

Evaluation Of Leak Elevation Effects On Ammonia Storage Release Consequences Using Aloha Simulation

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Abstract

Ammonia leakage from storage tanks poses significant risks to personnel, facilities, and surrounding communities due to its toxic and flammable properties. This study investigates the influence of leak hole elevation on Quantitative Risk Assessment (QRA) outcomes for the 5,000 MT Ammonia Storage Tank 4101-F at PT Pupuk Sriwidjaja Palembang, located near residential areas. Simulations were conducted using ALOHA 5.4.7 software to compare two scenarios: low elevation leak (0.5 m above ground) and high elevation leak (10 m above ground), with a 3-inch diameter hole under worst-case meteorological conditions (stability class F, wind speed 2 m/s). Four consequence scenarios were evaluated: toxic vapor cloud, flammable vapor cloud, vapor cloud explosion, and BLEVE. Results demonstrated that low elevation leaks generated significantly higher release rates (1.820 kg/min) compared to high elevation leaks (974 kg/min) due to greater hydrostatic pressure. The toxic vapor cloud ERPG-3 zone extended to 1.4 km for low elevation versus 0.953 km for high elevation. Similarly, flammable vapor cloud LEL zones reached 156 m and 105 m, while vapor cloud explosion overpressure (1 psi) zones extended to 168 m and 114 m, respectively. The findings reveal that leak elevation substantially affects consequence dispersion patterns and hazard zone extents, providing critical insights for emergency response planning and safety system optimization in ammonia storage facilities.

Keywords: Ammonia Storage; Quantitative Risk Assessment; Leak Elevation; ALOHA Simulation; Consequence Analysis

Cite This Article

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INTRODUCTION

Ammonia (NH_3) serves as a critical raw material in the fertilizer industry, particularly for urea production, and plays a vital role in supporting national food security [1]. PT Pupuk Sriwidjaja Palembang (PT Pusri), as one of Indonesia's largest fertilizer producers, utilizes ammonia extensively in its production processes. However, ammonia is classified as a hazardous and toxic material (B3) due to its corrosive, toxic, and volatile properties, necessitating stringent safety measures in its storage and handling [2].

At PT Pusri Palembang, ammonia is stored in low-pressure refrigerated tanks, including the 5,000 MT capacity Ammonia Storage Tank 4101-F. This tank is geographically located in the eastern part of Palembang City, in close proximity to residential areas and public facilities, with the nearest mosque approximately 450 meters away, residential areas at 800 meters, and hospitals at 900 meters. The large storage capacity combined with its proximity to populated areas creates significant potential hazards, particularly in the event of tank leakage.

Historical industrial accidents underscore the severe consequences arising from ammonia leakage. A notable incident occurred in 2013 at a refrigeration facility in Shanghai, China, resulting in 15 fatalities and 25 injuries, with impacts detected up to 15 km from the release point [3]. Similarly, the 2010 pipeline rupture in Theodore, Alabama, discharged approximately 32,000 pounds of ammonia, affecting around 800 individuals and generating concentrations of 500–600 ppm within a 0.25-square-mile radius [4]. Additional major incidents include the 1992 ammonia leak in Dakar, which caused 129 fatalities, and the 2019 release in Alabama that resulted in exposure among 120 individuals [5]. These events highlight the imperative of conducting comprehensive and systematic risk assessments for ammonia storage systems.

Upon leakage, liquid ammonia undergoes rapid flash vaporization, leading to multiple potential hazard scenarios, including toxic vapor cloud dispersion, formation of flammable vapor mixtures, vapor cloud explosions (VCE), and even Boiling Liquid Expanding Vapor Explosions (BLEVEs) if flammable concentration limits are reached. These outcomes pose substantial threats to personnel, infrastructure integrity, and surrounding communities [6].

To mitigate these potential hazards, Quantitative Risk Assessment (QRA) is employed to evaluate the level of risk associated with ammonia leakage. A key stage within the QRA framework is gas dispersion modeling, which aims to estimate the distance and direction of gas-cloud propagation under specific operational and meteorological conditions. The Areal Locations of Hazardous Atmospheres (ALOHA) software is widely utilized for this purpose.

Several studies have demonstrated the effectiveness of ALOHA as a modeling tool for hazardous chemical releases [7]. Compared to other software such as PHAST or RISKCURVES, ALOHA provides advantages including relatively simple data input requirements and the ability to generate hazard-zone visualizations that are straightforward yet sufficiently informative. Moreover, ALOHA is freely accessible, enabling broader use by industrial facilities and governmental agencies in risk assessment and emergency decision-making. In conducting dispersion simulations, ALOHA considers parameters such as leak hole size, internal pressure, temperature, wind direction, and atmospheric stability [8].

The elevation or vertical position of the leak source relative to ground level represents a geometric factor that influences gas dispersion patterns but is often overlooked in risk analysis. This factor potentially affects the direction of movement, concentration, and range of ammonia gas dispersion, particularly because ammonia has a density lower than air and tends to flow toward lower areas. Several studies have investigated various aspects of ammonia leakage consequences, but limited research has specifically examined the influence of leak hole elevation on QRA results [9].

Research by Herlambang et al. [10] conducted quantitative risk analysis due to ammonia storage tank leakage but did not consider elevation variations. Similarly, Nashira et al. [6] performed quantitative risk assessment of ammonia release from storage tanks using RISKCURVES software without evaluating the effect of leak position height. Skarsvag et al. [11] investigated the influence of ammonia-water fog formation on ammonia dispersion from liquid spills but focused on fog formation mechanisms rather than elevation effects.

Despite the increasing number of studies investigating ammonia storage risks, most existing work primarily emphasizes parameters such as leak diameter, internal pressure, release rate, meteorological conditions, and dispersion mechanisms. By contrast, the impact of leak elevation on hazard-zone consequences has not been comprehensively assessed, even though vertical leak position directly influences vapor cloud formation, accumulation behavior, and exposure distances to surrounding populations. Many prior studies assume ground-level rupture scenarios, which may not properly represent realistic industrial accidents where leaks can occur at various heights along tank walls. Furthermore, no published research has quantitatively compared risk contours generated by different leak elevations in industrial sites adjacent to populated areas such as PT Pupuk Sriwidjaja Palembang. This gap demonstrates the need for elevation-based release evaluation to obtain more realistic, site-specific QRA predictions and improve mitigation and emergency response planning.

Understanding the relationship between leak hole elevation and consequence modeling results is essential for developing more effective safety systems and emergency response strategies. Different elevation positions may result in variations in release rates, dispersion patterns, and affected area extents, which in turn influence mitigation priorities and evacuation planning.

Therefore, this study aims to evaluate the effect of leak hole elevation differences on Quantitative Risk Assessment (QRA) results using ALOHA 5.4.7 software for Ammonia Storage Tank 4101-F at PT Pupuk Sriwidjaja Palembang. The novelty of this research lies in its systematic comparison of leak consequences at two different elevation levels (low and high positions) under worst-case scenario conditions, providing comprehensive quantitative data on how vertical leak position affects hazard zone distribution. The findings are expected to contribute to enhanced process safety systems at ammonia storage facilities and provide valuable references for industrial risk management practices.

RESEARCH METHOD.

Research Design

This research employs a quantitative descriptive approach with simulation methodology using ALOHA version 5.4.7 software. The study compares two elevation scenarios through computational modeling to evaluate consequence differences

systematically. Spatial visualization through Google Earth enables mapping of hazard zones relative to actual geographical features and surrounding facilities.

Time and Place of Research

The research was conducted from August 1 to September 30, 2025, at PT Pupuk Sriwidjaja Palembang, located at Jl. Mayor Zen, Palembang, South Sumatra, Indonesia. The ammonia storage tank analyzed is located in the eastern part of Palembang City, with geographic coordinates obtained through direct field observation and Google Earth mapping, at coordinates 2°59'42.5"S 104°45'28.6"E.

Research Target/Subject

The research target is ammonia storage tank 4101-F with the following specifications: fixed dome roof tank type, capacity 5.000 MT, inner diameter 20.726 mm, inner height 21.953 mm, operating pressure 0,003 kg/cm², operating temperature -30°C, and construction material A 537 CL1. The tank operates at 45-70% capacity under normal conditions and is equipped with double containment double wall design consisting of an inner tank for liquid ammonia storage and an outer tank with nitrogen gas layer for protection.



Figure 1. Ammonia Storage Tank 4101-F

Research Procedure

The research procedure consists of five main stages:

1. Data Collection Phase: Gathering technical specifications of tank 4101-F including capacity, dimensions, operating temperature, and pressure from plant documentation. Collecting meteorological data from BMKG Palembang for 2024 including temperature, humidity, wind direction, and wind speed under worst-case atmospheric conditions (stability class F). Conducting site observation to identify surrounding facilities and population centers.
2. Scenario Definition Phase: Establishing two elevation scenarios based on operational and design considerations. Low elevation (0,5 m from ground) represents the outlet valve location and lower tank piping connections, which are critical failure points according to OGP Risk Assessment Data Directory showing 35% of leakage incidents occur at lower pipe connections. High elevation (10 m from ground) represents liquid surface level at 50% tank volume, calculated from the operational range of 45-70% capacity.

3. ALOHA Simulation Phase: Executing simulations for four consequence scenarios (toxic vapor cloud, flammable vapor cloud, vapor cloud explosion, and BLEVE) at both elevation levels. Input parameters include chemical properties (ammonia NH_3), atmospheric conditions (stability class F, wind speed 2 m/s from south, air temperature 29°C, relative humidity 60%, cloud cover 0), and source characteristics (hole diameter 3 inches, temperature -30°C, tank volume 50%).
4. Spatial Mapping Phase: Exporting simulation results in KML format and importing to Google Earth for geographical visualization. Overlaying hazard zones onto actual facility layout and surrounding areas to identify affected populations and critical infrastructure.
5. Comparative Analysis Phase: Quantitatively comparing hazard zone radius between elevation scenarios, analyzing physical mechanisms causing differences, and evaluating implications for safety management and emergency response planning.

Instruments and Data Collection Techniques

Primary instruments include ALOHA 5.4.7 software for dispersion modeling and consequence analysis and Google Earth for spatial visualization and mapping. Data collection techniques involve direct observation of tank 4101-F, tank specification sheets, meteorological data acquisition from BMKG Palembang database for year 2024, and photographic documentation of tank installation and surrounding facilities.

RESULTS AND DISCUSSION

Release Characteristics and Physical Mechanisms

Simulation results reveal substantial differences in ammonia release characteristics between elevation scenarios. At low elevation (0,5 m), release rate reaches 1,820 kg/min with total released mass of 108.661 kg over 60 minutes. High elevation (10 m) produces release rate of 974 kg/min with total mass of 57.698 kg. The low elevation release rate is approximately 87% higher than high elevation.

This significant difference is fundamentally explained by Pascal's law and Torricelli's theorem governing fluid behavior in confined systems. According to Pascal's law, pressure in a confined fluid increases linearly with depth: $P = \rho gh$, where P is hydrostatic pressure (Pa), ρ is fluid density (kg/m^3), g is gravitational acceleration ($9,81 \text{ m/s}^2$), and h is liquid column height above the point (m) [12]. This law states that pressure at any point in a static fluid is directly proportional to the height of the fluid column above that point. In the context of tank 4101-F, at low elevation (0,5 m from ground), the liquid column height above the hole is approximately 10,5 m (assuming 50% tank volume with total liquid height ~11 m), while at high elevation (10 m from ground) it is only 1 m. The ten-fold difference in liquid column height creates substantially higher hydrostatic pressure at the low elevation hole, generating greater driving force for fluid discharge.

Based on Torricelli's theorem, which is derived from Bernoulli's equation for ideal fluid flow from an orifice, the discharge velocity is determined by: $v = \sqrt{2gh}$. This theorem demonstrates that velocity is directly proportional to the square root of liquid column height above the orifice. Applying this relationship to the two scenarios: for low elevation with $h = 10,5 \text{ m}$, the velocity is 14,35 m/s, while for high elevation with $h = 1 \text{ m}$, it is 4,43 m/s, giving a ratio of 3,24. This shows that the lower-elevation scenario produces a discharge velocity over three times higher. Since mass flow rate is

proportional to discharge velocity ($\dot{m} = \rho A v$, where A is hole area), the nearly doubled mass release rate at low elevation directly results from this velocity difference predicted by Torricelli's theorem.

The practical implication of these fundamental fluid mechanics principles is that leakage position relative to liquid surface significantly affects both the intensity and duration of hazardous material release. Higher hydrostatic pressure at low elevation not only increases instantaneous release rate but also maintains higher discharge velocity as liquid level decreases, prolonging the period of dangerous release conditions. Conversely, high elevation leakage experiences rapidly declining discharge rate as the small liquid column above the hole depletes quickly.

Additionally, low elevation leakage produces mixture of gas and aerosol with mist pool formation. Liquid ammonia at -30°C absorbs heat from ground surface, causing gradual evaporation and producing white fog from water vapor condensation (Skarsvag et al., 2024). This mist pool acts as a continuous secondary source, extending vapor release duration and enhancing horizontal dispersion in the lower atmospheric layer. Conversely, high elevation leakage converts more rapidly to gas phase and disperses immediately through free air circulation, limiting aerosol formation. The combination of higher initial velocity (from Torricelli's theorem) and sustained evaporation from mist pool (resulting from higher total mass release governed by Pascal's law) explains why low elevation scenarios produce significantly broader hazard zones in all consequence categories.

Toxic Vapor Cloud Dispersion Analysis

A leak from an ammonia storage tank can generate a toxic vapor cloud that poses significant hazards to both human health and the surrounding environment. The cloud's dispersion behavior is strongly influenced by meteorological conditions, particularly wind direction and velocity. In this study, ALOHA software was used to model ammonia dispersion at two leak elevations: 0,5 m (low elevation) and 10 m (high elevation), to evaluate how vertical leak position affects the extent and concentration of the toxic plume.

To evaluate population exposure, ERPG thresholds issued by AIHA were applied. Toxic vapor cloud analysis was conducted using Emergency Response Planning Guidelines (ERPG) standards established by the American Industrial Hygiene Association. Three concentration thresholds define hazard zones: ERPG-1 (25 ppm) representing mild irritation, ERPG-2 (150 ppm) indicating serious health effects that may impede evacuation, and ERPG-3 (1.500 ppm) denoting life-threatening exposure within one hour [13]. The impact radius for both scenarios are summarized in Table 1.

Table 1. Summary of Results Toxic Vapor Cloud Simulation

Radiation Zone	Concentration	Low Elevation	High Elevation	Potential Impact
Red Zone (ERPG-3)	1.500 ppm	1,4 km	0,953 km	Life-threatening exposure within 1 hour
Orange Zone (ERPG-2)	150 ppm	5,3 km	3,8 km	Serious health effects; may hinder evacuation
Yellow Zone (ERPG-1)	25 ppm	>10 km	>10 km	Mild to moderate irritation; reversible effects

Results demonstrate that ERPG-3 red zone extends to 1,4 km radius for low elevation compared to 0,953 km for high elevation, representing a 47% increase in red zone area. ERPG-2 orange zone reaches 5,3 km for low elevation versus 3,8 km for high elevation, a 39% extension. ERPG-1 yellow zone exceeds 10 km modeling limit in both scenarios, though low elevation produces higher concentrations at equivalent distances.

The broader hazard zones at low elevation result from the combination of higher release rate (as explained by Pascal's law and Torricelli's theorem) and mist pool formation. At 1-meter radius from source, ground-level concentration reaches 12.300.000 ppm for low elevation versus 42.600.000 ppm for high elevation. Although high elevation shows higher local concentration near the source due to concentrated release from a smaller total mass in gaseous form, the lower total mass release (57.698 kg versus 108.661 kg) and rapid vertical dispersion limit downwind extent. Conversely, low elevation's higher mass release driven by greater hydrostatic pressure and horizontal spreading through mist pool evaporation produce broader ground-level contamination affecting larger geographical areas.

Google Earth spatial mapping reveals that low elevation red zone encompasses the entire PT Pusri facility including process units, administrative buildings, mosque (380 m), hospital (890 m), and residential areas (1.100 m). The orange zone extends into densely populated districts northwest of the plant, covering multiple schools, health centers, and commercial areas. High elevation red zone limits to internal plant areas, with orange zone reaching some residential zones but with lower severity.

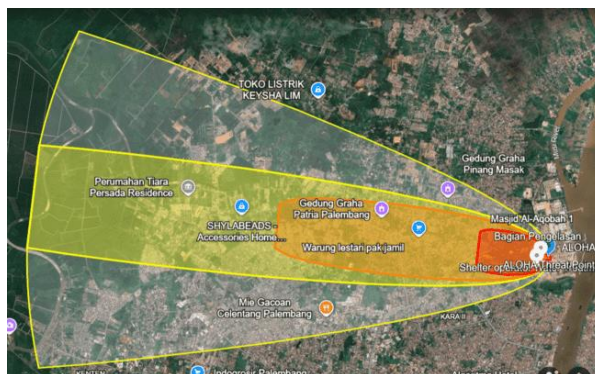


Figure 2. ALOHA Toxic Vapor Cloud Map Plotting for Low Elevation Leak

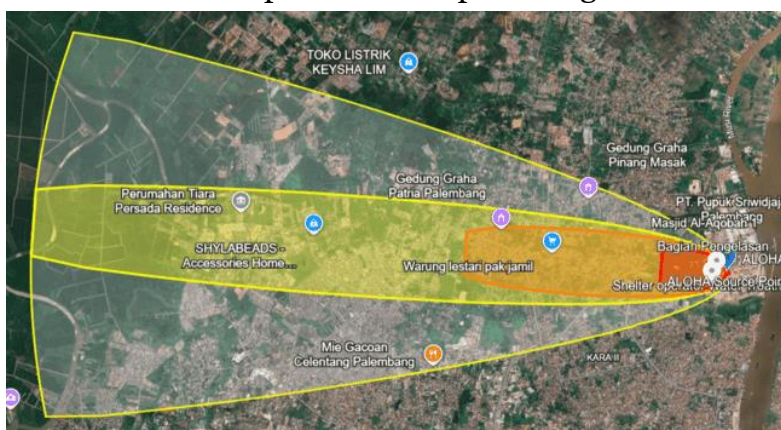


Figure 3. ALOHA Toxic Vapor Cloud Map Plotting for High Elevation Leak

These findings indicate that low elevation leakage poses significantly higher toxic exposure risk to both workers and surrounding population. The extended red

zone necessitates larger evacuation areas and more complex emergency response coordination involving external authorities and healthcare facilities.

Flammable Vapor Cloud Analysis

Leaks from ammonia storage tanks can generate a flammable vapor cloud, which may ignite or explode when the gas–air mixture enters the flammable range and encounters an ignition source. The extent of the cloud is strongly influenced by atmospheric conditions, particularly wind direction and speed, which determine the spatial distribution of fire and explosion hazards.

In this study, the flammable area is evaluated based on ammonia concentrations that reach the Lower Flammable Limit (LFL) using ALOHA 5.4.7 under the same conditions as the Toxic Vapor Cloud analysis. Flammable vapor cloud hazard zones are defined by ammonia's Lower Explosive Limit (LEL) of 15% volume (150,000 ppm). Three zones characterize flammability risk: red zone at $\geq 100\%$ LEL, orange zone at 60% LEL ($\sim 90,000$ ppm), and yellow zone at 10% LEL ($\sim 15,000$ ppm). Low elevation leaks produce higher discharge rates and greater gas mass due to larger hydrostatic pressure, while high-elevation leaks disperse more rapidly because of increased atmospheric mixing.

Table 2. Summary of Results Flammable Vapor Cloud Simulation

Radiation Zone	Threshold Value	Low Elevation	High Elevation	Potential Impact
Red Zone	$\geq \text{LEL}$	156 m	105 m	High likelihood of ignition or explosion upon direct exposure
Orange Zone	60% LEL	191 m	128 m	Moderate fire risk; may threaten adjacent non-process facilities
Yellow Zone	10% LEL	418 m	284 m	Low fire risk; limited and temporary hazard

Table 2 indicates that low elevation leaks generate a substantially larger hazard radius compared to leaks occurring at higher elevations. For low elevation releases, the red zone extends to 156 m and the yellow zone to 418 m, whereas for high elevation releases these distances decrease to 105 m and 284 m, respectively. This disparity is attributed to the higher hydrostatic pressure at lower elevations, which increases the release rate and the total mass of ammonia discharged, consistent with dispersion behavior observed in Toxic Vapor Cloud scenarios.

Additionally, low-elevation releases promote flashing and the formation of a cold, ground-hugging mist pool, allowing the flammable vapor cloud to spread further along the surface. In contrast, ammonia released from higher elevations vaporizes more rapidly and disperses upward into the ambient airflow, thereby reducing the resulting flammable cloud radius.



Figure 4. ALOHA Flammable Vapor Cloud Map Plotting for Low Elevation Leak

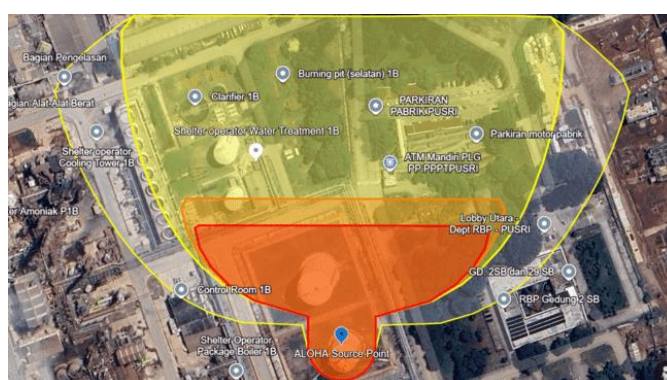


Figure 5. ALOHA Flammable Vapor Cloud Map Plotting for High Elevation Leak

Figure 3 and Figure 4 confirm that dispersion follows the dominant wind from south to northwest. In the low-elevation scenario, the red zone reaches critical plant facilities, including Pusri IB tanks, operator shelters, water treatment units, parking areas, and welding zones, indicating a high likelihood of ignition and potential domino effects. High-elevation leaks produce a smaller red zone concentrated around the main tank and adjacent units. The orange zone (191 m for low elevation; 128 m for high elevation) still poses a potential ignition risk due to possible flame pockets, particularly around burning pits, cooling tower shelters, and vehicle access routes. Meanwhile, the yellow zone extends to external areas such as parking areas and the Al-Aqobah mosque (low elevation) or parts of the burning pit and cooling tower (high elevation).

Overall, the analysis shows that flammable vapor clouds from low-elevation leaks pose significantly greater risks due to wider dispersion and the presence of multiple ignition sources within impact zones. Increasing leak elevation markedly reduces hazard extent, emphasizing the importance of structural design and elevation in mitigating flammable gas risks around ammonia storage facilities.

Vapor Cloud Explosion Analysis

In addition to generating a flammable vapor cloud, an ammonia release also poses the risk of a Vapor Cloud Explosion (VCE) when the gas–air mixture enters the flammable range and encounters an ignition source. Such explosions are most likely to occur when the cloud becomes trapped in areas with restricted ventilation or accumulates near densely packed process equipment, conditions that promote partial

confinement. Under these circumstances, combustion can lead to a rapid rise in pressure and the formation of a destructive blast wave [14].

Vapor cloud explosion simulation results showed that at low elevation, the yellow zone coverage (1 psi) or blast wave pressure threshold capable of breaking glass reached 168 meters, while at high elevation only 114 meters. Orange zones (3,5 psi, serious injury) and red zones (8 psi, building damage) did not form in either scenario, indicating that explosion energy was insufficient to cause severe structural damage.

This range difference is caused by larger mass and volume of flammable clouds at low elevation. Similar to FVC scenarios, higher hydrostatic pressure causes greater release rates and mist pool formation, resulting in formed gas clouds having more fuel mass. When this cloud ignites due to external flame sources, the explosion energy produced is greater and causes wider 1 psi pressure radius. Conversely, at high elevation, releases are relatively in ammonia gas form with smaller mass and rapid dilution, so flammable vapor cloud volume is limited and explosion pressure is lower.

Visualization results on Google Earth showed that the yellow zone in the low elevation scenario with 163 meter radius encompasses the area around ammonia tank 4101-F, partial cooling tower facilities, and internal parking area. Meanwhile, at high elevation, the yellow zone radius of 104 meters only covers the area around the main tank and pipe connections to process units. Although the produced pressure level is relatively low, secondary risk potential still requires vigilance, especially if explosions occur in equipment-dense areas because they can trigger subsequent fires or mechanical damage to other process equipment.

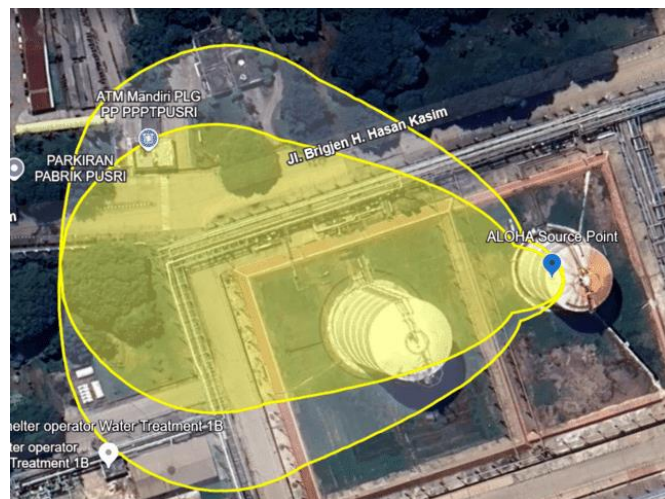


Figure 6. ALOHA Vapor Cloud Explosion Map Plotting for Low Elevation Leak



Figure 7. ALOHA Vapor Cloud Explosion Map Plotting for High Elevation Leak

BLEVE (Boiling Liquid Expanding Vapor Explosion) Analysis

Boiling Liquid Expanding Vapor Explosion (BLEVE) represents catastrophic tank failure with rapid phase transition and fireball formation [15]. Unlike previous scenarios, BLEVE consequences are independent of leakage hole elevation, as the event involves complete vessel rupture rather than localized leakage.

Table 3. Summary of Results Boiling Liquid Expanding Vapor Explosion (BLEVE) Simulation

Radiation Zone	Intensity (kW/m²)	Impact Radius	Potential Impact
Red Zone	10 kW/m ²	950 meters	Fatal within 60 seconds of exposure
Orange Zone	5 kW/m ²	1,4 km	Second-degree burns within 60 seconds of exposure
Yellow Zone	2 kW/m ²	2,2 km	Painful skin sensation within 60 seconds of exposure

Simulation results show 10 kW/m² red zone extending to 950 m radius, 5 kW/m² orange zone reaching 1,4 km, and 2,0 kW/m² yellow zone extending to 2,2 km. A fireball with 340 m maximum diameter forms over approximately 17 seconds. At 310 m radius, radiation intensity reaches 37,5 kW/m², sufficient for instant death and severe damage to steel structures.

BLEVE occurrence requires specific conditions: external fire exposure heating tank walls, pressure rise exceeding design limits, material strength reduction at elevated temperature, and catastrophic rupture. For ammonia tank 4101-F operating at low pressure and temperature, BLEVE probability is relatively low under normal conditions. However, scenarios such as external fire from adjacent facility, loss of cooling system, or severe mechanical impact could trigger BLEVE.

The extensive thermal radiation zones pose severe risks. Red zone encompasses multiple process units, storage tanks, and control buildings within PT Pusri facility. Orange zone extends to residential areas and public infrastructure. Domino effects are particularly concerning, as thermal radiation may damage adjacent tanks triggering secondary BLEVEs or fires.

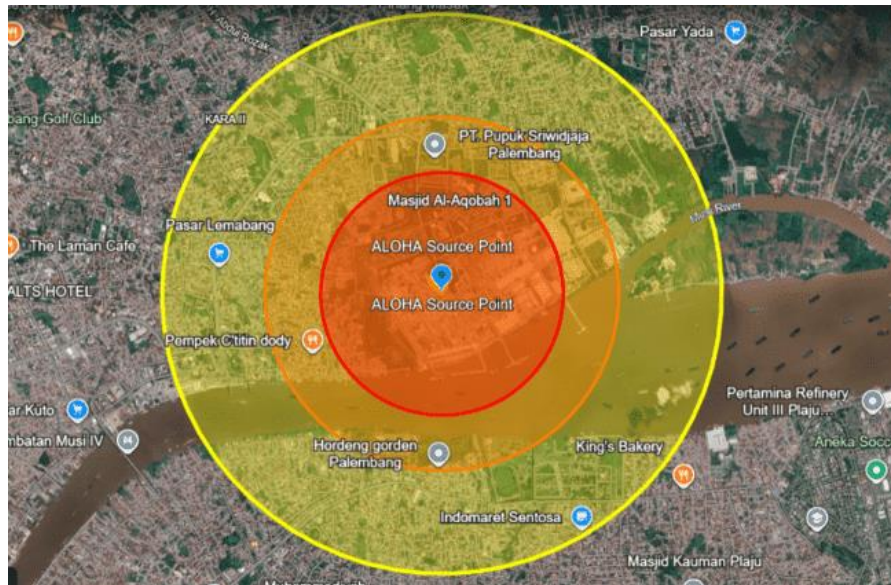


Figure 8. ALOHA Boiling Liquid Expanding Vapor Explosion (BLEVE) Map Plotting

Comparison of Elevation Effects on QRA Results

Overall simulation results demonstrated that leak hole elevation significantly affects consequence distribution patterns and hazard zone extents for toxic vapor cloud, flammable vapor cloud, and vapor cloud explosion scenarios. Low elevation leaks consistently produced wider impact areas due to: greater hydrostatic pressure generating higher release rates, mist pool formation causing gradual ammonia evaporation and wider horizontal dispersion, and higher momentum in horizontal direction causing gas to travel farther before diluting in the atmosphere.

Conversely, high elevation leaks showed: smaller hydrostatic pressure reducing outflow velocity, no mist pool formation so gas more rapidly disperses vertically, and higher initial dispersion position causing gas to more easily mix with upper air layers. Although local concentration near the source is higher at high elevation, the total affected area is narrower due to smaller released mass and faster dilution.

These findings have important implications for emergency response planning and safety system design. Low elevation leaks require wider evacuation area coverage and more extensive gas detection systems, while high elevation leaks require focus on rapid local concentration control around the tank. Both scenarios necessitate comprehensive mitigation through engineering controls (water spray curtains, containment dikes, emergency cooling systems) and administrative measures (routine inspections, operator training, emergency response procedures).

Risk Mitigation Strategies

Based on QRA analysis results, comprehensive mitigation steps are required to minimize risks from ammonia tank leakage. For toxic vapor cloud scenarios, mitigation focuses on early detection and dispersion control. PT Pupuk Sriwidjaja has provided water spray curtains around tanks that can help reduce evaporating ammonia gas cloud concentration through absorption processes. Combined with dike presence around tanks to contain liquid phase ammonia leaks in certain areas, the amount of ammonia evaporating into the atmosphere can be controlled. Installation

of ammonia-specific gas detectors connected to early warning alarm systems enables leaks to be immediately identified before reaching hazardous concentrations. For workers, availability of personal protective equipment such as self-contained breathing apparatus (SCBA) and ammonia-specific masks is absolutely necessary to reduce direct exposure risk.

For flammable vapor cloud scenarios, fire risk only emerges if ignition sources are present. Therefore, controlling potential fire sources around tanks becomes crucial. PT Pusri has prepared fire protection facilities in the form of fire extinguishers and hydrants placed not far from tanks. These facilities can be used to extinguish small fires before spreading more widely and prevent large-scale fires. Additionally, limiting high-risk activities around tanks is a step that must be maintained.

For vapor cloud explosion scenarios (overpressure), impacts are relatively small because they only reach yellow zones, but still potentially cause minor damage to surrounding facilities. Mitigation that can be done is maintaining facility layouts so no vital equipment exists within close radius to tanks and ensuring surrounding structures are sufficiently resistant to minor shock waves. In this case, dike presence around ammonia tanks also functions dually; besides containing liquid spills, dike structures can dampen part of small explosion energy or overpressure so impacts do not directly propagate to other facilities.

For BLEVE scenarios, one important mitigation step is maintaining tank wall temperatures to prevent excessive increases when fires occur in the vicinity. Around PT Pusri ammonia tanks, water curtains are already available that can be utilized as emergency cooling systems. However, water curtain positions are not very close to tanks, so their main function is more toward reducing ammonia concentration in air. With distances not directly attached to walls, their effectiveness in cooling tank surfaces becomes limited.

If tank ammonia leakage has occurred, rapid response through emergency response implementation is required, then continued with fire extinguishing efforts around tanks if fire potential exists. Emergency response is a series of planned activities conducted to address emergency situations due to work accidents, so resulting impacts can be minimized. The initial handling stage is sounding emergency sirens as danger signals for all workers. After that, workers are directed to assembly points through predetermined evacuation routes, ensuring that gathering points are outside potential ammonia tank leak impact ranges. Fire extinguishing around tanks may only be performed by authorized and trained parties, using fire equipment meeting standards. Subsequently, victim evacuation must be immediately implemented, followed by post-incident evaluation activities to assess incident causes and emergency response effectiveness that has been conducted.

At PT Pusri, Emergency Response Planning (ERP) has been prepared to anticipate possible explosions or tank leaks. This planning includes preventing fire emergence around tanks, supported by availability of fire extinguishing equipment such as fire extinguishers and hydrants. Control of explosive gas hazard potential is conducted by ensuring no activities that can generate flame sources, including strict prohibition of discarding cigarette butts or conducting open burning around tanks. Additionally, evacuation routes and assembly points have been clearly established to facilitate evacuation processes when emergencies occur. From the human aspect, implementing discipline toward work procedures involving heat (hot work) is very important to prevent spark occurrences potentially triggering explosions. With implementation of integrated emergency response and ERP systems, ammonia tank

leak management can be conducted faster, more directed, and effectively, so risks to workers, facilities, and surrounding communities can be minimized.

CONCLUSION

Leakage hole elevation significantly influences ammonia release characteristics and hazard zone extent for toxic, flammable, and explosion scenarios through fundamental fluid mechanics principles. Low elevation leakage (0,5 m) produces 87% higher release rate and approximately 47% larger hazard zones compared to high elevation (10 m) due to hydrostatic pressure differences quantitatively described by Pascal's law ($P = \rho gh$) and Torricelli's theorem ($v = \sqrt{2gh}$). The 10,5-fold difference in liquid column height creates 3,2 times higher discharge velocity and nearly doubled mass release rate, explaining the consistently broader hazard zones observed. For toxic vapor cloud, ERPG-3 zones reach 1,4 km versus 0,953 km; for flammable vapor cloud, LEL zones extend to 156 m versus 105 m; for vapor cloud explosion, 1 psi overpressure zones reach 168 m versus 114 m. BLEVE scenarios remain elevation-independent with thermal radiation zones extending to 2,2 km radius. Low elevation leakage presents higher risks due to mist pool formation, enhanced horizontal dispersion, and proximity to ground-level ignition sources and population exposure, all stemming from greater hydrostatic driving force. These quantitative findings with theoretical foundation enable optimized safety protocols including targeted gas detection placement, elevation-specific mitigation strategies prioritizing lower tank components, risk-informed facility layout planning, and enhanced emergency response procedures accounting for elevation-dependent release dynamics. Future research should investigate dynamic leakage scenarios with time-varying hole sizes, multi-point simultaneous leakages, and coupled CFD-consequence modeling for complex terrain and building interactions.

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AUTHOR CONTRIBUTIONS

Conceptualization, B.E.S., I.G.P., and A.H. Methodology, B.E.S., I.G.P., and A.H.; Software, B.E.S.; Validation, I.G.P, O.K., A.N.S., F.A., and A.H.; Formal Analysis I.G.P., A.N.S., and F.A.; Investigation, B.E.S., I.G.P., O.F.; Resources, I.G.P, O.K., A.N.S., F.A., and A.H.; Data Curation, B.E.S. and A.H.; Writing – Original Draft Preparation, B.E.S.; Writing – Review & Editing, B.E.S. and A.H.; Visualization, B.E.S.; Supervision, I.G.P, O.K., A.N.S., F.A., and A.H.; Project Administration, I.G.P, O.K., A.N.S.; Funding Acquisition, A.H.

CONFLICTS OF INTEREST

The authors declare no conflict of interest. This research was conducted as part of an academic practical work program without external funding or commercial interests that could influence the representation or interpretation of reported results.

REFERENCES

1. Ariq OA, Nurrahmadhanti BW, Kurniawansyah F, Mahfud M. Pra-Desain Pabrik Amonia Menggunakan Bahan Baku Batubara Melalui Proses Gasifikasi. *Jurnal Teknik ITS*. 2023;12(3):3-8. doi:10.12962/j23373539.v12i3.122536.
2. Novandhini DR, Mahfudz MA, Paskarini I. Risk Management in Work Activities at Ammonia Plant Fertilizer Production Industry. *The Indonesian Journal of Occupational Safety and Health*. 2020;9(2):196-204. doi:10.20473/ijosh.v9i2.2020.196-204.
3. Duong PA, Ryu BR, Song MK, Nguyen HV, Nam D, Kang H. Safety Assessment of the Ammonia Bunkering Process in the Maritime Sector: A Review. *Energies*. 2023;16(10):4012. doi:10.3390/en16104012.
4. U.S. Chemical Safety and Hazard Investigation Board. Hydraulic Shock: Anhydrous Ammonia Release at Millard Refrigerated Services, Inc. *Safety Bulletin*. Washington (DC): U.S. Chemical Safety and Hazard Investigation Board; 2015.
5. Tan W, Lv D, Guo X, Du H, Liu L, Wang Y. Accident consequence calculation of ammonia dispersion in factory area. *Journal of Loss Prevention in the Process Industries*. 2020;67:104271. doi:10.1016/j.jlp.2020.104271.
6. Nashira A, Nugrahani AP, Rahmah AU, Cahyono T. Quantitative Risk Assessment of Ammonia Release from Storage Tanks Using RISKCURVES Software. *Engineering Proceedings*. 2025;84(8):1-10. doi:10.3390/engproc2025084008.
7. Besiktas R, Baltaci H, Akkoyunlu BO. Simulation of the Jet Fire Using Atmospheric Dispersion Modeling (ALOHA): A Case Study of Natural Gas Pipeline in Istanbul, Türkiye. *Atmosphere*. 2024;15(7):833. doi:10.3390/atmos15070833.
8. Kumar S, Huang YS, Nagy Z, Reklaitis GV, Gonzalez M, Mort P. Semicontinuous Blending of Pharmaceutical Ingredients and the Impact of Process Parameters on the Blending Performance. *Processes*. 2024;12(7):1321. doi:10.3390/pr12071321.
9. Ge Y, Huang W, Li X, Yao J, Yang Q, Zhang C, et al. Numerical investigation on oil leakage and migration from the accidental hole of tank wall in oil terminal of pipeline company. *Process Safety and Environmental Protection*. 2024;184:1189-1200. doi:10.1016/j.psep.2024.02.063.
10. Herlambang A, Novendra RA, Supriyadi D, Saputra A, Fachlevi F. Analisis Risiko Kuantitatif Akibat Terjadinya Kebocoran Tangki Penyimpanan Amonia Pabrik PUSRI IIB. *Journal of Science and Applicative Technology*. 2023;7(2):89-96.
11. Skarsvag HL, Fyhn EH, Aasen A. Influence of ammonia-water fog formation on ammonia dispersion from a liquid spill. *Journal of Loss Prevention in the Process Industries*. 2024;92:105466. doi:10.1016/j.jlp.2024.105466.
12. White FM. *Fluid Mechanics*. 7th ed. New York: McGraw-Hill Science/Engineering/Math; 2010.
13. American Industrial Hygiene Association. *Emergency Response Planning Guidelines ERPGs*. Falls Church (VA): AIHA; 2022.
14. AIChE. *Vapor Cloud Explosions. Message for Manufacturing Personnel*. New York: American Institute of Chemical Engineers; 2011.
15. Laamarti EM, Heymes F, Birk AM. Consequences of Partial Vessel Failure in BLEVE and Liquid Full Fill Rupture Events. *Chemical Engineering Transactions*. 2024;111:331-336. doi:10.3303/CET24111056.