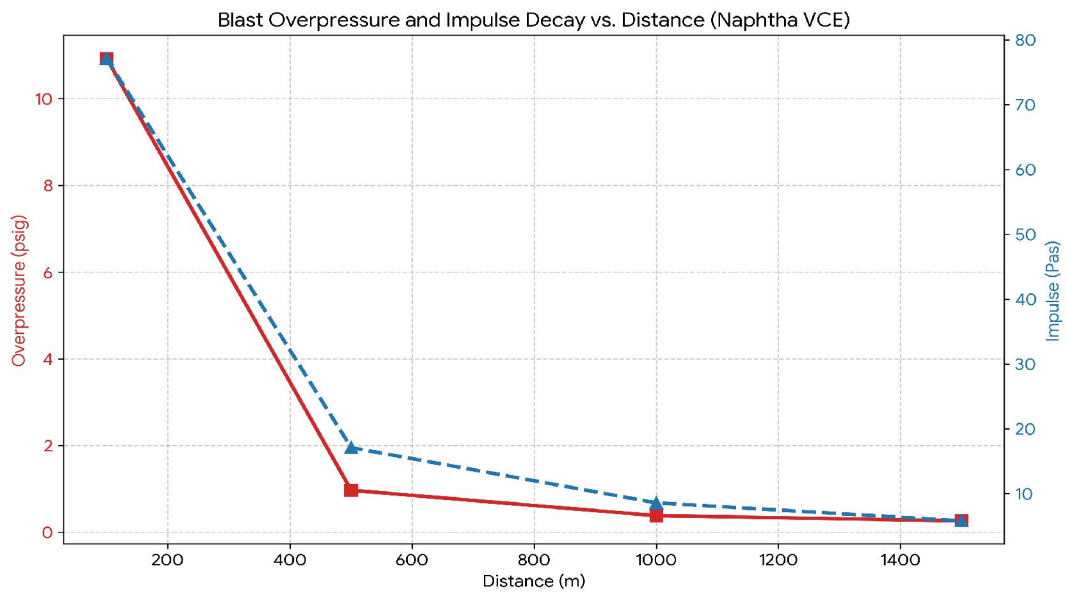

Figure 1: Blast Overpressure and Impulse Decay vs. Distance for Naphtha VCE.

The computational results demonstrate highly destructive blast characteristics. At a proximity of 100 meters, the overpressure peaks at 10.93 psig, a magnitude sufficient to cause the total destruction of heavily constructed concrete buildings and the overturning of major process equipment. At a distance of 500 meters, the blast wave attenuates to 0.969 psig; however, this pressure level remains highly hazardous, capable of causing the partial demolition of standard residential housing, rendering them uninhabitable. The overpressure decays to 0.262 psig at 1.5 kilometers, which is still sufficient to induce widespread glass breakage, presenting a secondary fragmentation hazard to the public.

6.2 Toxic Dispersion Modeling: Hydrogen Sulphide (H2S) Release

The transfer of highly toxic H_2S gas between the Amine Regenerator and the SRU presents a severe continuous release hazard. The modeled scenario assumes a full-bore guillotine rupture of the 10-inch transfer pipeline. Operating parameters dictate a release rate of 1.2 kg/s. Assuming a conservative 10-minute window for detection and subsequent valve isolation, a total of 360 kg of H_2S is discharged directly into the atmosphere.

The spatial and temporal propagation of this toxic plume was modeled using the Pasquill-Gifford continuous dispersion equations. To establish the absolute worst-case scenario, the model was parameterized with highly stable atmospheric conditions (Pasquill Stability Class F) and a low ambient wind speed of 2.0 m/s, which drastically inhibits vertical and horizontal turbulent mixing and lateral cloud diffusion.

DOI: 10.48175/IJARSCT-38129

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 2, August 2026
Impact Factor: 8.2

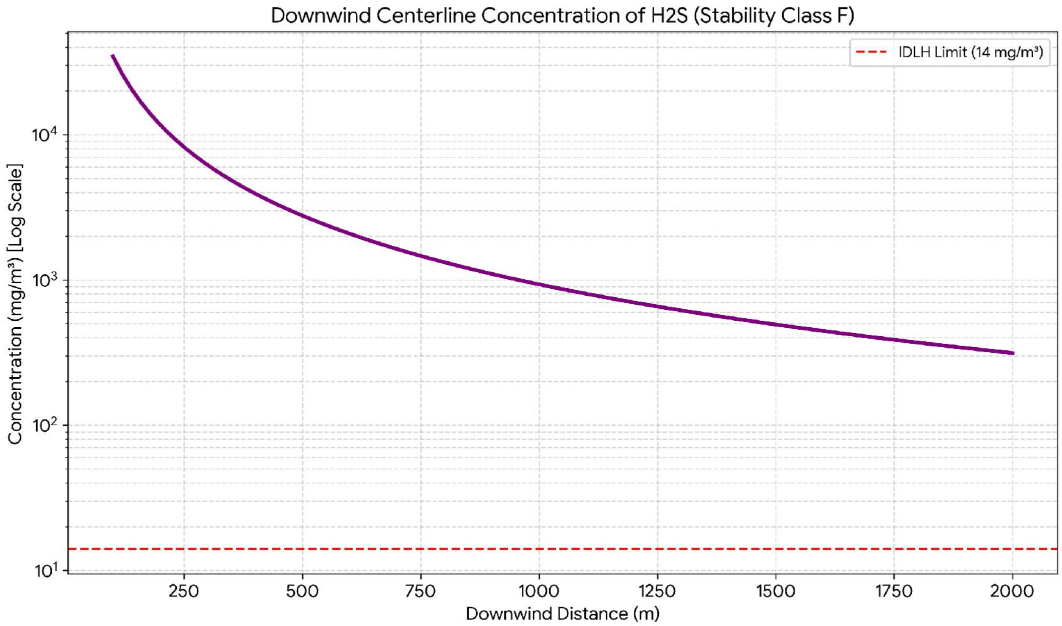

Figure 2: Downwind Centerline Concentration of H2S Plume (Pasquill-Gifford Class F).

The dispersion profile reveals a highly elongated, lethal toxic corridor. The centerline concentration of the H2S plume remains alarmingly high over vast distances. Crucially, the model indicates that the concentration remains above the IDLH (Immediately Dangerous to Life and Health) threshold of 14 mg/m³ at a downwind distance exceeding 1,200 meters. Given that the wind speed is merely 2 m/s, the passage of this lethal plume over adjacent residential areas would expose populations to incapacitating and fatal concentrations of H2S with almost zero evacuation lead time.

6.3 Thermal Radiation Modeling: BLEVE of LPG and Propylene Spheres

The Boiling Liquid Expanding Vapour Explosion (BLEVE) represents the apex hazard within the refinery's risk profile. This catastrophic event is typically initiated by prolonged external fire impingement on a pressurized storage vessel (e.g., a Horton sphere). The intense thermal flux weakens the metallurgical integrity of the vessel shell above the liquid level while simultaneously increasing the internal vapor pressure. Upon sudden catastrophic rupture of the containment shell, the superheated liquid inventory undergoes instantaneous, violent depressurization and flash boiling. The ensuing ignition of the massive vapor-aerosol mixture generates a rapidly expanding, highly luminescent, ascending fireball.

Semi-empirical thermodynamic models were utilized to quantify the specific geometry and radiative properties of the BLEVE fireballs. For the LPG Horton sphere, operating at 80% volume capacity (releasing 1,200,000 kg of mass), the equations predicted a maximum fireball diameter (D_max) of 616.3 meters. The duration of the fireball combustion phase was calculated at 26.8 seconds, with the center of the fireball ascending to a height of 462.3 meters. The surface emitted thermal flux was determined to be a staggering 516 kW/m². Similar modeling for the 750 MT Propylene sphere yielded a fireball diameter of 527 meters and a duration of 24.8 seconds.

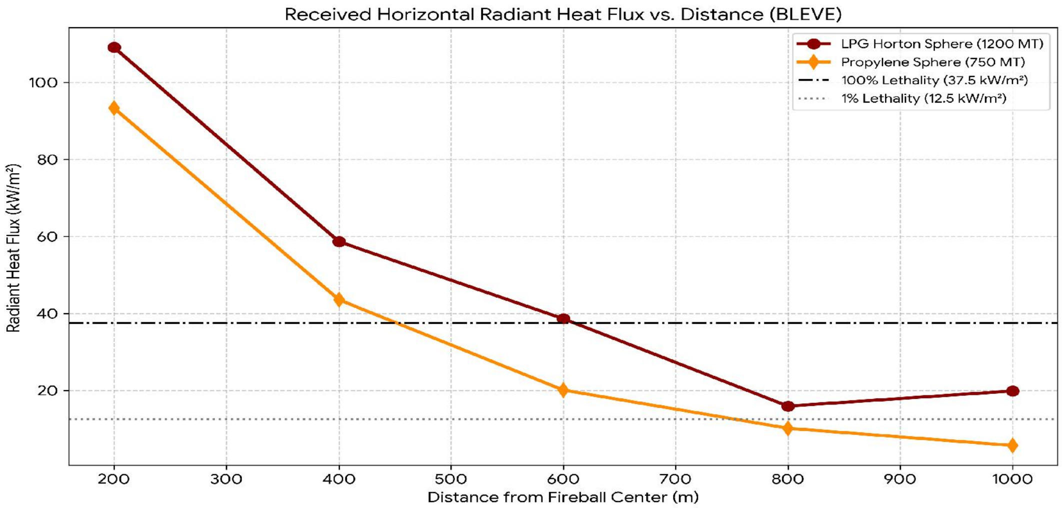

Figure 3: Received Horizontal Radiant Heat Flux vs. Distance (BLEVE).

The attenuation of this intense thermal radiation through atmospheric transmissivity to ground-level targets was calculated using established view-factor equations. For the LPG BLEVE, at a radial distance of 200 meters from the fireball center, the received horizontal radiant heat flux is 109.04 kW/m². According to standard lethality probit models, an exposure to a flux exceeding 37.5 kW/m² guarantees 100% lethality within seconds and induces the spontaneous ignition of cellulose materials (e.g., wood, clothing). The 1% lethality threshold (12.5 kW/m²) extends beyond a radius of 800 meters. Consequently, a BLEVE in the tank farm would instantly envelop massive sections of the off-site residential colonies in a lethal thermal wave.

VII. FREQUENCY ANALYSIS AND SOCIETAL RISK CHARACTERIZATION

While consequence modeling visually delineates the catastrophic severity of these hazards, comprehensive risk characterization requires the integration of statistical occurrence probabilities. Fault Tree Analysis (FTA) was employed to construct detailed logical models representing the failure pathways leading to the top events. By populating the base events of the fault trees with validated, generic failure rate data sourced from established reliability databases (e.g., TNO, PERD, OREDA), the expected annual frequencies of the catastrophic scenarios were computed.

The FTA determined that the overarching frequency of a catastrophic failure culminating in a BLEVE for a standard, well-maintained Horton sphere in this specific configuration is 3.6E-7 per year. Similarly, the probability of a full-bore rupture of the H_2S transfer pipeline was calculated at 9.0E-5 per year, based on a base failure rate of 1.8E-6 per meter per year over its 50-meter run length. While these individual event frequencies are statistically low—reflecting standard industrial reliability—their combination with the sheer magnitude of the consequences generates significant cumulative risk.

To formally evaluate this risk against regulatory and societal tolerance thresholds, Societal Risk was calculated. Societal Risk is graphically represented by the F-N curve, which plots the cumulative frequency (F) of accidents resulting in 'N' or more fatalities. By superimposing the calculated thermal and toxic consequence footprints (the 'kill zones') over the precise demographic grid of the surrounding area—which possesses a high population density of 2,159 persons per square kilometer—the potential fatality numbers were derived for each scenario.

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 2, August 2026
Impact Factor: 8.2

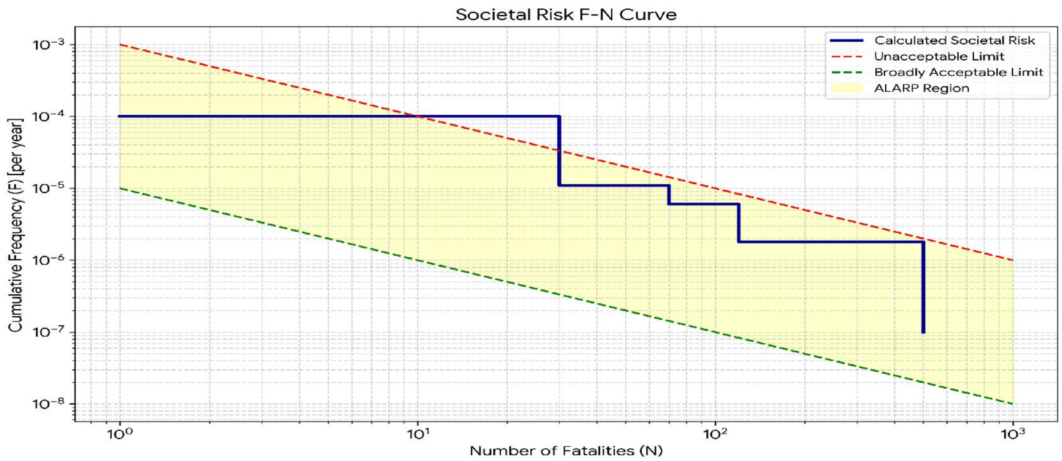

Figure 4: Societal Risk F-N Curve for Refinery Operations.

The plotted F-N curve demonstrates a critical finding: the calculated societal risk profile of the refinery clearly breaches the upper 'Unacceptable' boundary limit established by standard ALARP (As Low As Reasonably Practicable) criteria. This unacceptable risk excursion is almost entirely driven by the profound fatality potential associated with the pressurized LPG and Propylene Horton spheres. The intersection of extremely large, lethal consequence radii with high-density off-site populations creates a risk dynamic that cannot be tolerated under modern safety paradigms, necessitating immediate and aggressive strategic interventions.

VIII. CONCLUSION AND STRATEGIC RECOMMENDATIONS

This exhaustive Quantitative Risk Assessment (QRA) has successfully integrated advanced safety engineering methodologies—specifically HIRA, FMEA, and FTA—to systematically deconstruct and quantify the complex hazard profile of a major petrochemical refinery. The analytical results unequivocally establish that while continuous process units and atmospheric storage tanks present significant, albeit localized, risks, it is the bulk pressurized storage of Liquefied Petroleum Gas (LPG) and Propylene in above-ground Horton spheres that constitutes the absolute dominant threat to societal safety and facility integrity. The consequence models confirmed that a BLEVE event in these units possesses the physical capability to generate massive fireballs, delivering lethal thermal radiation fluxes up to 1 kilometer from the epicenter. When overlaid onto the local demographic topology, this hazard translates into an F-N societal risk curve that severely violates the acceptable ALARP thresholds.

To aggressively suppress this risk profile and force the facility's operations back into the broadly acceptable ALARP region, the following comprehensive, tiered engineering and administrative interventions are strongly recommended:

1. Implementation of Inherently Safer Design (ISD): The most definitive and effective risk mitigation strategy is the phased decommissioning of all above-ground Horton spheres in favor of Mounded Bullet storage technology. By completely encapsulating the pressure vessels in earth or sand, mounded storage inherently eliminates the primary mechanism of catastrophic failure—external fire impingement—effectively rendering a BLEVE scenario physically impossible.

2. Enhancement of Safety Instrumented Systems (SIS): For the operational lifespan of the existing spheres, the facility must implement highly reliable, redundant Safety Instrumented Systems (SIS). These systems must be logically linked to rapid-response, high-capacity deluge mechanisms and automated Remote Operated Shut-off Valves (ROVs) on all bottom connections to prevent prolonged fire exposure and halt large-scale liquid leaks instantly.

3. Aggressive Land Use Planning and Zoning: The progressive encroachment of civilian populations toward the industrial fence line must be decisively halted. Local municipal authorities, in coordination with refinery management,

must legislate and strictly enforce a sterile exclusion/buffer zone based on the 1% lethality contours derived from this QRA.

4. Advanced Dynamic Condition Monitoring: Routine maintenance protocols must be upgraded to include dynamic FMEA applications. This should be coupled with state-of-the-art, real-time Acoustic Emission (AE) testing and continuous Ultrasonic Thickness (UT) gauging of the sphere shells to preemptively identify and arrest metallurgical fatigue and micro-cracking before they propagate to catastrophic failure.

REFERENCES

1. AIChE/CCPS (2000). Guidelines for Chemical Process Quantitative Risk Analysis, 2nd ed. New York: Center for Chemical Process Safety.
2. AIChE/CCPS (1999). Guidelines for Consequence Analysis of Chemical Releases. New York: Center for Chemical Process Safety.
3. Alonso, F. D. et al. (2006). 'Characteristic overpressure-impulse-distance curves for vapour cloud explosions using the TNO Multi-Energy model,' Journal of Hazardous Materials, A137, 734-741.
4. Arendt, J. S. (1990). 'Using Quantitative Risk Assessment in the Chemical Process Industry,' Reliability Engineering and System Safety, 29, 133-149.
5. Beerens, H. I., Post, J. G., & Uijt de Haag, P. A. M. (2006). 'The use of generic failure frequencies in QRA: The quality and use of failure frequencies and how to bring them up-to-date,' Journal of Hazardous Materials, 130, 265-270.
6. Chang, J. I., & Lin, C. C. (2006). 'A study of storage tank accidents,' Journal of Loss Prevention in the Process Industries, 19, 51-59.
7. Crowl, D. A., & Louvar, J. F. (2001). Chemical Process Safety: Fundamentals With Applications, 2nd ed. NJ: Prentice Hall.
8. Delvosalle, C., Fiévez, C., & Pipart, A. (2004). 'Generic frequencies data for the critical events,' ARAMIS D1C, Appendix 10.
9. Ditali, S. et al. (2000). 'Consequence analysis in LPG installation using an integrated computer package,' Journal of Hazardous Materials, 71, 159-177.
10. Early, W. F. (2006). 'Database management systems for process safety,' Journal of Hazardous Materials, 130, 53-57.
11. Khan, F. I., & Abbasi, S. A. (1998). 'Techniques and methodologies for risk analysis in chemical process industries,' Journal of Loss Prevention in the Process Industries, 11, 261-277.
12. Khan, F. I., & Abbasi, S. A. (1999). 'Major accidents in process industries and an analysis of causes and Consequences,' Journal of Loss Prevention in the Process Industries, 12, 361-378.
13. KLG-TNO (2000). Risk Analysis Study at HPCL-VR. KLG-TNO Safety Technology Limited.
14. Lees, F. P. (2005). Loss Prevention in the Process Industries, 3rd ed. Elsevier Butterworth-Heinemann.
15. Melchers, R. E., & Feutrill, W. R. (2001). 'Risk assessment of LPG automotive refuelling facilities,' Reliability Engineering and System Safety, 74, 283-290.
16. Mercx, W. P. M. et al. (2000). 'Developments in vapour cloud explosion blast modeling,' Journal of Hazardous Materials, 71, 301-319.
17. Moosemiller, M. (2006). 'Avoiding pitfalls in assembling an equipment failure rate database for risk assessments,' Journal of Hazardous Materials, 130, 128-132.
18. Pietersen, C. M., & van het Veld, B. F. P. (1992). 'Risk assessment and risk contour mapping,' Journal of Loss Prevention in the Process Industries, 5(1).
19. Tasneem Abbasi, & Abbasi, S. A. (2007). 'The boiling liquid expanding vapour explosion (BLEVE): Mechanism, consequence assessment, management,' Journal of Hazardous Materials, 141, 489-519.

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 2, August 2026
Impact Factor: 8.2

20. Tweeddale, H. M., Cameron, R. F., & Sylvester, S. S. (1992). 'Some experiences in hazard identification and risk shortlisting,' Journal of Loss Prevention in the Process Industries, 5(5), 279-288