ASSESSMENT OF THE HUMAN AND ENVIRONMENTAL IMPACT OF AN AMMONIA INCIDENT IN THE INDUSTRIAL AREA OF MATANZAS (CUBA)

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Abstract

A predictive study is described of a virtual ammonia release accident from tanks in the industrial area of Matanzas, and its effect on the population and in the environment. Climate data of the study area were characterized using the ALOHA software (*Area/ Locations of Hazardous Atmospheres*) which entails different scenarios to estimate effects. Predictions are made for three scenarios: "Toxic Vapor Cloud", "Flammable Area" and "Vapor Cloud Explosion". The results show that the worse scenario is the toxic cloud of ammonia affecting a vast area with a dense population and causing environmental damages. Under this scenario 294 fatalities should be expected.

Keywords: atmospheric pollution, ammonia, toxic cloud, industrial risk

1. Introduction

Agenda 21 (UNCED, 1992) defines cleaner production as "the permanent application of a preventive and integrated environmental strategy for processes, products and services in order to increase efficiency and reduce risks to human populations and the environment". This concept entails the importance of predictive risk studies for the chemical industry.

This sector faces a high potential risk as a result of its processes, and the storage and transfer of hazardous materials. The storage of high volumes of hazardous substances requires particular attention in risk studies.

Large stocks of chemicals with a high potential risk near densely populated areas demand an assessment of the risk and preparedness for major accidents. The prediction necessitates knowledge about the hazard to properly plan emergency actions and to optimize the safety of the installation.

As a result of emissions of hazardous pollutants and explosions industrial accidents affect both the environment and human health (Nolan, 2011).

It is imperative assessing and analyzing to which extent a particular region might be affected by an industrial accident. This will facilitate the preparation of prevention plans, the training of the industry personnel, and the information for the citizens.

In 1990, an accidental release of 4 tons of ammonia in the Cuban city of Matanzas caused six deaths, while more than 400 people were poisoned. This incident demonstrated the need for a predictive study forecasting, attitudes during a massive release of ammonia and the extent to which the population might to be affected.

This study predicts the environmental and human effects of a theoretical but realistic ammonia release in the industrial zone of Matanzas. The results obtained will allow the company to analyze the feasibility of the permanence of the ammonia tanks.

2. Materials and methods

To define the natures and calculate the extent of a possible release of ammonia on the population of Matanzas and its surroundings, a 5 steps approach with 3 scenarios was applied are shown in figure 1.

Figure 1. Research rationale

2.1 Characterization of the area and the installation under study

Figure 2 and Table 1 show the characteristics of the emission source and the territory of the city of Matanzas. The city of Matanzas has 138 303 inhabitants and is located 100 km from Havana, capital of the country. The location of the emission point and the evaluation points are also presented in figure 2. Three points of concern were identified, corresponding with high risk, both from an occupational and an urban population at large point of view.

Esc 1:100 000

Figure 2: Study area. The dotted lines indicate the geographical limits of points 2 and 3 (Jose Luis Dubrock and Versailles neighborhood)

Table 1: Source and assessment point characteristics

Location	Distance from the source (m)	Official Name	Characterization
Source	0	Ammonia tanks	Four ammonia tanks, carbon steel, with capacity of 120 t each Operating Pressure=12–14 kg/cm ² . Maximum pressure = 14 kg/cm ² .
Point 1	50	Rayonitro Facilities	Offices & workers restaurants. Maximum 45 people present.
Point 2	1700	José Luis Dubrock Neighborhood	First possible affected community, 1433 inhabitants
Point 3	2600	Versalles Neighborhood	Second possible affected community, 20 640 inhabitants. Hospitals in this area: 3 Schools: 4

2.2 Weather variables and climatology

The climatological characterization uses weather parameters which affect the spread of the pollution cloud. These parameters are based on data from 2004 to 2013. The data are provided by the Institute of Meteorology of the province of Matanzas under the Ministry of Science Technology and Environment (CITMA) (Moya, 2013) and processed statistically using the program Statgraphics Plus 5.1.

The variables taken into account for this study are: cloudiness, air temperature, relative humidity, speed and direction of the wind.

2.3 ALOHA software and the of scenarios under study

The Area Locations of Hazardous Atmospheres (ALOHA) software is used to forecast the impacts of an ammonia release incident. ALOHA was developed by the National Jointly Oceanic and Atmospheric Administration (NOAA) and the Environmental Protection Agency (EPA) of the United States. ALOHA is recognized by the Ministry of Science, Technology and Environment of Cuba (CITMA) as the advised tool for this type of studies. This computer program predicts the amounts of chemicals released in the atmosphere through of pipes, tanks and other infrastructure, during explosions, or other main operation incidents (Tseng et al., 2012).

A dataset of the physical properties of more than a thousand chemicals is based on the DIPPR collection (Department of Chemical Engineering of Brigham Young University for the Design Institute for Physical Property Data, of the American Institute of Chemical Engineers) is part of the basic data. ALOHA models the geographic zone

within which a particular hazard (toxicity, flammability, thermal radiation, or overpressure) is predicted to exceed the preset Level of Concern (LOC) at defined periods following a release.

The software uses models to estimate the movement and dispersion of the chemical cloud, and includes a set of scenarios as fire, explosion and toxic gas dispersion. Table 2 provides a summary of the different sources and scenarios that are modeled by ALOHA.

Table 2: ALOHA sources and scenarios, (User's Manual ALOHA, 2013 and NOAA Technical Memorandum NOS OR&R 43, 2013).

Source	Toxic Scenarios	Fire Scenarios	Explosion Scenarios
Direct			
Direct Release	Toxic Vapor Cloud	Flammable Area (Flash Fire)	Vapor Cloud Explosion
Puddle			
Evaporation	Toxic Vapor Cloud	Flammable Area (Flash Fire)	Vapor Cloud Explosion
Burning (Pool Fire)		Pool Fire	
Tank			
Not Burning	Toxic Vapor Cloud	Flammable Area (Flash Fire)	Vapor Cloud Explosion
Burning		Jet Fire or Pool Fire	
BLEVE (Boiling liquid expanding vapor explosion)		BLEVE (Fireball and Pool Fire)	
Gas Pipeline			
Not Burning	Toxic Vapor Cloud	Flammable Area (Flash Fire)	Vapor Cloud Explosion
Burning (Jet Fire)		Jet Fire	

To assess the risk of an ammonia release three aspects are considered: Toxic Vapor Cloud, Flammable Area, and Vapor Cloud Explosion. The information provided to the software as the magnitude of the release, the container capacity and the other related emissions were taken from the characterization made by the plant.

ALOHA provides results on:

1) Threat zones plots and footprints: Provides a map indicating the areas at risk (toxicity, flammability, thermal radiation, or damaging overpressure). When LOCs are exceeded in these areas, threats to people and property are calculated.

2) Threat at point: A graph showing the variation of the concentration over time at a specific point of interest in or around the threat zone

3) A text summary: Provides scenario information including the physical properties of the selected chemical and describes the threat zone and the selected points. This allows to verify at any time the values entered into ALOHA, and to review the results of the program.

2.4 Human health risk assessment

Estimating the level of damage caused by a hazardous agent necessitates the quantification of the exposure in terms of the intensity, duration of exposure and consequences of effect (Hui and Guoning, 2012). This allows calculating the estimated exposure (dose) which can be compared with health guidelines or standards to determine the probability of damage of an exposed population or an individual. Criteria can be used to determine dose levels that result in consequences for vulnerable groups (children, diseased persons, elderly).

Probits exist for almost any hazardous agent, but are typically available for thermal radiation, toxic gas and blast overpressure effects. Probit functions have been developed for NH_3 , SO_2 , and HF. Probit equations for gasses are described as (Lees, 2005):

$$Y = k_1 + k_2 \ln(C^n xt) \quad (1)$$

In which;

Y= probit value; C = (hazard) concentration (ppm); t = time of exposure in minutes and n, K_1 , K_2 constants, which depend on the substance type

3. Results and discussion

3.1. Climate characterization in the area under study

Climate is influenced by both physical and geographical conditions. The area under study is located in the tropics. The climate in Cuba is also influenced by the proximity of the North American subcontinent, with its high pressure air masses which results in subtropical conditions, during part of the year.

Core climatic variables entail:

3.1.1 Cloudiness

The least cloudiness is recorded in the month of April, with an average of 3 okta, while the highest values are found during the months of June, July, August and September with 5 okta as an average value.

3.1.2 Air temperature

The yearly average temperature is 23.8 °C. The highest monthly averages are recorded in July (26.3 °C) and August (26.1 °C), while the lowest monthly averages occur in February (20.5 °C) and January (20.6 °C). July and August are the warmer months with average maximum temperatures of 31.4 and 31.3 °C, respectively. January and February are the coldest months when average minimum temperatures of 15.7 and 15.6 °C, are recorded.

The temperature does not vary more than 3 % over the months of the year. This shows the stability of the monthly temperature during the analyzed decade.

3.1.3. Humidity

The highest relative humidity values throughout the year are found near the coast. The annual average relative humidity in Matanzas is 79%, with average monthly values above 75% most of the year. April, is the least humid month with 73% relative humidity on average. During September and October, the relative humidity reaches on average 84%.

Just as for the air temperature, the coefficient of variation does not exceed 2% showing how stable the monthly relative humidity is during the analyzed decade.

3.1.4 Wind

The prevailing wind direction in the area is East (E), (15.2% of the measurements), followed by East-North-East (ENE) winds with a frequency of 9.2%. 46.7% of the winds are N-E. 25.3% of the time is windless. The remaining, 28.0%, winds are from other directions. The wind (speed) is strongest for the dominant directions.

Figure 3 shows the frequency of occurrence of each wind direction and the average wind speed in that direction.

Figure 3: Wind speed and frequency of occurrence for each wind direction in study area

3.2 Working conditions for the software

Avoiding redundant results, some preliminary considerations facilitate their interpretation without compromising their representativeness:

- The study was carried out on a months basis, taking into account climatic variations between different months. For the weather variables monthly average values were used as the coefficient of variation over the considered decade (2004-2013) was low.
- The analysis of the dispersion considers 16 possible wind directions.

The following climate parameters are required for the software to estimate the dispersion of the ammonia:

Air temperature: Average monthly values of the maximum were used as this guarantees estimating the most accurate dispersion.

Relative humidity: Average monthly values were used. They show a limited variation (2%) during the months, showing the stable character of this parameter during the studied decade.

Cloudiness: Monthly average cloudiness values are used.

Wind: 16 directions are considered with their corresponding monthly average wind speed.

3.3 Analysis of ammonia release for three scenarios

Figures 4, 6 and 8, show the results for each of the studied scenarios for January: an average East wind direction with a speed of 15.4 km/h is taken into account. Moreover, the analysis is carried out for every month of the year and for all 16 realistic wind directions and speeds (figure 3).

Scenario 1: Toxic Vapor Cloud

The objective of this scenario is to determine the scope, focus and direction of the toxic ammonia cloud.

Figure 4 shows the threat zones plot of the ammonia cloud in case of an accidental release. The X-axis indicates the distance to the source and the Y-axis the width of the cloud. The three plotted areas (indicated by different colors) represent the geographic zone in which the ammonia concentration exceeds the preset LOC value, established by the EPA (NOAA, 2013; NOAA, 2016). The black lines show the likely affected area taking into account statistical variation.

Figure 4. Footprint of the "ammonia toxic cloud" dispersion

The red zone shows the expected concentrations equal to or above 750 ppm which corresponds to the Emergency Response Planning Guideline (ERPG-3), (the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing or developing life-threatening health effects) (NOAA, 2016).

In the orange area, the ammonia concentration exceeds 150 ppm, which corresponds with the ERPG-2 level (the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing or developing irreversible or adverse health effects or symptoms).

In the yellow zone, the ammonia concentration is above 25 ppm, which is the ERPG-1 level (the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing more than mild, transient, adverse health effects or without perceiving a clearly defined odor nuisance). This toxicity level (ERPG-1) corresponds to the Cuban Standard NC 1/19/63: 1991 as the maximum allowable concentration.

The software, equally allows establishing contingency plans for the affected population in case of a chemical accident, and it forecasts exposure levels in the affected area.

The concentration can be estimated at any point in the territory affected by the toxic cloud (Figure 2).

Figures 5a and 5b provide detail for two specific points in the red zone.

Figure 5a: Pollution behavior inside the plant at 50 m. from the source (Point 1 in Table 1 and Figure 2)

Figure 5b: Pollution behavior inside the plant at 1700 m. from the source (Point 2 in Table 1 and Figure 2)

For both figures the dotted blue line is the concentration of the toxin inside the buildings; the continuous red line is the outdoor concentration, The ERPG 1, 2 and 3 levels are indicated using full (yellow, orange and red) lines.

Figure 5a corresponds to point 1, located at 50 m from the emission source in the red zone. Only after 5 min. the incident causes an indoor concentration exceeding the ERPG-3. This points to a life threatening situation. During the first 15 min. of the incident, a maximum outdoor concentration exceeding 600 000 ppm is likely to be reached. This exposure is lethal for almost all exposed persons; this concentration exceeds almost 40 times the median lethal concentration (LC50) of ammonia for 5 min. (corresponding with 15 240 ppm) (NORSOK, 2010).

Point 2 is located at a distance of 1700 m from the emission source (Figure 5b). Although this area is still part of the red zone, the situation is different from point 1: Inside the buildings at point 2, the ammonia concentration reaches the ERPG-2 level. Outside, maximum ammonia concentrations exceeding the ERPG-3 level occur 15 min. after the incident. There air concentrations are about 300 times lower than the point 1 levels (Figure 5a). The over-all results show that the most dangerous situation occurs during the first 15 min. after the onset of the ammonia incident.

This analysis was performed for each month of the year and for all wind directions. Table 3 summarizes the results indicating the maximum range of the three risk zones (with maximum concentrations corresponding to the three ERPG levels), for all 12 months and wind directions.

Scenario 2: Flammable Area

The objective of this scenario is to determine the potential flammability of the ammonia which is released during the accident (Table 1).

LEL: Lower Explosive Limit

Figure 6: Zone threatened by fire risk

Figure 6 shows the zones at risk of fire caused by the ammonia cloud. Two zones are represented using two colors: in the red zone the ammonia concentration is above 96 000 ppm, which corresponds to the LOC-3 level i.e. 60% of the lower explosive limit (LEL) of ammonia; the yellow zone faces ammonia concentrations above 16 000 ppm, which corresponds to the LOC-1 concentration i.e. 10% of the lower explosive limit (LEL) of ammonia

Figure 6 also shows that the fire risk is limited to a distance of 220 m from the source. Everything below these 220 m has a high risk of fire.

Figure 7 is about the flammability risk of ammonia indoors at Point 1, where there is a restaurant in a frequently used zone.

Figure 7: Pollution indoor as compared to outdoor at a distance from the source of 50 m.

As in figure 5, the blue dotted line shows the forecasted indoor ammonia concentration, whereas the continuous red line represents the outdoor ammonia concentration.

After 2 min following the ammonia release, the indoor concentration reaches the LOC-1 level. Even though outdoors there are concentrations of fire risk, the indoor fire risk is limited. The analysis also shows at the points 2 and 3 (Figure 2) the ammonia concentrations do not cause an incineration risk.

Scenario 3: Vapor Cloud Explosion

The objective of this scenario is to determine the explosion potential of the ammonia cloud.

Figure 8: Scenario 3: Explosion risk.

The yellow area (LOC-1) in figure 8 shows the area at risk for explosion, related to the levels established by the EPA. This area experiences a force of 1 psi (5.7 kPa) what causes breakage of glass, and destruction of windows and frames. A scenario 3 situation is the least risk: the cloud has a low explosion potential which does not go beyond 160 m, while causing the least damage.

A summary of the results for the worst of the three scenarios is shown in Table 3. Data relate to all 12 months of the year and all wind directions.

Table 3: Summary of the worst cause analysis during the year for the three scenarios studied.

Scenario	Month with highest risk	Maximum range for each zone (m)			Wind direction
		Red	Orange	Yellow	
Scenario 1: Toxic Vapor Cloud	Very similar behavior for every month of the year	3400	8380	10 000	Very similar behavior for all wind directions
Scenario 2: Flammable Area	February June July August September October November	240	—	543	WSW SW WSW SW WSW SW- WSW WSW
Scenario 3: Vapor Cloud Explosion	July	—	—	280	WSW

In scenario 1 the maximum distance of the ammonia concentration reaches a level, which is equivalent to the maximum allowable concentration according to the Cuban Standard NC 1/19/63: 1991. This concentration corresponds with the EPA ERPG-1 level. The ammonia cloud reaches the whole year an area of 10 km from the incident plant, anywhere the wind blows. The software does however not predict the dispersion of the toxin at larger distances. Unquestionably this is the scenario with highest potential risk: the red zone (ERPG-3) extends to 3400 m from the ammonia tanks, exceeding the distance of point 3, where many people live and the population density is high. This shows that in case of an ammonia release from the existing tanks, the population living around the points 2 and 3 will be exposed to ammonia concentrations exceeding 750 ppm (ERPG-3).

Scenario 2, shows that the ammonia induced incineration risk exists until 543 m (10% LEL) from the source. The highest risk zone (60% LEL) is limited to 240 m. These distances apply to wind directions which do not affect the populated areas of Matanzas. The North to East wind directions that directly impact the city, cover an area limited to 210 m. This exceeds slightly the boundaries of the chemical plant and therefore the fire risk is limited to the surrounding residents.

Scenario 3 is similar to scenario 2: The highest explosion risk of the ammonia cloud is identified for wind directions that do move the pollution towards the populated areas. Moreover the affected areas are relatively small, and the highest explosion risk is within the boundaries of the plant.

Table 4 summarizes the most dangerous situations that arise from the accidental release of ammonia, for the three selected study points (Table 1, Figure 2). For these points and the wind directions of the first quadrant the expected concentrations are

indicated. The data show that scenario 1 has most impact. In this scenario the pollution results in toxic outdoor; concentrations which exceed the most impacting level of the EPA (ERPG-3). Indoors ERGP-3 levels are reached at point 1, whereas at points 2 and 3 ERGP-2 and ERGP-1 levels are reached, respectively. For scenario 2 (incineration risk) the cloud only shows a fire risk for point 1.

Table 4: Summary of the most impacting situations that might arise after a chemical accident in 3 places close to the emission source

Distance from the emission source (m)	Max Concentration Outdoor (ppm)		Most dangerous moment		Max Concentration indoor (ppm)	
	Scenario 1: Toxic Vapor Cloud	Scenario 2: Flammable Area	Scenario 1: Toxic Vapor Cloud	Scenario 2: Flammable Area	Scenario 1: Toxic Vapor Cloud	Scenario 2: Flammable Area
Point 1 50 m	650 000 (ERPG-3)	60% LEL (LOC-3)	First 15 min. after the release	First 15 min. after the release	58 800 (ERPG-3)	10% LEL (LOC-1)
Point 2 1700 m	2380 (ERPG-3)	10% LEL (LOC-1)	First 15 min. after the release	First 15 min. after the release	213 (ERPG-2)	—
Point 3 2600 m	1150 (ERPG-3)	—	First 15 min. after the release	—	102 (ERPG-1)	—

3.4 Impacts on the study area

This study provides information that enables prevention measures protecting the population (i.e. Civil Defense and the CITMA) in case a chemical accident with ammonia happens in the industrial zone of Matanzas.

The variation of the climatology shows that the predominant wind directions in the area are North-East. These are exactly the directions where the main populations affected by the effects of the accident live. Any accidental release of ammonia in the industrial zone will affect a high percentage to the surrounding population.

Figure 9: Dispersion of ammonia as predicted by scenario 1, in an overlay of the ALOHA plot with a satellite map of the area

Figure 9 shows the area at risk for the toxicity of ammonia after an accidental release in the industrial zone (the red star in figure 9). The red line shows the concentration limit coinciding with ERPG-3 in which the ammonia covers a large part of the inhabited area of the city. The orange line indicates the ERPG-2 area, which spans an area of 8 km from the source and covers the whole habitation area of Matanzas. The orange zone is hardly affected by the wind direction.

In particular the people in the Versailles district (Point 3) are at risk. It should be noted that three hospitals are located in this red zone area.

The Probit equation (Lees, 2005) allows estimating for scenario 1, the number of affected people:

$$Y = -9,82 + 0,71 \ln(C^2 \times t)$$

The Probit (Y) estimates the percentage of injured persons living in the affected areas. The likely number of injured people can be estimated using the probit transformations tabulated by Finney (1971).

Table 5: Probit values, percentage of humans damaged and likely number of fatalities for the inhabitants living around the three points under study

Point Analysis (Distance to the source)	Concentration (ppm)	Number of inhabitants	Exposure time (min)	Probit Value (Y)	Percentage of injured persons (%)	Number of likely injured persons
Point 1 (50 m)	650 000	45	15	11,11	100	45
Point 2 (1700 m)	2380	1433	15	3,14	3	43
Point 3 (2600 m)	1150	20 640	18	2,64	1	206

The results in table 5 show the likely effects an accidental ammonia release will have in Matanzas: the total number of fatalities is estimated at 294. In addition to the harmful effects on human health, ammonia impacts the environment (Vogt et al., 2013).

4. Conclusions

The climatic variables show a prevailing wind direction (46.7%) in the first quadrant (North to East), which favors the dispersion of the pollution over the city of Matanzas.

The main risk of an accidental ammonia release is the toxicity of the vapour cloud that is dispersed. The fire and explosion risks are less.

The model shows that the whole population of Matanzas will be exposed to ammonia concentrations exceeding EPRG-2 levels. The north-eastern neighborhood Versalles is most seriously affected as the ammonia concentration will surpass EPRG-3 levels, which causes an estimated 294 fatalities.

At the conclusion of this study, the company decided to remove the ammonia tanks from the place where it are located, due to the danger it represents for the population and the environment.

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