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RISK MODELING AND CONSEQUENCE ANALYSIS OF ACCIDENTAL AMMONIA EMISSIONS PROCESS SAFETY RISK ASSESSMENT OF UNINTENDED AMMONIA RELEASES

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ABSTRACT:

The Krishak Bharati Co-operative Limited, a government fertilizer plant, faces a variety of hazards due to its processing of numerous chemicals, including natural gas and hydrogen sulphide. To mitigate risks, KRIBHCO uses quantitative risk analysis (QRA) to estimate potential risks from hazardous scenarios and conducts consequence modelling using PHAST software. Recommendations for risk reduction are based on the analysis of individual and societal risk levels compared to unacceptable standards. Particularly in India's chemical sector, which sustains the country's largely agrarian population, quantitative risk analysis (QRA) is emphasized as a reliable technique for risk reduction. Because it processes a variety of chemicals, including hydrogen sulphide and natural gas, the government fertilizer factory Krishak Bharati Co-operative Limited confronts a number of risks. KRIBHCO uses PHAST software for consequence modelling and QRA to predict possible hazards from hazardous scenarios in order to reduce risks. The examination of society and individual risk levels in comparison to unacceptable criteria forms the basis of risk reduction recommendations.

KEYWORDS: Chemical release, HAZID, ETA, Individual risk, societal risk, Phast.

INTRODUCTION

Given its enormous population of 135 crores, India is a developing nation that primarily depends on agriculture for a living. Fertilizer use is essential for disease-free crop cultivation due to agriculture's vital role. But there are serious risks associated with the production process, including as handling hazardous chemicals and gasses in harsh environments. In the past, this has led to poisonous gas leaks, explosions, and fire incidents that put neighbouring residents, workers, livestock, and the environment at risk. Therefore, in order to put preventive measures in place, it is crucial to identify scenarios that could result in catastrophic catastrophes. The project's main objective is to evaluate such scenarios at KRIBCHO Ltd. in Hazira, calculating individual and societal risks while analysing their effects on people, property, and the environment both on and off site.

OBJECTIVE OF WORK

- To determine the risky situations in the plant that could have serious repercussions.to obtain the plant's metrics and data that are required for the risk assessment study, such as process conditions and weather data
- To identify potential causes by doing a fault tree analysis of the identified scenarios
- To simulate the identified scenarios using PHAST 7.2.7 software and determine the impact of the hazardous event both within and outside the plant
- To do probity analysis for the scenarios in order to ascertain the impact and harm inflicted onto individuals
- To conduct event tree analysis for every scenario in order to ascertain the frequency of occurrence and to analytically assess the individual and societal risk

LITERATURE REVIEW

Research on accidental ammonia emissions has focused extensively on consequence modeling, toxic dispersion analysis, quantitative risk assessment (QRA), and process safety management due to ammonia's toxic, corrosive, and flammable nature. Early studies by Kaiser et al. (1982) established the foundational understanding of atmospheric dispersion behavior of anhydrous ammonia following accidental releases. Their work demonstrated how release conditions influence ammonia cloud density and dispersion characteristics, which became essential for later consequence modeling studies.

Recent literature emphasizes advanced risk assessment methodologies integrating computational fluid dynamics (CFD), fault tree analysis, event tree analysis, and Bayesian networks. Khudhur et al. (2022) reviewed safety issues in industrial ammonia refrigeration systems and highlighted that traditional static risk assessment methods such as fault tree and bow-tie analyses remain widely used despite limitations in handling dynamic dependencies and cascading failures. The authors recommended more dynamic and integrated approaches for ammonia safety assessment in industrial facilities.

Several studies have investigated ammonia release scenarios in maritime and transportation applications due to the increasing use of ammonia as an alternative fuel. Duong et al. (2023) analyzed ammonia bunkering operations and identified toxic vapor dispersion as the dominant hazard associated with accidental releases. Their review synthesized findings from over 100 studies and emphasized the importance of consequence analysis, dispersion modeling, and emergency response planning in minimizing health impacts.

Similarly, Pocitarenco et al. (2025) conducted a systematic literature review on ammonia safety in marine fuel applications. The review discussed hazard identification techniques, ISO safety standards, and risk assessment frameworks for ammonia storage and transfer operations. The authors concluded that comprehensive QRA approaches are necessary for assessing accidental ammonia releases in ports and industrial facilities.

Jang et al. (2023) evaluated regulatory gaps associated with ammonia-fueled ships and emphasized the lack of standardized methodologies for assessing accidental ammonia release scenarios. Their findings highlighted the need for harmonized international regulations and improved consequence modeling techniques for toxic gas dispersion and exposure assessment.

Case-study-based investigations have also contributed significantly to ammonia consequence analysis research. Abdurrohman et al. (2024) performed quantitative risk assessment of ammonia dispersion and explosion scenarios in an ammonia plant using event tree analysis and dispersion modeling. The study demonstrated that ammonia leakage can expose nearby populations to concentrations exceeding safety thresholds, emphasizing the need for effective mitigation systems and emergency preparedness.

Masia et al. (2024) further expanded the field by assessing human health consequences associated with accidental ammonia releases from damaged storage tanks. Their study used advanced dispersion simulations and toxic exposure models to evaluate injury and fatality risks, reinforcing the significance of process safety management and protective design measures in ammonia handling systems.

OBJECTIVES OF THE STUDY

The main scope of the study is to carry out the QRA as per the Indian Standard (IS) 15656, Hazard Identification and Risk Analysis - Code of Practice, including identification, screening and ranking of various risk scenarios, consequence analysis of the various risk scenarios, and probabilistic assessment of risks, recommendation and preparation of reports and relevant drawing showing damage and risk contours.

The scope of the QRA is given below:

- Study and identify the hazards and loss of containment events
- Calculation of physical effects of accidental scenarios, which includes frequency analysis for incident scenarios leading to hazards to people and facilities (flammable gas, fire & smoke, explosion, overpressure and toxic gas hazards) and consequence analysis for the identified hazards covering impact on people and potential escalation.
- Individual risk quantification
- Societal risk quantification
- Hazard mitigation recommendations based on QRA
- The Indian standard IS 15656: Code of practice – Hazard Identification and Risk analysis to be adopted for this study.

The first step in preventing fires is to systematically identify hazards and evaluate risks. This proactive strategy is essential for reducing or eliminating fire hazards before they cause problems.

Techniques for Identifying Hazards:

Process Hazard Analysis (PHA) is the methodical analysis of processes to find possible explosion and fire risks. What-If Analysis, FMEA (Failure Mode and Effects Analysis), and HAZOP (Hazard and Operability Study) are common PHA techniques.

Evaluation of the probability of a fire and its effects on various locations and activities is known as fire risk assessment. Risk assessment takes into account potential fire spread methods, fuel availability, oxygen supply, and ignite sources.

Job Safety Analysis (JSA) is the process of analysing certain tasks to find fire risks related to both normal and non-routine work activities.

Incident investigation is the process of identifying recurrent risks and systemic flaws by learning from previous incidents, both internal and external.

Calculating the amount and properties of flammable materials at various locations in order to estimate the prospective fire's intensity and duration is known as fire load calculation.

Important elements assessed in a fire risk assessment are as follows:

- Hazardous material types and amounts
- Process parameters (pressure, temperature)
- Identification of the ignition source
- The possibility for fire to spread
- The effectiveness of fire safety precautions
- The effects of fire situations
- Critical equipment vulnerability
- Effects on the environment, property, and employees

RISK ASSESSMENT METHODOLOGY

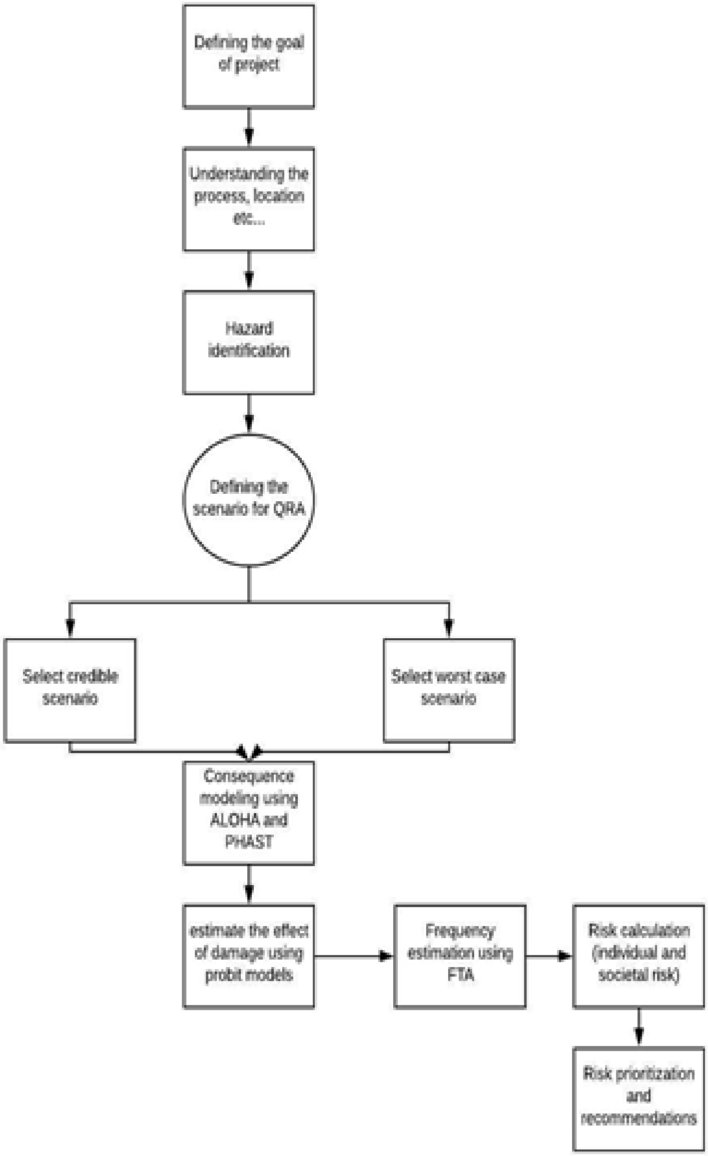

Figure 1: Adopted methodology for QRA study.

METHODOLOGY ADOPTED

The project for Quantitative Risk Analysis (QRA) at the KRIBHCO, Hazira facility encompasses several steps essential for assessing risks associated with the fertilizer plant located in Surat, Gujarat. Key steps include:

1. Data Collection: Gathering specific information about the facility, including the plant layout, equipment locations, loss of containment scenarios, process conditions, consequence modelling, equipment failure rates, meteorological data, onsite building details, surrounding population data, and risk criteria.

2. HAZID: Conducting a Hazard Identification (HAZID) session to assess potential release scenarios. This involves a team discussion focused on reviewing processes, storage areas, and operations to identify risks of hazardous material releases that may lead to fire, explosion, or toxic exposures.

The subsequent steps in the QRA process further include developing release scenarios, conducting consequence and impact analysis, performing frequency analysis, integrating risks with the acceptability triangle (ALARP), and providing recommendations based on risk acceptability.

Risk integration and results

Once the onsite/ offsite population data, consequence modeling results, likelihood calculations and weather data were collected, the information was combined to generate the final risk results, the following results were developed:

Individual Risk: Defined as the risk at a specific location to a single person/ individual to a hazard. The hazard can be a single incident, or a collection of incidents (e.g., the release scenarios developed for the Hazira facility.

Societal Risk: Defined as the risk to a group of people to a hazard. The hazard can be a single incident, or a collection of incidents (e.g., the release scenarios developed for the Hazira site). Thus, societal risk evaluated the scale of the incident in terms of the number of people that could be impacted from the hazard(s). Societal risk is expressed as the cumulative risk to a group(s) of people who might be affected by accidental release events. The calculation for societal risk uses the same consequence and frequency results as the individual risk calculation, but uses information about the number, geographical distribution, occupied building construction and occupancy levels of the population group(s) to determine the risk level.

PROCESS DESCRIPTION

The group of trainers will be selected from each site /location based on the locations as per Fig-1. 180 Employees will be nominated from different sites and GGI marketing team. Site Safety head and Site HR will identify the site teams to be nominated as train the trainers.

The ammonia plant consists of seven different units whose raw materials start with natural gas provided by ONGC. The steam reforming process consists of the following steps desulfurization, steam reforming, shift conversion, carbon dioxide removal, methanation, and ammonia synthesis and refrigeration system. The purpose of desulphurization is to remove Sulphur from the natural gas. Sulphur is poisonous for the catalyst used in Ammonia plant and hence its removal is essential. The chemical reaction for the desulfurization is shown below. The sulfur content can be reduced from 10 ppm to less than 0.25 ppm in this section.

$$RSH + H_2 = H_2S + RH \text{ (COMOX bed)}$$

$$H_2S + ZnO = ZnS + H_20 \text{ (zinc oxide bed)}$$

The steam reforming of hydrocarbon feedback to syn gas production is carried out in two catalyst reactions stages. The first stage, called primary reforming, produces a partially reformed gas containing approximately 10 % by vol. Of methane (dry basis) and in the secondary reformer this gas is further processed to achieve to methane content desirable for syn gas production approximately 0.3% by vol. (dry basis). Since the reaction is endothermic, the heat is supplied from natural gas from the synthesis loop. The outlet gases from the primary reformer with a methane content of about 10% in enter the secondary reformer at a temperature of 800 c. Followed by this section the CO is converted to carbon dioxide in the two-phase shift conversion reaction system (HT&LT). The gases coming out of the secondary reformer at a temperature of about 985 c are cooled in Waste Heat Boiler and enter high temperature shift converter at a temperature of 350c.

Followed by the shift conversion system, there is a carbon dioxide absorbing unit from the raw materials for urea is removed in this section and send to the urea plant. The gases leaving L.T. shift converter at around 221c are cooled to 94c and the unreacted steam is condensed and removed. Absorption is accomplished in two stages with lean, semi lean Ben field solutions consisting of potassium carbonate and di-ethanolamine as the main absorbent and vanadium pent oxide as a corrosion inhibitor. Rich Benfield solution from the bottom of the absorber at a pressure of about 28kg/cm2 is sent to the top of CO2 striper through hydraulic turbines.

The gases leaving CO2 absorber contains traces of carbon monoxide and carbon dioxide which are highly poisonous to synthesis catalyst in ammonia converter and hence these are converted to methane in methanation in the presence of Nickel catalyst at a temperature 285 to 305c. The reaction followed in
this step is as follows in the figure. At exit of methanation pure synthesis gas containing N2 and H2 in the ratio of 1:3 has a CO+CO2 contain of less than 1 PPM.

$$CO + 3H_2 = CH_4 + H_2O \text{ Exothermic}$$

$$CO_2 + 4H_2 = CH_4 + 2H_2O \text{ Exothermic}$$

The synthesis gas containing nitrogen and hydrogen in the volumetric ratio of 1:3 is compressed in a turbine driven centrifugal compressor from 28.5 kg/cm2 to 185 kg/cm2. The compressed gas is preheated by heat exchange with converter effluent and is passed over iron oxide catalyst where about 17 % ammonia is formed.

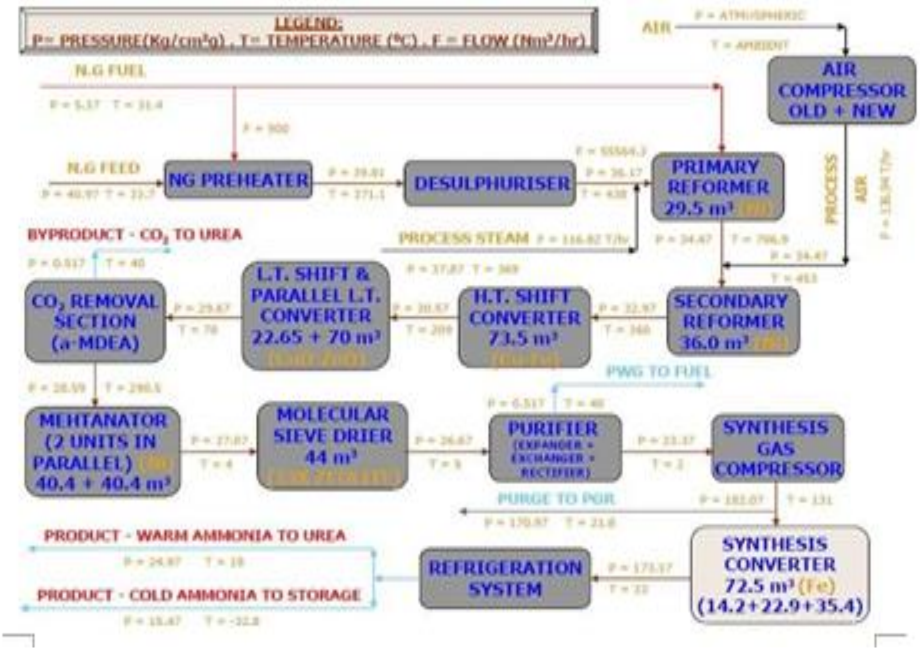

Figure 2: Process flow followed in KRIBHCO facility

RISK REPRESENTATIONS

The Individual Risk (IR) calculation for the Quantitative Risk Assessment (QRA) involves considering plant-specific location details and the population of personnel present in potential effect zones during accident scenarios. During the QRA study, employee presence probabilities were based on daily average population distribution. Key considerations included scenarios where exposure contours do not extend outside the establishment, such as in cases of flammable liquid spills within a bund, under the assumption that ignition does not occur. All potential outcomes of each scenario were analysed for creating a contour plot, which was overlaid onto a population map to identify individuals likely within each effect zone.

The CCPS guidelines for Consequence-Probability Quantitative Risk Assessments (CPQRA) offer a clear foundation for calculating individual risk, though certain assumptions are inherent in the QRA, including uniform wind distribution and effect zone delineations from the source of release for toxic substances and jet and pool fires. Conversely, scenarios involving Vapor Cloud Explosions (VCE) and flash fires require representation of ignition source-based contour zones, considering unknown distances and delayed ignition times.

To calculate individual risk at specific locations, the IR values are summed across all points. The analysis assumes a 100% probability of fatality in the effect zones, recognizing that this assumption is not universally valid; the contour distances represent the threshold where 100% fatality is deemed possible, as inferred from probit models. The formula utilized, $IRx,y = \sum IRx,y,i$ with $IRx,y,i = fiPfi$, calculates average individual risk based on total population presence, which can misrepresent actual risk by using total population data rather than just those exposed.

Contouring for scenarios reflects outcomes, plotting 100% fatality distances from explosion or fire sources, with the largest contour associated with VCE, succeeded by flash fire and then jet fire within the inner contour circle, as illustrated in accompanying figures.

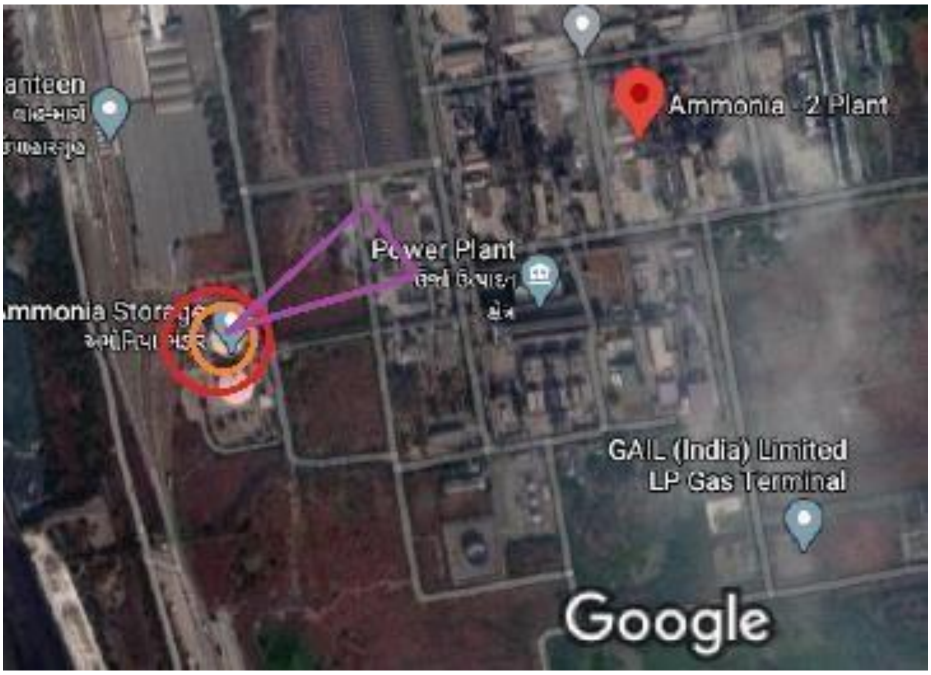

Figure 3: Risk contour based on 100 % fatality for scenario 8.

CONCLUSION

This QRA was completed to address risks of the existing ammonia plant to onsite employees and the offsite community from accidental releases from the ammonia production, storage and tanker loading operations. Different hazards resulting in accidents are identified for the facility, Consequence assessment has been carried out for the identified fire, explosion and toxic release scenarios. All possible scenario outcomes were studied and analyzed in the study using PHAST v7.2.7 software. The damage criteria for different radiation levels and overpressure levels are presented in the report and the damage modeling for explosion and fire was carried out using the concepts of probity models as presented in CCPS guidelines for CPQRA, and for toxic release scenarios the probity model was directly analyzed from the software, the graphical results of the same has been given in ANNEXURE B of this report.

Since there is no specific risk criteria published for our country, in this QRA with reference to **IS-15656,** the level of risk was compared to the risk criteria published by the Health and Safety Executive of the United Kingdom (UK-HSE), which is a widely accepted international authority, and their criteria are utilized by many organizations globally for existing hazardous industries to justify the hazards and risks for similar operations and industries. As it can be noted from the risk calculations and the FN curve, the individual risk related to the cement type double containment vertical ammonia storage tank are not in the red region, i.e., one of the scenarios has risk level in the ALARP region which implies control measures must be applied to further try and reduce the risk to acceptable region, whereas another scenario related to the storage tank is already in the acceptable region in terms of risk. For the storage area onsite personnel, the risk is in the As Low as Reasonably Practicable (ALARP) range, at this risk level prudent risk reduction measures should be considered.

The major risk reduction and mitigation measures must be applied in the reforming section and compressing section of the ammonia plant, which is evident from the risk values provided in the tabular results. The FN curve also supports the above presented statement. The suggestions provided in this report are based on technical knowledge, standard legislations and codes of practice given by globally recognized safety authorities and organizations, the recommendations given has been divided in three sections for reducing to acceptable region or maintaining the risk in the acceptable region. The three sections of recommendations are applicable only to those particular region risk values as per the calculated results.

FUTURE SCOPES

- Develop dynamic and AI-based risk models for real-time ammonia leak prediction.
- Improve CFD and dispersion modeling under varying weather and terrain conditions.
- Study domino effects involving fire, explosion, and toxic releases together.
- Integrate human reliability and safety culture into process safety assessments
- Use IoT and smart sensors for continuous leak monitoring and early warning systems.
- Assess environmental impacts of ammonia emissions on air, water, and soil.
- Explore safety challenges of green ammonia and ammonia-fueled systems.

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