The ammonia release hazard and risk assessment: A case study of urea fertilizer industry in Indonesia

A S Danasa¹, T E B Soesilo¹, D N Martono¹, A Sodri¹, A S Hadi², and G T Chandrasa²
¹School of Environmental Science, Universitas Indonesia, Jakarta 10430, Indonesia.
²Agency for Meteorology, Climatology, and Geophysics, Jakarta 10720, Indonesia.

E-mail: soesilo@indo.net.id

Abstract. Ammonia is a raw material of fertilizer, refrigerant, and other commercial cleaning products which commonly stored in a large capacity. The higher storage capacity, the higher risk possibly occurs impacted to the population and environment. The study aims to provide a modeling of ammonia release scenarios, escape from the storage facility, Urea Fertilizer Industry X, located in Indonesia. This model is utilizing Area Location Hazardous Atmosphere (ALOHA) software to forecast the threat zone of ammonia release scenario and QGIS to overlay and spatial analysis. The result shows that the incident causes a significant impact on the area of 41.7 km² and potentially threaten a massive scale of the inhabitant with higher evacuation factor (Ef), lower affected population (Ap). The risk determined by estimated probability and consequence considered as high risk, therefore, besides the main aim of establishing an emergency response plan, this study could also be used as a reference in risk evaluation of chemical release.

Keywords: ammonia release, gas dispersion, risk assessment, toxic.

1. Background
The most common alkaline gas on the atmosphere, called ammonia, is significantly contributing to the neutralization of various processes that occur in the atmosphere [1]. Ammonia has used in many sectors of industries (Anhydrous Ammonia/synthetic). It is a toxic and corrosive agent that could threaten the health of humans and the environment [2], where the air, water, and soil possibly threatened in case of uncontrolled ammonia release occur. Ammonia threatens the atmosphere as ammonia vapor instigated by an organic material decomposition, cattle manure, soil-applied fertilizer; gas ventilation, leakage or spill during the synthetic industrial process, production, transportation, failure in cooling/refrigeration equipment; liquid waste; coal and wood firing; and as result of volcanic activity. Ammonia contaminates the water through the leftover of waste treatment facility, waste of process, run off of fertilizer pitch, and livestock area. Ammonia defects the soil through the application of either natural or synthetic fertilizer, degradation of cattle manure, decaying of organic materials, and by indirectly fixation of nitrogen [3].

Ammonia has the exposure limit of Time Weighted Average (TWA) 25 ppm (18 mg/m³) and Short Term Exposure Limit (STEL) 35 ppm (27 mg/m³); it is a colorless gas having an overpowering smell and suffocating effect; causes health effect if exposed to human such as irritation to eye, nose and throat; dyspnoea (breathing difficulty), wheezing, chest pain; pulmonary edema; frothy pink sputum; skin burns, and vesiculation; the exposure occur from liquid ammonia is likely to cause a freeze

³To whom any correspondence should be addressed (jacky.mucklow@iop.org)
burn/frostbite; it is corrosive to copper and galvanic [4]. This gas could liquefy under pressure, where it commonly sent to the consumer in the form of liquified compression ammonia gas. It also liqufied by reducing its temperature down to -33°C, particularly for raw material of fertilizer and refrigerant cold storage industry.

As a raw material, anhydrous ammonia commonly stored in a vast volume; consequently, this could increase the risk of chemical release where it could initiate by a human error, lack of training, substandard production, and lack of maintenance and inspection program [5]. The incident is also possible to suffer the surrounding area with a certain level of toxicity, depending on its level of dispersion where it determined by a calculation of the release rated [6]. Henceforth, the risk could be escalated to be a catastrophic event that the impact could be as much as the population, location characteristic, meteorological factors, and geographical features [5]. Because of its soluble characteristic in water as well as toxic to aquatic biota, the exposure of ammonia release could cause extensive ecological damage [7].

This study develops a model by extending Orozco et al., 2019 [8], which calculated the effect of an ammonia release incident in order to estimating the consequence as well as to predict the number of people being affected; while, this paper expands it in determining the level of risk (low, moderate and high) of an ammonia release scenario. The risk is acceptable if it is in an acceptable area; the risk must be reduced if it is in an unacceptable area; procedures must be complied with if the risk in the ALARP (As Low as Reasonably Practicable) region, which represents a moderate risk area. By calculating the consequence, it expected that the prevention and mitigation of chemical release emergency conditions could be established appropriately to minimize the impact of such a disaster.

2. Method

The law of chemicals dispersion determined by its physical properties, the stability of the atmosphere, and the conditions of the release source [9]. Ammonia could behave like a heavy gas that has a deadly higher risk since it is longer exposure duration compared to other lighter gases [10]. The highest risk of ammonia release incident is a toxic vapor cloud, while it does not represent a serious flammability hazard (mixtures of air and ammonia containing from 15% to 28% ammonia vapor by volume will ignite when sparked, or exposed to temperatures exceeding 651°C) [8]. This study utilizes ALOHA Software to forecast the toxic threat zones and QGIS to overlay and spatial analysis; 6 stages of research were used (figure 1). By utilizing the threat zone area and the population density, the affected population can be estimated as the following form:

\[
Ap = (Tz \times Ds) - (Ef \times Tz \times Ds)
\]  

\(Ap\): Affected Population  
\(Tz\): The AEGL-3/Red Zone  
\(Ds\): Density  
\(Ef\): Evacuation factor

The parameter of evacuation factor that is a level of emergency preparedness procedure of the inhabitants in the event of a real disaster occur, includes: (1) Personnel and Organisational Structure; (2) Standard Operation Procedure during emergency situation; (3) Emergency Drills and Exercises; (4) Emergency Equipment; (5) Communication System. They weighted by utilizing the scoring method.

At the end stage of the research, the risk shall determine by calculating the probability and consequence arise by the worst scenario of the ammonia release incident. The risk metric provides guidelines for prioritizing and assessing the acceptability of risk concerning risk criteria. The general form of the risk equation shall be as follows:

\[
\text{Risk} = \text{Probability} \times \text{Consequence}
\]
2.1. Identification of Location Characteristic
The subject of study is an ammonia storage facility located in Urea Fertilizer Industry X, Industrial Area Y, Indonesia. The industry employs 1,133 workers with an occupied area of 510 Ha, adjacent to 8 other industries (most of them are petrochemical), housing area (4 villages), educational facilities, and other public facilities. Based on statistical data, this area has a density of 1,321 inhabitants/km$^2$ [11]. This research location is one of the eight rice barns in Indonesia; therefore, maintaining the sustainability of this facility means to assure national food security.

2.2. Identification of Atmospheric Characteristic
The significant factors affecting the dispersion of gas clouds are the speed and direction of the wind and atmospheric turbulence [12]. Stability is the property of the low-lying atmosphere that governs the vertical movement of air, the tendency of the atmosphere to resist or enhance vertical motion, and thus turbulence. ALOHA uses the Pasquill-Gifford-Turner scheme consisting of six stability classes based on five surface wind speed categories, three types of daytime solar radiation, and two types of nighttime cloud cover [13], as shown in table 1 as follows:

| Wind Speed$^a$ (at 10 m) (m/s) | Day$^b$ | Night Cloud Cover |
|-------------------------------|--------|------------------|
|                               | Solar Radiation | >50% | <50% |
| Strong$^c$                    |                |      |      |
| <2                            | A               | E    | F    |
| 2-3                           | A-B             | E    | F    |
| 3-5                           | B               | E    | F    |
| 5-6                           | B-C             | D    | D    |
| >6                            | C               | D    | D    |

$^a$ Wind speed measured at 10 m above ground  
$^b$ A, very unstable; B, moderately unstable; C, slightly unstable; D, neutral; E, slightly stable; F, stable  
$^c$ Solar altitude greater than 60° on a clear day  
$^d$ Solar altitude between 60° and 35° on a clear day  
$^e$ Solar altitude between 15° and 35° on a clear day

Solar radiation plays a large role in atmospheric stability. Therefore two different scenarios (day and night) were considered in this study to model the dispersion of ammonia. The weather data refers to the ERA5 Reanalysis Datasets from European Centre for Medium-Range Weather Forecast (ECMWF) [14]. This dataset describing the recent history of the atmosphere from 2008 until 2018 of the location, with the summary of data, as shown in table 2 as follows:
| Weather Data (2008-2018) | Day (1.00 p.m.) | Night (1.00 a.m.) |
|-------------------------|-----------------|-------------------|
| Wind Speed<sup>a</sup>  | 2.7 m/s         | 1.6 m/s           |
| Wind is from<sup>b</sup> | NE              | NNW               |
| Humidity<sup>a</sup>    | 66 %            | 88 %              |
| Air Temperature<sup>a</sup> | 30.7°C         | 24.8°C            |
| Stability Class         | A               | E                 |

<sup>a</sup>The average of data

<sup>b</sup>The highest percentage of data

2.3. Determining the Worst-Case Scenario

Based on the Failure Rate and Event Data for use within Risk Assessments of The Chemicals, Explosives and Microbiological Hazardous Division 5 (CEMHD5), Health & Safety Executive (HSE), the highest failure rate of large vessels is $2.5 \times 10^{-3}$ with a leak hole diameter of 300 mm where the leakage occurs due to deteriorated of component integrity, corrosion or lack of maintenance and inspection [15]. The release source scenario is shown in table 3 as follows:

| The leak from a hole in a vertical cylindrical tank | Hole at bottom |
|----------------------------------------------------|----------------|
| Tank Capacity                                      | 10,000 MT      |
| Tank Diameter                                      | 32,004 meters  |
| Tank Length                                        | 18,313 meters  |
| State of Chemical                                  | Tank Contains Liquid |
| Internal Storage Temperature                       | -33°C          |
| Chemical Mass in Tank                              | 60%            |
| Circular Opening Diameter                          | 300 mm         |
| Opening is                                         | Bottom of Tank |

Source: Secondary Data of Urea Fertilizer Industry X

3. Result and Discussion

The results of the modeling are ammonia escaped from the tank (not burning) as a mixture of gas and aerosol (two-phase flow). Ammonia is one of the pollutants that is lighter than air, but it behaves as a dense gas because it could form an aerosol and requires a longer dispersion time compared to other pollutants so that it tends to be closer to the ground due to the effect of gravity [10].

3.1. Human Health Risk Assessment

The consequences of the toxic effect referred to the Acute Exposure Guideline Level (AEGL), which represent threshold exposure limits for the general public; has multiple exposure limit from 10 minutes (min) to 8 hours (h). Three levels – AEGL-1, AEGL-2, and AEGL-3 – are developed for each of five exposure periods (10 min, 30 min, 1 h, 4 h, and 8 h) and are distinguished by varying degrees of severity of toxic effects. By referring to Summary of AEGL Values for Ammonia in Acute Exposure Guideline Levels for Selected Airborne Chemicals: Volume 6 (table 4), people who are exposed to AEGL-3 potentially suffer lethality; AEGL-2 potentially suffer disabling (irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape); AEGL-1 potentially suffer non-disabling (notable discomfort, irritation, or specific asymptomatic non-sensory effects) [16]. Ammonia causes discomfort at a general level with a concentration of 150-200 ppm; significant irritation at a
concentration of 400-700 ppm; serious health effects at 500 ppm; and death within a few minutes at 2000 ppm [17].

### Table 4. Summary of AEGL Values for Ammonia.

| Classification | 10 min | 30 min | 1 h  | 4 h  | 8 h  | End Point (Reference)                  |
|----------------|--------|--------|------|------|------|----------------------------------------|
| AEGL-1 (nondisabling) | 30 ppm | 30 ppm | 30 ppm | 30 ppm | 30 ppm | Mild irritation (MacEwen et al., 1970) |
|                | (21 mg/m³) | (21 mg/m³) | (21 mg/m³) | (21 mg/m³) | (21 mg/m³) |                                       |
| AEGL-2 (disabling)   | 220 ppm | 160 ppm | 110 ppm | 110 ppm | 110 ppm | Irritation: eyes and throat; urge to cough (Verberk, 1977) |
|                | (154 mg/m³) | (112 mg/m³) | (77 mg/m³) | (77 mg/m³) | (77 mg/m³) |                                       |
| AEGL-3 (lethal)     | 2,700 ppm  | 1,100 ppm | 550 ppm | 390 ppm | 390 ppm | Lethality (Kapeghian et al., 1982; MacEwen & Vernot, 1972) |
|                | (1,888 mg/m³) | (769 mg/m³) | (385 mg/m³) | (273 mg/m³) | (273 mg/m³) |                                       |

Source: National Academy of Sciences, 2007

Figure 2(a) display threat zone on a daytime; figure 2(b) display threat zone on nighttime; table 5 shows the range of dispersion for each time. The biggest impact/farthest exposure radius occurs on nighttime, with AEGL-3 zone: 6.1 km; AEGL-2 and AEGL-1 zone are greater than 10 km. On daytime, AEGL-3 zone: 3.1 km; AEGL-2 zone: 8.9 km; and AEGL-1 zone is greater than 10 km. This result parallel with Inanloo (2016) that releases during the daytime would have relatively smaller impact areas in comparison with those that occur at nighttime [18]. In the daytime, strong solar radiation warms the ground and the low-lying air, and then the warm air rises to generate eddies and high-level turbulence. This unstable atmosphere enhances vertical mixing and turbulence so that the gas cloud will be dispersed quickly and homogenous. In contrast with the nighttime, when the air temperature increases with height, buoyancy forces act to inhibit vertical mixing creating a highly stable atmosphere.

**Figure 2(a). Threat Zone on daytime**  
**Figure 2(b). Threat Zone on nighttime**
Table 5. Range of Dispersion

| Dispersion Model                  | Daytime    | Nighttime   |
|-----------------------------------|------------|-------------|
| AEGL-3/Red Zone [1100 ppm; 60 min]| 3.1 km     | 6.1 km      |
| AEGL-2/Orange Zone [160 ppm; 60 min]| 8.9 km     | greater than 10 km |
| AEGL-1/Yellow Zone [30 ppm; 60 min]| greater than 10 km | greater than 10 km |

Reflecting figure 3(a), 3(b), 3(c), and 3(d) (QGIS-overlay), the incident potentially impacts 41.7 km² area if it occurs at nighttime and 6.8 km² if occur in the daytime.

Figure 3(a). Based on QGIS-overlay, the dispersion of ammonia on daytime potentially impacts to 4 villages (6.8 km² area).

Figure 3(b). By considering the highest percentage of wind is from the northeast (NE) to southwest (SW), then the potential threatened areas are Employee Housing of Urea Fertilizer Industry X; Public Housing 1 & 2; Educational Facility; Industrial Area Z; and Highway.
Figure 3(c). Based on QGIS-overlay, the dispersion of ammonia on nighttime potentially impacts to 16 villages (41.7 km² area).

Figure 3(d). By considering the highest percentage of wind is from north-northwest (NNW) to south-southeast (SSE), then the potential threatened areas are most of the Urea Fertilizer Industry X (Industrial Area Y) and Industrial Area Z; Public Housing 3, 4, & 5; and Highway.

After acquiring the affected area, the next stage is calculating the evacuation factor and affected people. The affected population is estimated by 55,086 - (55,086 x Ef) inhabitants during the nighttime and 8,983 - (8,983 x Ef) inhabitants during the daytime (table 6). By considering the evacuation factors, the affected population determined, as seen in table 7. A higher evacuation factor results in the lower affected population.
Table 6. Affected Area and Population.

| Time                | Daytime | Nighttime | Unit       |
|---------------------|---------|-----------|------------|
| Red Zone Area       | 6.8     | 41.7      | km^2       |
| Density             |         | 1,321     | inhabitants/km^2 |
| Possibly Affected Population | 8,983 | 55,086     | inhabitants |
| Evacuation Factor   | Ef      |           | %          |
| Evacuated Population| 8,983 x Ef | 55,086 x Ef | inhabitants |
| Affected Population | 8,983 x Ef | 55,086 - (55,086 x Ef) | inhabitants |

Table 7. Affected Population.

| Evacuation Factor | Affected Population on Daytime (inhabitants) | Affected Population on Nighttime (inhabitants) |
|-------------------|---------------------------------------------|-----------------------------------------------|
| 100%              | 0                                           | 0                                             |
| 75%               | 2,246                                       | 13,771                                        |
| 50%               | 4,491                                       | 27,543                                        |
| 25%               | 6,737                                       | 41,314                                        |
| 0%                | 8,983                                       | 55,086                                        |

3.2 Determining the Risk Level

The Probability (which is estimated by the highest failure rate of large vessels is 2.5 x 10^{-3} (minor type) with a leak hole diameter of 300 mm) expressed in terms of frequency as several events occurring during a specific timeframe. This frequency of 2.5 x 10^{-3} will be expressed as 0.0025 failures per year. The event frequency is associated with probability by following table 8. It means that the frequency of 2.5 x 10^{-3} can be classified as a moderate level with a statistical range of 0.001 to 0.01 or 1 x 10^{-3} to 1 x 10^{-2}. The consequence is expressed as a numerical value or characterized by a consequence category associated with the severity of potential fatality, serious injury, medical treatment or first aid that may result from such an ammonia release event. The consequence criteria showed in table 9.

Table 8. Probability Criteria

| Possible Qualitative Rank | Annual Failure Probability or Frequency |
|---------------------------|-----------------------------------------|
| Very high                 | >0.1                                    |
| High                      | 0.01 to 0.1                             |
| Moderate                  | 0.001 to 0.01                           |
| Low                       | 0.0001 to 0.001                         |
| Very low/Remote           | <0.0001                                 |

Source: API 580

Table 9. Consequence Criteria

| Description | Health Consequence |
|-------------|--------------------|
| Catastrophic| A large number of fatalities |
| Major       | Single fatality    |
| Serious     | Serious injuries   |
| Significant | Minor injuries     |
| Minor/      | First-aid injuries/ |
| insignificant| No significant     |

Source: API 580

The calculated risk assigned to the boxes on the risk matrix as high, medium, and low (figure 4); the risk level, as shown in Table 10, is calculated as high risk (3E), which represent the moderate level of probability and very high level of consequence. The risk at these criteria shall be reduced to the ALARP region.
Table 10. Risk Level

| Probability | 2.5 x 10^{-3}  |
|-------------|-----------------|
| Consequence  | Large number of fatalities (Catastrophic) |
| Risk        | 3E              |

4. Conclusion

Based on ALOHA modeling, the worst-case scenario occurs in the nighttime, because a highly stable atmosphere inhibits vertical mixing of air and pollutant cloud. The risk considered as high risk; it expected that the prevention and mitigation of chemical release emergency conditions could be established appropriately to reduce the risk of this scenario.

5. References
[1] Felix E P, Cardoso A A 2004 Atmospheric Ammonia: Sources, Transformation, Sinks, and Methods of Analysis Quim 27(1) 123–30
[2] Kwak D, Lei Y, Marc R 2019 Ammonia gas sensors: A comprehensive review Nov;204(March):713–30
[3] Agency for Toxic Substances and Disease Registry 2004 Toxicological Profile for Ammonia (September):269
[4] NIOSH 2018 NIOSH Pocket Guide to Chemical Hazards
[5] Anjana N S, Amarnath A, Harindranathan Nair M V 2018 Toxic Hazards of Ammonia Release and Population Vulnerability Assessment using Geographical Information System J Environ Manage Mar;210:201–9
[6] Namboothiri N V, Soman A 2018 Consequence assessment of anhydrous ammonia release using CFD-probit analysis. Process Saf Prog Mar 24
[7] US EPA 2001 Hazards of Ammonia Releases at Ammonia Refrigeration Facilities (Update) 1–8
[8] Orozco J L, Van Caneghem J, Hens L, González L, Lugo R, Díaz S, et al 2019 Assessment of an ammonia incident in the industrial area of Matanzas J Clean Prod Jun;222:934–41
[9] Tan W, Du H, Liu L, Su T, Liu X 2017 Experimental and numerical study of ammonia leakage and dispersion in a food factory. J Loss Prev Process Ind May;47:129–39
[10] Khan F I, Husain T, Abbasi S A 2001 Safety Weighted Hazard Index (Swehi). A New, User-Friendly Tool for Swift Yet Comprehensive Hazard Identification and Safety Evaluation in Chemical Process Industries. Process Saf Environ Prot. 79(2):65–80
[11] Regency B-S of 2018 Karawang Regency in Figures
[12] Inanloo B, Tansel B 2015 Explosion Impacts During Transport of Hazardous Cargo: GIS-Based Characterization of Overpressure Impacts and Delineation of Flammable Zones for Ammonia
Acknowledgment

This work financially supported by the Universitas Indonesia through PITMA B (International Indexed Publication for Master Students) funding program in the 2019 fiscal year.