Technical Papers

36th Annual Meeting

International Institute of Ammonia Refrigeration

March 23–26, 2014

2014 Industrial Refrigeration Conference & Heavy Equipment Show
Nashville, Tennessee

ACKNOWLEDGEMENT

The success of the 36th Annual Meeting of the International Institute of Ammonia Refrigeration is due to the quality of the technical papers in this volume and the labor of its authors. IIAR expresses its deep appreciation to the authors, reviewers and editors for their contributions to the ammonia refrigeration industry.

ABOUT THIS VOLUME

IIAR Technical Papers are subjected to rigorous technical peer review.

The views expressed in the papers in this volume are those of the authors, not the International Institute of Ammonia Refrigeration. They are not official positions of the Institute and are not officially endorsed.

International Institute of Ammonia Refrigeration
1001 North Fairfax Street
Suite 503
Alexandria, VA 22314

+ 1-703-312-4200 (voice)
+ 1-703-312-0065 (fax)
www.iiar.org

2014 Industrial Refrigeration Conference & Heavy Equipment Show
Nashville, Tennessee

Technical Paper #1

Comparison of Various Methods of Mitigating Over Pressure Induced Release Events Involving Ammonia Refrigeration Using Quantitative Risk Analysis (QRA)

Donald Fenton and Tyler Hodges
Department of Mechanical Engineering
College of Engineering
Kansas State University
Manhattan, Kansas

Abstract

The objective of this project was to determine the effectiveness of different methods of mitigating ammonia releases through a pressure relief device in an ammonia refrigeration system. A literature review was conducted and among the methods discovered, five were selected for further study and include: discharge into a tank containing standing water, discharge into the atmosphere, discharge into a flare, discharge into a wet scrubber, and an emergency pressure control system. All the methods were compared applying quantitative risk analysis where failure rates of each system were combined with ammonia dispersion modeling and with the monetized health effects of a system's failure to contain an ammonia release.

It was determined that the ammonia release height had the greatest influence on the downwind cost impact relative to the other variables, including weather conditions and release from multiple sources. While the discharge into a tank containing standing water was determined to have the lowest failure rate, the other discharge methods can be designed to have comparable failure rates and comparable release consequent cost. The emergency pressure control system, now required by codes, used in conjunction with the other ammonia release mitigation systems, was determined to be very effective.

Acknowledgement

The authors graciously thank the Ammonia Refrigeration Foundation and the International Institute of Ammonia Refrigeration (IIAR) for their financial support of this project. Further, the excellent guidance provided by the technical monitoring committee is acknowledged as well, especially Tim Chapp, Jim Wright, and Bruce Nelson.

1.0 Introduction

Ammonia is by far the most common refrigerant chosen as the working fluid in industrial refrigeration systems today. The thermal physical characteristics of ammonia drive this choice because ammonia requires a low mass flow rate to achieve a given refrigeration rate, resulting in smaller refrigerant charges than would otherwise be needed. The smaller charge and lower flow rate allows for smaller vessel volumes and piping diameters. The drawback of ammonia is that it is a strong irritant and causes human health problems when concentrations reach around 150 ppm (v/v). The health hazards associated with ammonia result in stringent code requirements regarding health, both in the plant facility and outside the facility's perimeter.

The applicable codes identify requirements for all refrigeration systems that result in system designs that are safe. Special requirements are identified for large industrial refrigeration systems utilizing ammonia. An important requirement given in the codes for industrial refrigeration systems using ammonia involves a means to mitigate ammonia that may be released through a pressure relief valve, thereby preventing the ammonia from leaving the facility. The codes may or may not require specific methods by which the ammonia should be mitigated, but the final decision is usually the responsibility of the local authority having jurisdiction. The codes are in place to limit the quantity of ammonia that leaves the facility's perimeter and jeopardizes the health of the people living and working in the surrounding area.

Ammonia may be released from a refrigeration plant by means other than through a pressure relief valve system. These include: leaks through rotating seals, piping and vessel structural failures, failures associated with ammonia delivery such as hose leaks; and forklifts and other vehicles breaking pipes, valves, or other components. All ammonia releases not involving pressure-relief valves are outside the scope of this project.

2.0 Reference Ammonia Release

In order to select and design an ammonia mitigating system, the mass flow rate of ammonia that would be expected to be released must be considered. This assessment is generally based on the mass of ammonia liquid contained in the largest vessel vented over a period of one hour. In practice, it is not likely that all of the ammonia would be vented from the vessel, so this is a conservative value. For the purposes of this study, a conservative assumption was made concerning the pressure relief of a vessel. Namely, the flow of ammonia through the pressure relief valve will continue at the rated condition for one hour. An example of this situation would be if the vessel were involved in a facility fire and engulfed in flames. The thermal energy absorbed by the vessel surface by convection and radiation heat transfer is vaporizing the liquid ammonia inside at a rate equal to the rated flow of the pressure relief valve. This condition is used to establish a “reference release” and will be the basis for quantitatively comparing the effectiveness of the different release mitigation techniques.

The “reference release” is defined based on a typical sized modern refrigerated warehouse with both freezer and cooler space. The refrigeration system is a two-stage vapor compression system using ammonia as the refrigerant. The total refrigeration load is 362 tons (1270 kW) which is the sum of the -25°F freezer, the +28°F coolers, and the +40°F truck dock. The largest vessel in this system is the high pressure receiver whose dimensions are 60 inches (152 cm) diameter and 24 ft (7.3 m) long which contains 316 ft^3 (9.0 m^3). The design condensing temperature is taken as 95°F (35°C) giving the liquid mass of ammonia of 11,590 lbm (5,300 kg).

Using ANSI/ASHRAE Standard 15-2010 to estimate the needed ammonia flow rate to protect the high pressure receiver, the relationship in Standard 15 is applied

$$C = fDL \tag{1}$$

where

f = 0.5 for ammonia

D = vessel internal diameter, ft (m)

L = vessel internal length, ft (m)

C = ammonia mass flow rate, lbm (air)/min

For this situation, the value for C is 60 lbm (air)(27.3 kg) per minute. This corresponds to a flow rate of 35.27 lbm (NH_3) (16.0 kg) per minute. Pressure relief valves are available from several manufacturers' meeting this flow capacity. For a time duration of one hour at this rate, the mass of ammonia released is 2,116 lb NH_3 (959.8 kg).

This reference release will be applied to each of the methods proposed for handling ammonia releases from the refrigeration plant.

3.0 Application of Codes

ANSI/ASHRAE Standard 15 (2010), IIAR 2, and the International Fire Code – 2012 have provisions requiring, to a varying extent, the mitigation of ammonia released by pressure relief valves as in this project. It is noted that the codes "flag" ammonia as an exception from those refrigerants that are considered toxic in the requirements related to its mitigation upon release. Specifically, Section 606.12.3 of the International Fire Code, "Ammonia Refrigerant," states the following:

> "Systems containing ammonia refrigerant shall discharge vapor to the atmosphere through an *approved* treatment system in accordance with Section 606.12.4, a flaring system in accordance with Section 606.12.5, or through an *approved* ammonia diffusion system in accordance with Section 606.12.6, or by other *approved* means."

and continues with the following exceptions for ammonia:

> "1. Ammonia/water absorption systems containing less than 22 pounds (10 kg) of ammonia and for which the ammonia circuit is located entirely outdoors.
>
> "2. When the fire code official determines, on review of an engineering analysis prepared in accordance with Section 104.7.2, that a fire, health or environmental hazard would not result from discharging ammonia directly to the atmosphere.

Importantly, the codes do not necessarily require ammonia to be mitigated at the site of the facility. It is possible, depending on the circumstances that exist at the facility (closeness of adjacent human activity, etc.) that the released ammonia may be discharged to the atmosphere in compliance with section 11.3.6 of Standard ANSI/IIAR 2-2010.

Appendix K of IIAR 2 provides requirements and guidance to the application of an "Emergency Pressure Control System" for an ammonia refrigeration system to internally relieve overpressure in the system to another vessel in the system. This prevents the operation of pressure relief devices causing the release of ammonia from the system. If the internal relief of overpressure does not resolve the situation, the relief pressure valves will relieve the pressure. The installation of pressure relief valves is required by the codes where the set pressure is determined in conjunction with the design pressure of the component at that location.

4.0 Ammonia Mitigation Methods

For this study, several different ammonia mitigation methods were considered. Some of these methods are used more than others. The most commonly used mitigation method is discharging the ammonia into the atmosphere as described in IIAR 2. In some jurisdictions, for example California, the preferred method of mitigating an ammonia release involves a water diffusion tank. Also considered is burning the discharged ammonia using a flare system. There are very few instances in the refrigeration industry where flares are used, but it is a common practice in the petrochemical and ammonia production industries. Another method, which is not commonly used for this application in industry, is a scrubber system. Chemical solutions may be used in conjunction with water as the scrubbing agent to improve effectiveness. In many cases, the ammonia may be released directly to atmosphere when complying with the requirements in Standard IIAR 2 to reduce downwind ammonia concentrations to safe levels.

4.1 Ammonia Dispersion into the Atmosphere

In areas where it is safe and legal to do so, direct venting to the atmosphere is the cheapest, easiest, and lowest maintenance cost method of mitigating an ammonia release. In W.F. Stoecker's handbook, *Handbook of Industrial Refrigeration* (1998), he reports that ammonia released to the atmosphere does not contribute to ozone depletion or global warming (Federal Register 1996), and that ammonia is naturally occurring in air.

By section 9.7.8 of ANSI/ASHRAE Standard 15, the refrigerant must be discharged

> "at a location not less than 15 feet (4.57 m) above the adjoining ground level and not less than 20 feet (6.1 m) from any window, ventilation opening, or exit in any building. The discharge shall be terminated in a manner that will prevent the discharged refrigerant from being sprayed directly on personnel in the vicinity and foreign material or debris from entering the discharge piping."

Figure 1 shows a typical arrangement for an ammonia discharge stack at a refrigeration facility where acceptable dimensions are shown.

The IDLH (Immediately Dangerous to Life or Health) for ammonia is 300 ppm (v/v) (CDC 2012). Generally, a value of one-half the IDLH is acceptable for downwind concentrations for designing and selecting mitigating equipment for emergency releases of chemicals such as ammonia.

The main concern is having the plume disperse as quickly as possible to minimize the risk of damage downwind. A concentrated ammonia cloud can be harmful and even deadly. Fenton et al. (2001) reports downwind measured concentrations of more than 80 ammonia vapor releases investigating the influence of stack height, upward velocity, and ammonia concentration in the discharge stream. The experimental data, supported by the dispersion model ISCST2 (1992) predictions, showed that ground level ammonia concentrations were influenced the most by the discharge height – increasing the stack height from 6 ft (1.8 m) to 20 ft (6.10 m) reduced the downwind ground level ammonia vapor concentrations by about 80%. The next most effective source characteristic in reducing ground level concentration was the ammonia vapor concentration, reducing the downwind ground level concentration by about 50%.

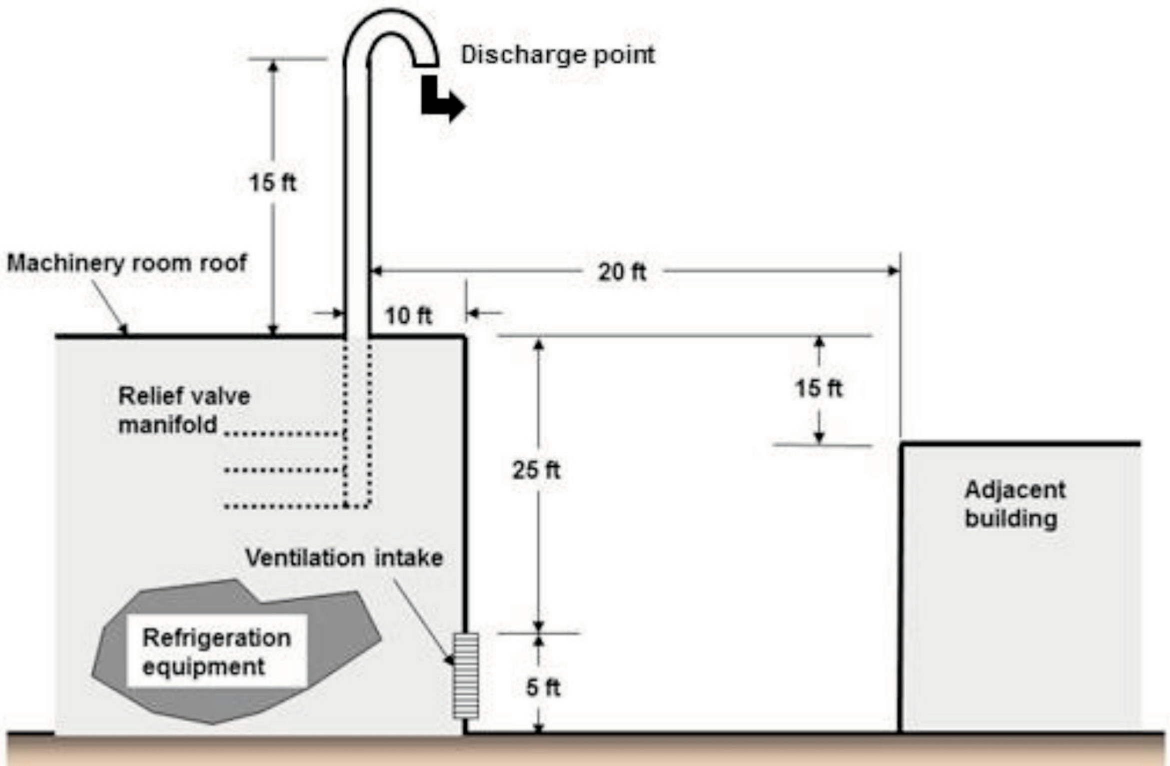

Figure 1: Schematic diagram of an ammonia discharge stack at a refrigeration facility showing an acceptable stack height.

The least effective source variable was the source ammonia vapor upward velocity, reducing concentration by 20% when going from a low velocity (32.8 ft/s (10 m/s)) to a high velocity (164 ft/s (50 m/s)). These factors are based on the specific releases that were compared in the research by Fenton et al.

Additionally, several studies have been done on predicting the effects and behavior of ammonia plumes. The following studies utilize computer models available that adequately predict how the ammonia dispersion in plumes will occur: John Woodward's, "Improving Effect of Atmospheric Stability Class on Hazard Zone Predictions for an Ammonia Release (Woodward 1997)"; Geoffrey Kaiser's paper, "Identification and Modeling of Worst-Case Scenarios for Ammonia Refrigeration Systems (Kaiser 1996)"; Anders Lindborg's paper, "Risk Assessment on a Large Industrial Ammonia Refrigeration System in Central Copenhagen, Denmark" (Lindborg 2006)." All of these studies show that depending on the amount of ammonia released, whether the ammonia is an aerosol or a vapor, the weather conditions, and the surrounding topography all influence the ammonia concentrations in the downwind plume,

The monograph, *Guidelines for Use of Vapor Cloud Dispersion Models (2nd Edition)* (1996), provides a useful review of the dispersion models available at the time, including those which handle two-phase jet releases and 3-dimensional dispersion plumes. Vapor cloud dispersion models are currently available that are capable of modeling ammonia aerosol releases, including the prediction of a cloud's movement along the ground, as influenced by local topography and atmospheric winds. Representative examples of these software packages are: CHARM (2013), DEGADIS (2012), ALOHA 1999),and SLAB (2012). Review of software capable of predicting ammonia aerosol cloud behavior is outside the scope of this study.

4.2 Ammonia Absorption into Water Contained in a Tank

This concept's general requirements originate with ASHRAE Standard 15 paragraph 9.7.8.2.b which states that if a water dilution tank is used, the water and ammonia quantities must meet or exceed the stated amounts.

> "A tank containing one gallon of water for each pound of ammonia (8 kg of water for each kilogram of ammonia) that will be released in one hour from the largest relief device connected to the discharge pipe. The water shall be prevented from freezing. The discharge pipe from the pressure-relief device shall distribute ammonia in the bottom of the tank, but no lower than 33 ft (10 m) below the maximum liquid level. The tank shall contain the volume of water and ammonia without overflowing."

In some locations, it is required by code to discharge ammonia into a tank of water. The California Mechanical Code section 1120.0 states,

> "Ammonia shall discharge into a tank of water that shall be used for no purpose except ammonia absorption. At least one gallon of fresh water shall be provided for each pound of ammonia that will be released in one hour from the largest relief device connected to the discharge pipe."

This rule had been in ASHRAE Standard 15 for some time without validation. Upon the adoption of the BOCA Uniform Mechanical Code during the late 1980's, ASHRAE initiated a research project to experimentally check the above recommendation in Standard 15. The results of this project were reported by Fenton et al. (1991) where the ratio of one gallon of water for each pound of ammonia was confirmed for both liquid and vapor ammonia.

Figure 2 shows experimental results supporting the ammonia-to-water ratio given in Standard 15 where the final concentration of ammonia in water is near the saturated condition – nearly the ratio of 1 lbm NH_3 per gallon of water. This approach to capturing ammonia released through pressure relief valves has been successfully implemented in many areas of the United States, but has posed challenges concerning relief piping design, equipment maintenance, disposal of captured ammonia, and freeze protection where needed.

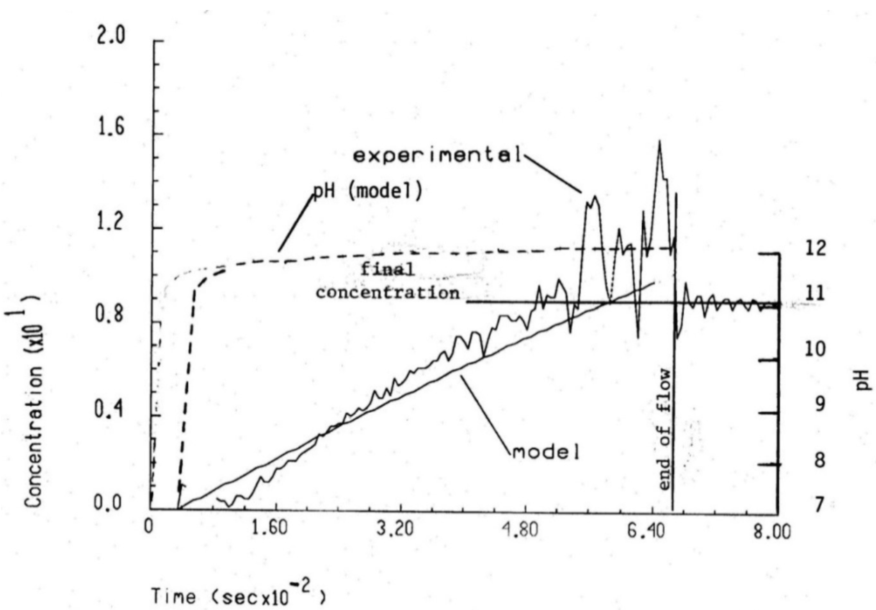

Figure 2: Experimental results and model predictions of ammonia concentration in water for ammonia absorption into water ending at 1 pound of ammonia per gallon of water (Fenton et al. 1991).

Figure 3 is a schematic diagram of a water diffusion tank setup for the absorption of ammonia. While the absorption of ammonia in water is a relatively passive system, there are some issues that must be addressed. Standard 15 says that the water storage tank must be prevented from freezing, and that the ammonia must enter in the bottom of the dilution tank. A rupture disk (or other device) prevents the migration of moisture into the relief piping preventing failure of the pressure relief valve caused by rust. The released ammonia enters the top of the tank, is piped to near the bottom, and there contacts the standing water after leaving the distribution piping or sparger. Mechanical agitation of the water to promote the ammonia's absorption is not needed because of the high affinity between ammonia and water.

Reference Release: Using the quantity of ammonia in the defined reference ammonia release, 2,116 lb NH_3 (959.8 kg) over a one hour period, the quantity of water standing in the tank cannot be less than 2,116 gal (8.0 m^3). However, with the likelihood of the ammonia being primarily vapor and knowing that only 90% of the

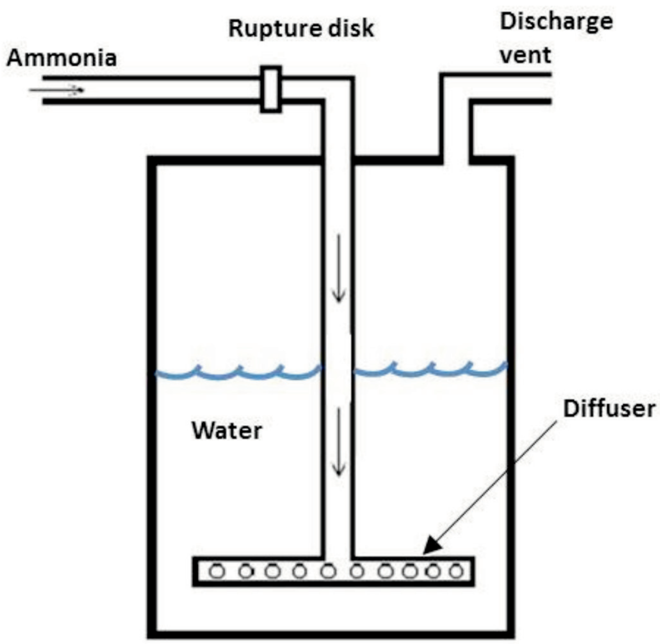

Figure 3: Schematic diagram of a water diffusion tank for the absorption of ammonia into standing water.

ammonia would be captured, the water volume is increased to 2500 gal (9.5 m^3). Allowing for sufficient volume above the water surface to accommodate the movement of the water and possible bubbling, the volume of the tank is doubled giving a final tank volume of 5000 gal (18.9 m^3).

4.3 Ammonia Dispersion into a Flare

One alternative method of capturing ammonia from a release is burning the ammonia using a combustion flare system. This method is commonly used in ammonia manufacturing plants and in the petrochemical industry, but is rare in the ammonia refrigeration industry. The reason is that in these process industries, the source gas to be “flared” flows continuously, but variable in rate depending on the plant’s operating condition, providing modulated, but uninterrupted operation of the flare. In a food refrigeration plant , the flare will only operate when one or more pressure relief valves are open releasing ammonia, or possibly when blowdown occurs at a rate or time when recovery is not possible. Therefore, flares applied to refrigeration plants are generally classified as “emergency” flares because they only function when needed.

Shepherd (1988) first reported the use of flares for the disposal of ammonia released from a refrigeration plant where he indicates the first application was in 1970. The combustion flame in the flare oxidizes the ammonia converting it to essentially water, nitrogen, and hydrogen. Since ammonia does not contain carbon, carbon compounds *CO* and CO_2 do not appear in the products of combustion. The flare does require careful design, as ammonia does not sustain a flame, even though the reaction is exothermic. A pilot flame is needed to initiate and sustain the combustion of ammonia.

The simplest version of a flare is a “gas burner with a very large operating range that permits it to operate from very large flows of waste gas down to very small flows while maintaining its efficiency” (Shepherd 1988, 1990). That efficiency is typically in the mid-ninety percent range, but in order for this level of efficiency to occur, all liquid ammonia must be removed from the relief system before it gets to the flare. Ammonia droplets evaporate slowly due the liquid’s high latent heat and they may pass through the flare without fully evaporating. For this reason and because the combustion is often incomplete, ammonia may pass through the flare unburned. Shepherd handles the ammonia liquid problem by piping the released ammonia through a phase separator or “knock-out drum” before it gets to the flare as shown by the vessel labeled “V-1” in Figure 4.

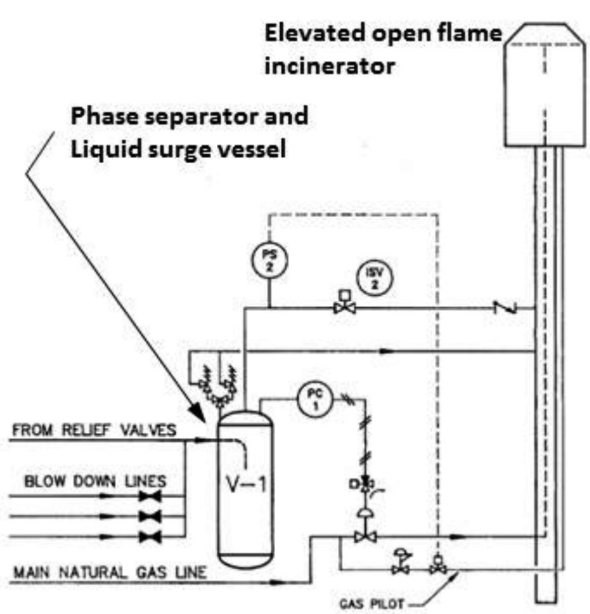

Figure 4. Ammonia elevated open flare diagram where V-1 is a liquid phase separator and liquid surge tank (Shepard 1990)

The flare system must be able to operate without electrical power or natural gas and be able to easily and reliably switch to backup systems because many fire departments will shut these off in the case of a fire or leak at an ammonia facility. This can be done with a supply of propane to back up the ignition gas and a battery backup for the electrical parts. This backup equipment requires maintenance and periodic testing to ensure its functionality. In contrast, the water diffusion tank, because water is always present, does not require backup equipment during an electrical power outage.

Fenton et al. (1995) developed a laboratory sized ammonia flare system in the shape of a venturi where a flame holder was placed immediately downstream of the throat. Natural gas was used as the pilot fuel and ammonia was supplied by regulating the flow from a storage tank by means of a gas pressure regulator. Experiments were conducted varying the natural gas and ammonia flows over the full range of flammability for the two fuels. The measured flame temperature ranged from a high 2100°F to a low of 1200°F for the ammonia–air mixture. The higher temperature was achieved when the fuel-air supply mixture was near stoichiometric conditions with lower temperatures resulting when the fuel and ammonia supplies are unbalanced. Figure 5 shows the measured ammonia vapor concentrations downstream from the combustion zone.

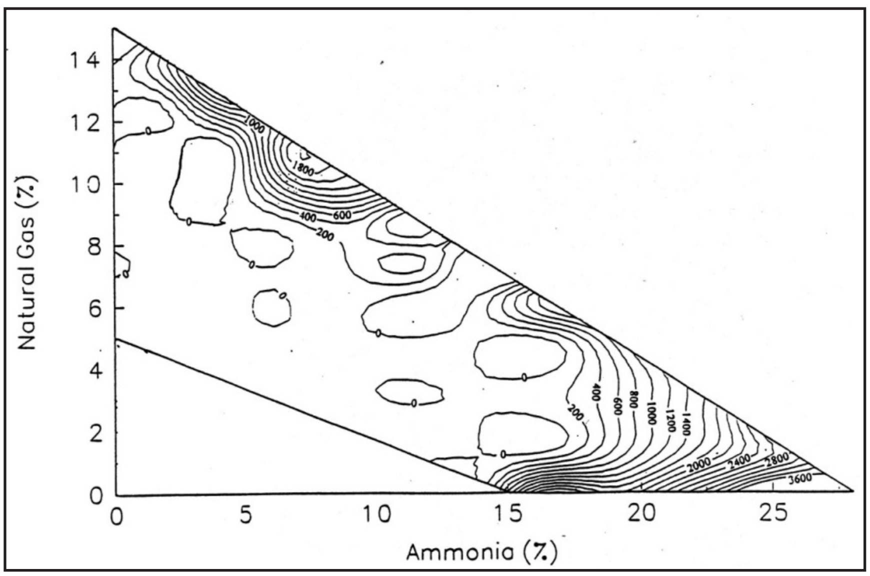

Figure 5. Variation of ammonia (ppm, v/v) measured downstream from the combustion zone as a function of the fuel mixture (Fenton et al. 1995).

Reference Release: The stack height flare offers several advantages when applied to refrigeration plants. The flare combustor does not require warming to maintain a standby condition, thus lowering its cost of operation. Also, the elevated flare, if for some reason not operational at the time of a release, will disperse the ammonia to the atmosphere in the same manner as if discharged from the stack without treatment.

For the reference release of 2,116 lb (959.8 kg) NH_3 vapor per hour, a 10 inch (25.4 cm) diameter flare tip size is appropriate requiring three pilots at a pressure drop of 4 inches water gauge (12 Pa).

4.4 Ammonia Dispersion into a Scrubber

A water spray scrubber system works similarly to the water diffusion tank in that the ammonia is absorbed into the water. The scrubber is an active system rather than a passive system. The water is sprayed into the ammonia as it enters the vessel, rather than the water standing in the vessel. In the event of a release, the end product is the same ammonia-water solution as in the water diffusion tank. Fenton et al. (1991) found that a water spray scrubber was “an 85% effective ammonia vapor trap at the ratio of two gallons water to one pound of ammonia. This was a crudely designed device, and Fenton (2012) believes that a system specifically designed for the application would have an effectiveness approaching 100%, similar to the water diffusion tank. In line with that expectation, commercially available ammonia scrubbing systems claim over 99% effectiveness in capturing ammonia.

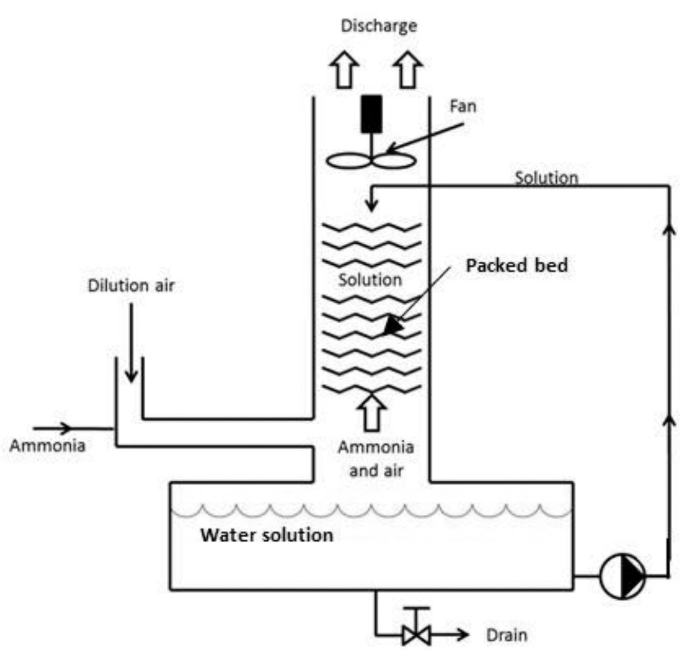

Figure 6. Schematic diagram of an emergency scrubber suitable for capturing ammonia

Although scrubbers are not commonly used in the ammonia refrigeration industry, there are commercially available scrubbers suitable for emergency service and several applications are already in place (Biondi 2012). Figure 6 is a schematic diagram of a counterflow packed bed scrubber suitable for use with ammonia. Many products use an acid-water solution instead of only water as the scrubbing agent (Advanced Air Technologies, Inc., 2012). The most common acid used is sulfuric acid, because when reacted with ammonia, it forms ammonium sulfate, which is a salt, and a common fertilizer ingredient. Additionally, sulfuric acid is low cost and has very low volatility. With the salt precipitated out of the solution, the water in the scrubber system can be recycled and the ammonium sulfate can be used or sold. The emergency scrubber may, or may not, need dilution air to operate depending on its configuration. In addition to the features of the scrubber shown in Figure 6, spray chambers and water jets may also be suitable scrubber configurations for emergency service (Heil 2012).

Reference Release: The reference release is 2,166 lb (959.8 kg) NH_3 vapor per hour. The packed bed vertical configuration is used by manufacturers of emergency scrubbers for ammonia and is recommended for this study. Water will be used as the scrubbing agent in the quantity recommended by the manufacturer.

4.5 Emergency Pressure Control System

The International Mechanical Code section 1105.9 requires that an ammonia refrigeration system containing more than 6.6 pounds (3 kg) of ammonia have an emergency pressure control system as detailed in Section 606.10 of the International Fire Code. This system requires that:

> "each high and intermediate pressure zone in a refrigeration system shall be provided with a single automatic valve providing a crossover connection to a lower pressure zone."

The valves are set to open automatically at 90% of the pressure set point for emergency pressure relief devices. Also, all zones that are connected by a crossover valve must be designed to contain the maximum pressure achieved by connecting the two zones as can be seen in Figure 7. The idea behind relieving pressure to another vessel, is to have

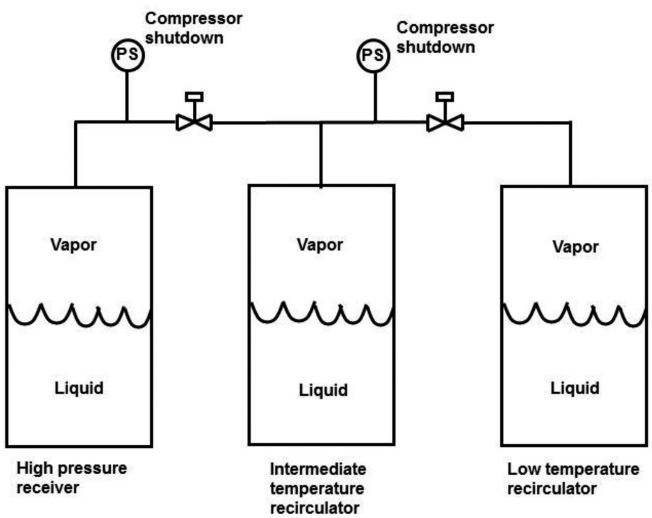

Figure 7: Diagram showing the basic components of an ECPS internal pressure relief system (stop valves, flow strainers, and pressure gauges not shown.)

the ammonia go from a higher pressure vessel to a lower pressure vessel and prevent it from being released from the system.

Because EPCS systems are now required by the codes, all up-to-date industrial ammonia systems incorporate internal pressure relief. The consequence of these systems is that when ammonia is released to limit high pressure in vessels, the ammonia remains contained within the refrigeration system and not released through the relief valves to an open stack for dispersion to the air or an ammonia mitigation system. In the situation of a major facility fire engulfing several or all the ammonia pressure vessels, the EPCS may be overwhelmed resulting in the release of ammonia through the pressure relief valves.

5.0 Ammonia Dispersion Modeling

In order to determine the off-site consequences of the ammonia release, the dispersion of the ammonia vapor must be determined. The model chosen was SLAB (2012), which is specifically designed as a dense gas dispersion model. SLAB requires many of the same inputs as Turner's workbook model (Turner 1970), but also requires the properties of the pollutant, the ambient and source temperatures and pressures, and other parameters. The requirements for the input file are described in the final report of this project (Hodges and Fenton 2013). In contrast to more complex models, such as CalPuff, AERMOD, and ALOHA, SLAB does not require the surrounding terrain or the specific weather patterns to be supplied – rather, the surrounding terrain is assumed flat. SLAB uses a surface roughness parameter, and for the weather, it uses Pasquill's atmospheric stability classes. CalPuff (2012) and AERMOD (2012) are two models recommended by the US EPA for atmospheric dispersion modeling, but they require extremely detailed weather and terrain inputs that are not conducive to the more general modeling needed for this application. Furthermore, CalPuff (2012) and AERMOD (2004) cannot handle dense gases such as ammonia. If ammonia dispersion modeling were necessary for a specific installation, a more detailed dispersion study could be done and combined with the other facets of this project to develop a more precise QRA for that site.

SLAB (2012) was evaluated by predicting the downwind ammonia vapor concentrations measured by Fenton et al. (2001) in their releases. The measured downwind concentrations for several representative releases were predicted by SLAB to within a factor of two or three which is acceptable for atmospheric dispersion studies.

The source temperature is not input to SLAB as the temperature of the ammonia while it is in the pressurized tank, but rather as the temperature after it has fully expanded. The source area is also treated as such. Equations (2) and (3), respectively, show how the source temperature and source area are calculated (Ermak 1990).

$$TS = \left(\frac{1}{\gamma}\right) * \left[1 + (\gamma - 1) * \left(\frac{P_a}{P_{st}}\right)\right] * T_{st} \quad \mathbf{(1)} \tag{2}$$

$$AS = \left(\frac{P_{st}}{P_a}\right) * \left(\frac{TS}{T_{st}}\right) * A_r \tag{3}$$

where,

TS = Source Temperature (K)

γ = Ratio of specific heats (C_p/C_v)

P_a = Ambient pressure

P_{st} = Storage Pressure

T_{st} = Storage Temperature (K)

A_r = Actual area of opening (m^2)

AS = Source area (m^2)

It is important to note that if the calculated source temperature is less than the boiling point temperature, SLAB resets the source temperature to be equal to the boiling point temperature. For the simulations in this project, the source duration is always input as 3600 seconds, and the mass source rate is 0.5683 lbm/s (0.2583 kg/s). The instantaneous source mass velocity is zero for any jet or stack release. The source height was varied between 30 feet (9.14 m) for the direct release to the atmosphere, and 20 feet (6.10 m) for the flare, scrubber, and diffusion tank. The averaging time for the ammonia concentrations is an input. This is important because the US EPA has different limits on concentrations based on exposure time (SLAB 2012). For this analysis, concentration averaging times of 10 minutes (input as 600 s) and 1 hour (input as 3600 s) were simulated. Another input sets the limit for downwind distance in the simulation, which was 6.21 miles (10,000 m). Receptor heights where the downwind concentrations were predicted were 16.4 ft (5 m), 6.56 ft (2 m), and 0.13 ft (0.04 m) and were selected to simulate the range of heights occupied by humans. Other inputs were:

- Surface roughness parameter, which was set at 1.0. The surface roughness can vary wildly based on the surrounding terrain, but 1.0 is in the range for an urban or suburban application, and was kept the same for each simulation. Building windows were assumed open.
- Height for ambient wind speed measurement, and was set at 6.56 ft (2 m).
- Ambient temperature and relative humidity were maintained at 68°F (293.15 K) and 35% RH for all simulations.
- Pasquill stability class. The stability classes have a range of wind speeds and weather conditions are shown in Table 1 along with how they were paired in the simulations. Some of the stability classes share a wind speed, but have different dispersion characteristics. The stability classes vary from very unstable at Class A

to very stable at Class F, and are dependent on the incoming solar radiation or the cloud cover at night, in addition to the wind speed.

Stability Class	Wind Speed
Class A	6.26 ft/s (2 m/s)
Class B	9.84 ft/s (3 m/s)
Class C	16.4 ft/s (5 m/s)
Class D	19.7 ft/s (6 m/s)
Class E	9.84 ft/s (3 m/s)
Class F	6.26 ft/s (2 m/s)

Table 1: Stability and Wind Speed Relation

A simulation was run for each combination of stability class, release height, and concentration averaging time for a total of 36 different simulations:

- 3 release heights: 9.14 m (30 ft), 6.10 m (20 ft), 3.05 m (10 ft)
- 2 averaging times: 10 minutes, 1 hour
- 6 atmospheric stability classes: A, B, C, D, D, and F.

The release is characterized by the release of 2,116 lbm (959.8 kg) of ammonia over the time interval of one hour. The release was modeled through a stack with a 1 foot (0.3048 m) opening, and Equation 2 was used to calculate the ‘Source Area’ input required by the program. Similarly, Equation 1 was used to calculate the ‘Source Temperature’ variable, and the result is a number below the boiling point temperature. SLAB automatically resets the source temperature to be the boiling point temperature in this case.

5.1 Dispersion Modeling Output

The important part of the output file is the time-averaged volume concentrations, at the specified measurement heights. For each downwind distance, SLAB calculates an “effective half-width” for the ammonia plume. This half-width is a parameter that represents the distance from the cloud centerline to the edge of the main part of the plume. The output file displays and calculates the average ammonia concentration at six multiples (0, 0.5, 1.0, 1.5, 2.0, and 2.5) of this effective half-width. This gives specifically defined concentrations at the x-y coordinates that are along those lines.

Figures 8, 9, and 10 show downwind ammonia concentrations predicted by SLAB (2012) for the reference release at a stack height of 30 ft for 16.4 ft, 6.56 ft, and 0.13 ft receptor height, respectively. Observe that the ammonia concentration is highest at the plume's centerline and decreases as the receptor moves further away from the centerline at a particular downwind distance. Also note that as the receptor heights become shorter, the concentration peaks move further downwind, and the concentrations are lower.

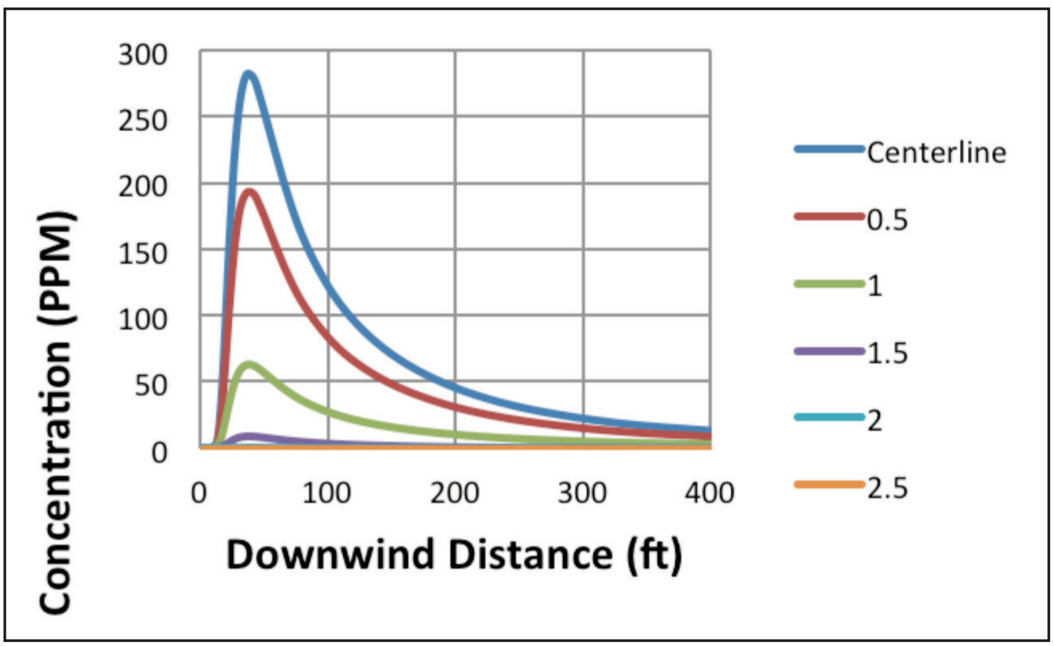

Figure 8. Concentration along plume half-width multiples, 30 ft (9.14 m) release, 16.4 ft (5 m) receptor height (stability class A, 10 minute average)

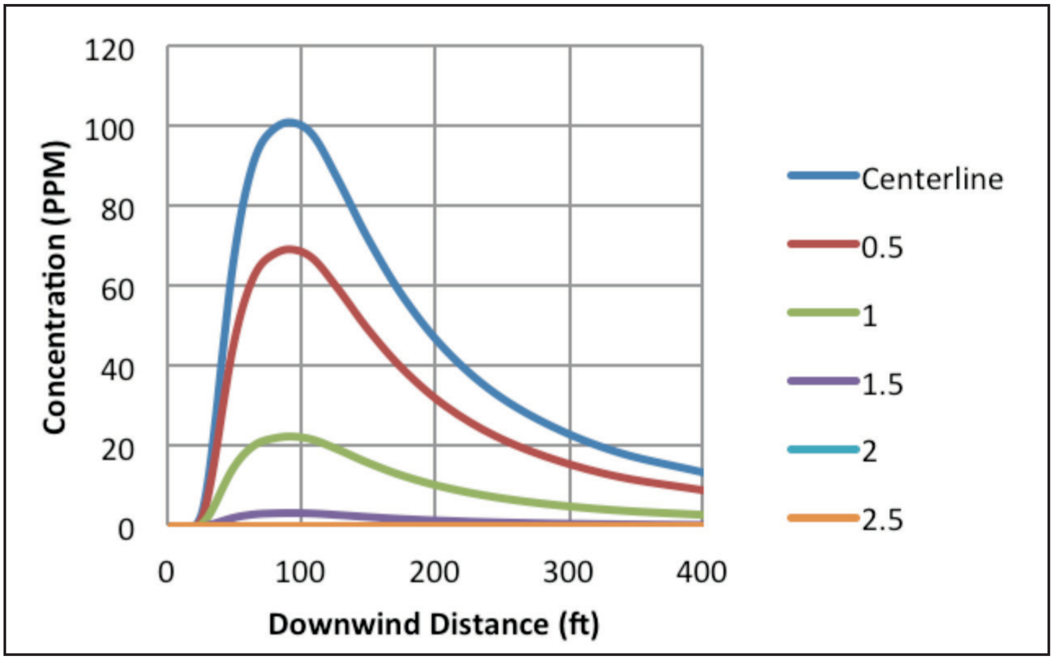

Figure 9. Concentration along plume half-width multiples, 30 ft (9.14 m) release, 6.56 ft (2 m) receptor height (stability class A, 10 minute average)

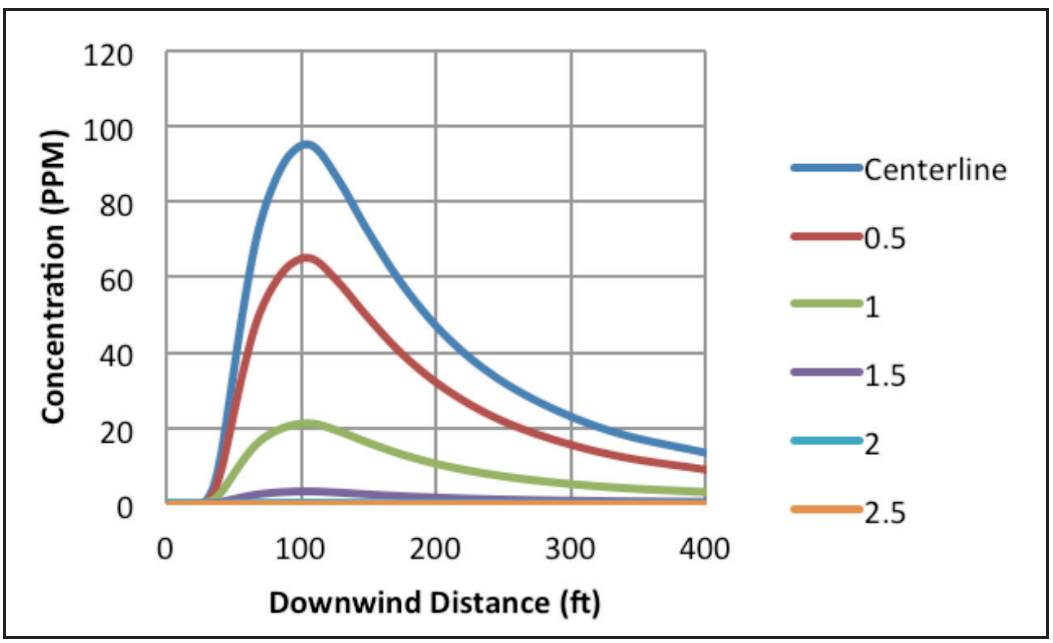

Figure 10. Concentration along plume half-width multiples, 30 ft (9.14 m) release, 0.13 ft (0.04 m) receptor height (stability class A, 10 minute average)

Figures 11, 12, and 13 shows the influence of atmospheric stability class on centerline ammonia concentrations for the six stability classes at each receptor height for a 30 ft stack (9.14 m) height release. The least stable classes, A and B, have higher concentration peaks occurring over a shorter distance. In contrast, the most stable classes result in smaller concentration peaks but persist for a much greater distance. A comparison of centerline concentrations for releases under stability Class B and a receptor height of 6.56 feet (2 m) are shown in Figure 14 for stack heights of 30 ft (9,14 m), 20 ft (6.10 m), and 10 ft (3.05 m) where dramatic reductions in peak concentration occur with high stack heights.

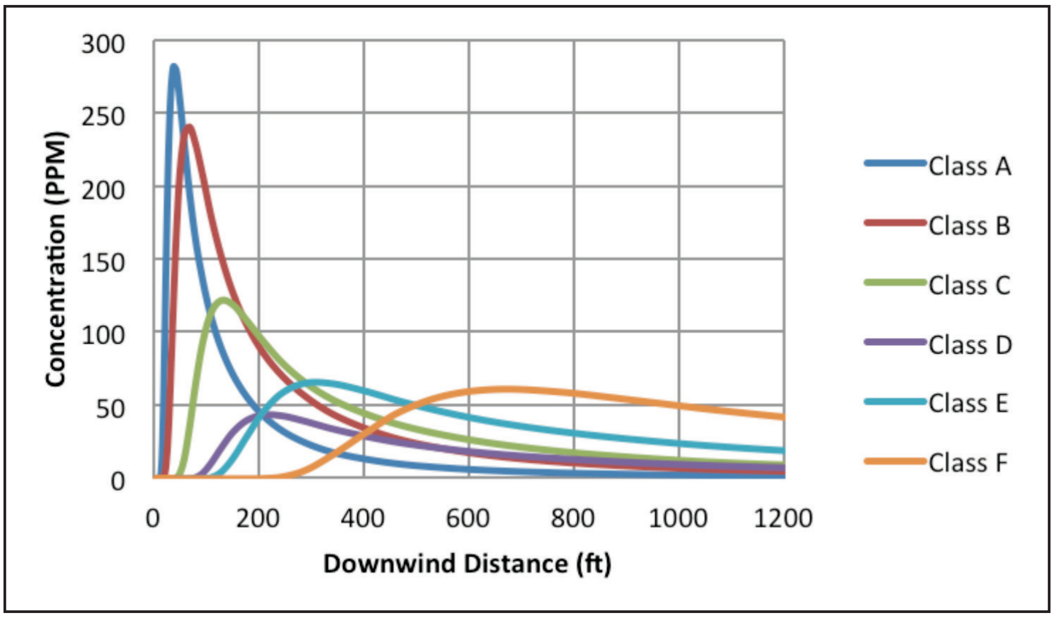

Figure 11. Centerline concentrations by stability class, 30 ft release (9.14 m), 16.4 ft (5 m) receptor height (10 minute average).

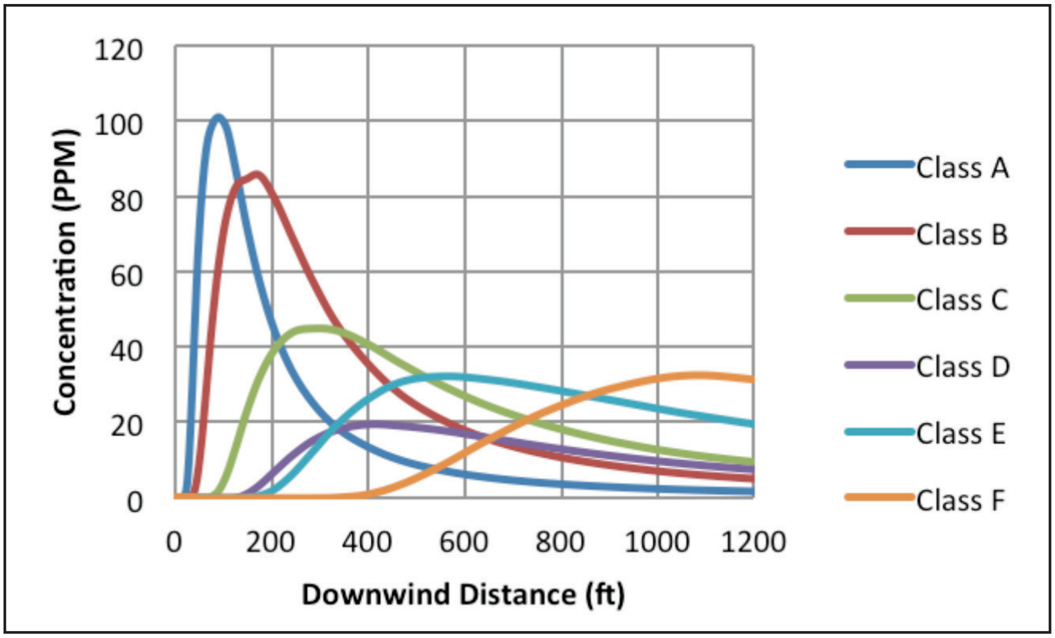

Figure 12. Centerline concentrations by stability class, 20 ft (6.1 m) release, 6.56 ft (2 m) receptor height (10 minute)

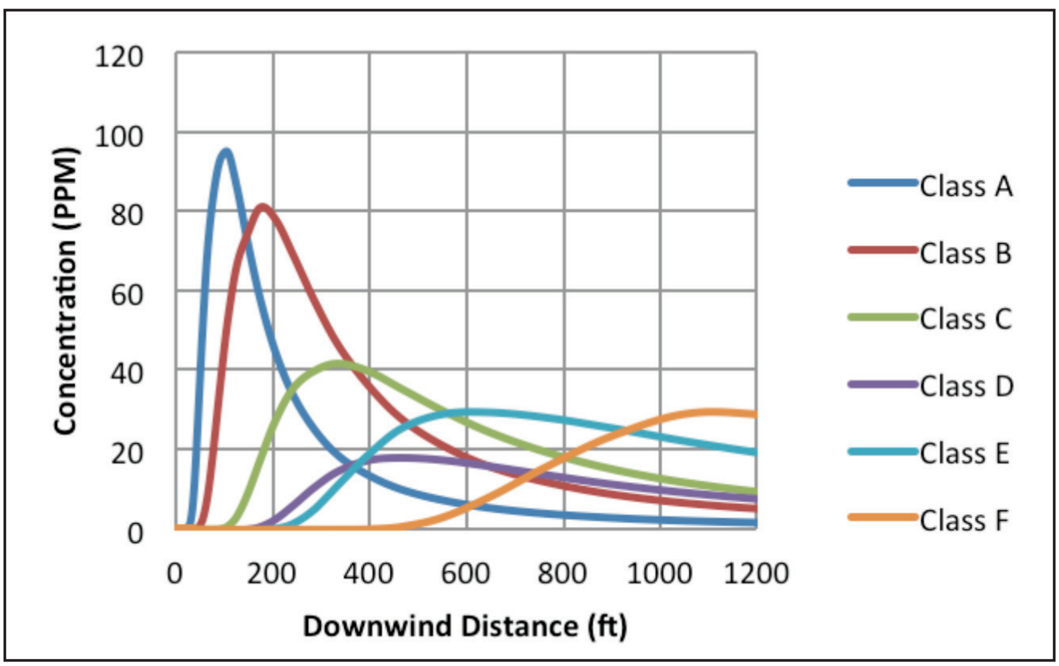

Figure 13. Centerline concentrations by stability class, 10 ft release (3.05 m), 0.13 ft (0.04 m) receptor height (10 minute average)

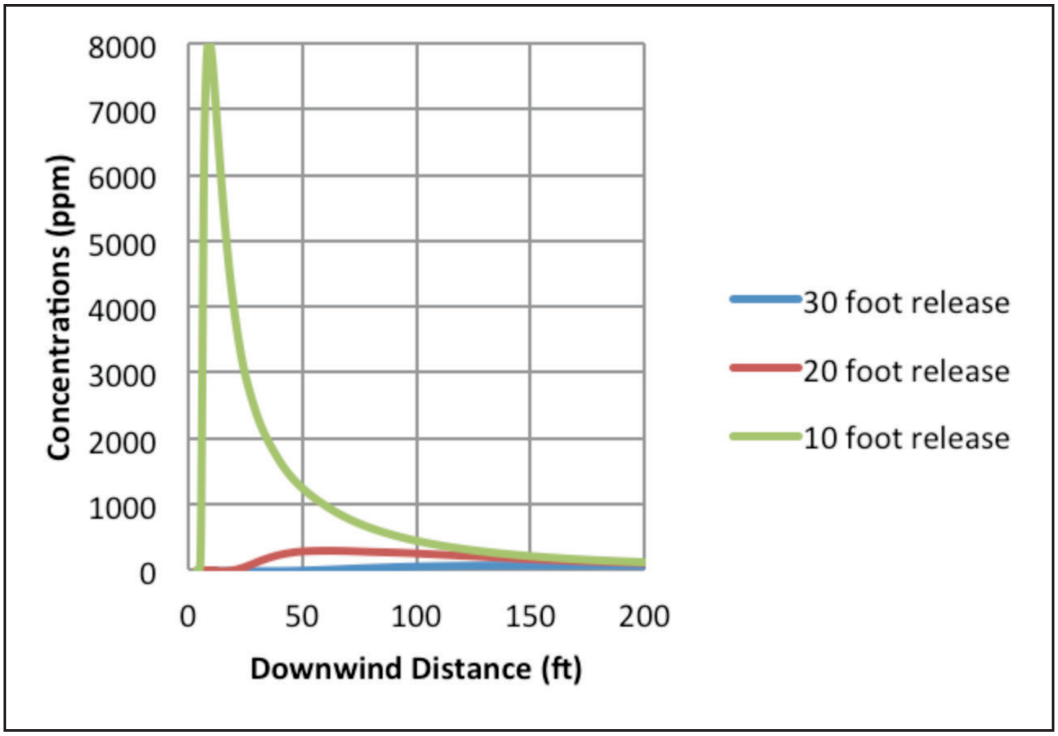

Figure 14. Comparison of releases under the same conditions at different release heights (1 hour average, 6.56 ft (2 m) receptor height)

5.2 *Correlating Ammonia Exposure with Health Cost*

The California Air Resources Board's documentation shows the financial cost associated with health effects caused by air contaminants (Air Resources Board 2006). The table in Figure 15 details these costs. Combined with the data from an US EPA publication outlining the Acute Exposure Guideline Levels (AEGL) for ammonia (National Research Council of the National Academies 2007), the cost associated with an exposure to a certain concentration of ammonia is known which in turn defines which AEGL Classification is associated with that certain health event. Thus, the average cost for all the health events associated with each of the AEGL Classifications are determined. The overall human health cost is calculated by application of Figure 16, Table 2, and Table 3 in conjunction with the predicted ammonia downwind concentrations.

$$Human\ Cost\ =\ \sum_i RA_i\ *\ C_{AEGL,i} *\ P_{dens} \qquad (4)$$

where,

RA = Representative Area

C_{AEGL} = Average Cost by AEGL Classification

P_{dens} = Population density

An ammonia concentration was calculated at every point along a square grid spaced 3.28 feet (1 m) apart. These concentrations were calculated by linearly interpolating between the actual known points from SLAB's output. This was done in order to later overlap releases from different release points. SLAB does not generate outputs at regular intervals, making this impossible to do without manipulating the output. For each newly defined point with an associated concentration, a representative area of 10.76 square feet (1 square meter) was assigned in order to cover all of the area affected. The representative area was summed based on the amount of area falling under a certain AEGL Classification, then multiplied by the average health cost for that AEGL classification, and then multiplied by the population density. For the calculations, a population density of 1000 people per square mile was used to simulate an urban area. Since there are data points for three different heights at which the released ammonia could affect humans, 16.4 feet (5 m), 6.56 ft (2 m), and 0.13 ft (0.04 m), the height with the maximum cost was chosen for each of those simulations. The maximum cost was also chosen from the 10 minute and 1 hour exposure times. This gives a conservative estimate. Tables 4, 5, and 6 show the calculated costs for each detector height for the 30 foot releases, for the 20 foot, and for the and 10 foot releases, respectively. Table 7 shows the maximum costs for each type of release for stack heights of 30 ft (9.14 m), 20 ft (6.10 m), and 10 ft (3.05 m), respectively.

Health Endpoint	2005	2010	2020	References
Mortality				
Premature death ($ million)	7.9	8.1	8.6	U.S. EPA (1999), (2000), (2004)
Hospital Admissions				
Cardiovascular ($ thousands)	41	44	49	CARB (2003), p.63
Respiratory ($ thousands)	34	36	40	CARB (2003), p.63
Minor Illnesses				
Acute Bronchitis	422	440	450	U.S. EPA (2004), 9-158
Lower Respiratory Symptoms	19	19	20	U.S. EPA (2004), 9-158
Work loss day	180	195	227	2002 California wage data, U.S. Department of Labor
Minor restricted activity day (MRAD)	60	62	64	U.S. EPA (2004), 9-159
School absence day	88	95	111	U.S. EPA (2004), 9-159

Figure 15. Undiscounted Unit Values for Health Effects in US Dollars (Air Resources Board 2006)

Classification	10 min	30 min	1 h	4 h	8 h	End Point (Reference)
AEGL-1 (nondisabling)	30 ppm (21 mg/m^3)	30 ppm (21 mg/m^3)	30 ppm (21 mg/m^3)	30 ppm (21 mg/m3)	30 ppm (21 mg/m3)	Mild irritation (MacEwen et al. 1970)
AEGL-2 (disabling)	220 ppm (154 mg/m^3)	220 ppm (154 mg/m^3)	160 ppm (112 mg/m^3)	110 ppm (77 mg/m3	110 ppm (77 mg/m3)	Irritation: eyes and throat; urge to cough (Verberk 1977)
AEGL-3 (lethal)	2,700 ppm (1,888 mg/m^3)	1,600 ppm (1,119 mg/m^3)	1,100 ppm (769 mg/m^3)	550 ppm (385 mg/m3)	390 ppm (273 mg/m3)	Lethality (Kapeghian et al. 1982; MacEwen and Vernot 1972)

Figure 16. Summary of AEGL Values for Ammonia (National Research Council of the National Academies 2007)

Health Event	Associated Cost ($/person)	AEGL Classification
Acute Bronchitis	$440	AEGL-1 (nondisabling)
Lower Respiratory Symptoms	$19	AEGL-1 (nondisabling)
Work Loss Day	$195	AEGL-1 (nondisabling)
Minor Restricted Activity Day	$62	AEGL-1 (nondisabling)
School Absence Day	$95	AEGL-1 (nondisabling)
Cardiovascular Hospital Admission	$44,000	AEGL-2 (disabling)
Respiratory Hospital Admission	$36,000	AEGL-2 (disabling)
Premature Death	$8,100,000	AEGL-3 (lethal)

Table 2. Health Events Related to Ammonia Exposure Classification

AEGL Classification	Average Cost ($/person)
AEGL-1 (nondisabling)	$162
AEGL-2 (disabling)	$40,000
AEGL-3 (lethal)	$8,100,000

Table 3. Average Cost by AEGL Classification

5.3 Releases from Multiple Points

To test the effect of releasing from multiple points instead of one single release point as shown earlier, the reference release was split in half and the two source points were placed 32.81 feet (10 meters) apart. The two-point release is simulated as 17.635 lbm (NH3) (8 kg) per minute through each of the release points, which combines to be the same amount as the reference release rate. Three different orientations of the release points, relative to the wind direction were tested: the wind in line with the release points, perpendicular to the line between the release points, and at a 45° angle.

In superimposing the results from the two release points (each half of release rate total), the maximum concentrations were added, even though they might have occurred at different times. This gives a concentration that will almost always be slightly higher than the actual concentration over any time period. The output of the SLAB model does not allow for the calculation of the exact concentration at any particular time, so this method was developed and used. When the release points are parallel to the wind direction, the ammonia concentrations are the highest, when the release points are 45° to the wind direction, the ammonia concentrations are roughly intermediate, and when the release points are normal to the wind direction, the ammonia concentrations are the least.

30 Feet	16.4 feet (5 m)		6.28 feet (2 m)		0.13 feet (0.04 m)		Maximum
Atmospheric Stability	10 min	1 hour	10 min	1 hour	10 min	1 hour	Cost
Class A	$ 964	$ 2,687	$ 152	$ 152	$ 148	$ 148	$ 2,687
Class B	$ 508	$ 165	$ 182	$ 130	$ 175	$ 118	$ 508
Class C	$ 164	$ 116	$ 96	$ 4	$ 76	$ -	$ 164
Class D	$ 48	$ 86	$ -	$ -	$ -	$ -	$ 86
Class E	$ 267	$ 338	$ 23	$ 122	$ -	$ 71	$ 338
Class F	$ 643	$ 852	$ 39	$ 243	$ -	$ 114	$ 852

Table 4: Human health costs for 30 foot ammonia releases at three receptor heights (1000 people per square mile)

20 Feet	16.4 feet (5 m)		6.28 feet (2 m)		0.13 feet (0.04 m)		Maximum
Atmospheric Stability	10 min	1 hour	10 min	1 hour	10 min	1 hour	Cost
Class A	$ 48,740	$ 169,212	$ 2,928	$ 5,728	$ 1,634	$ 4,618	$ 169,212
Class B	$ 62,222	$ 144,870	$ 2,732	$ 2,619	$ 944	$ 460	$ 144,870
Class C	$ 5,936	$ 44,698	$ 244	$ 204	$ 237	$ 193	$ 44,698
Class D	$ 2,968	$ 6,919	$ 150	$ 187	$ 128	$ 169	$ 6,919
Class E	$ 8,519	$ 17,231	$ 539	$ 597	$ 514	$ 578	$ 17,231
Class F	$ 17,264	$ 40,876	$ 1,508	$ 1,734	$ 1,437	$ 1,682	$ 40,876

Table 5: Human health costs for 20 foot ammonia releases at three receptor heights (1000 people per square mile)

10 feet	16.4 feet (5 m)		6.28 feet (2 m)		0.13 feet (0.04 m)		Maximum
Atmospheric Stability	10 min	1 hour	10 min	1 hour	10 min	1 hour	Cost
Class A	$ 43,070	$ 169,920	$ 75,339	$ 75,339	$ 6,751	$ 6,751	$ 169,920
Class B	$ 19,177	$ 164,472	$ 82,999	$ 203,895	$ 8,466	$ 23,027	$ 203,895
Class C	$ 6,747	$ 126,336	$ 39,734	$ 128,641	$ 44,543	$ 9,739	$ 128,641
Class D	$ 5,799	$ 126,464	$ 52,447	$ 91,000	$ 8,328	$ 9,137	$ 126,464
Class E	$ 61,221	$ 533,870	$ 178,331	$ 220,356	$ 23,135	$ 26,370	$ 533,870
Class F	$ 402,224	$ 1,499,712	$ 360,230	$ 349,441	$ 67,732	$ 72,107	$ 1,499,712

Table 6: Human health costs for 10 foot ammonia releases at three receptor heights (1000 people per square mile)

Atmospheric	10 feet	20 Feet	30 Feet
Stability	Cost	Cost	Cost
Class A	$ 169,920	$ 169,212	$ 2,687
Class B	$ 203,895	$ 144,870	$ 508
Class C	$ 128,641	$ 44,698	$ 164
Class D	$ 126,464	$ 6,919	$ 86
Class E	$ 533,870	$ 17,231	$ 338
Class F	$ 1,499,712	$ 40,876	$ 852

Table 7. Maximum cost for each release stack height (1000 people per square mile)

5.4 Varying the Reference Release

The effects of doubling and halving the reference release rate were also modeled. The doubled release rate is 70.53 lbm NH3 (32 kg) per minute, while the halved release rate is 17.64 lbm NH_3 (8 kg) per minute. In all situations examined, the cost associated with the double release was more than double that of the reference release and the cost associated with the half release was always less than half of the reference release. The doubled release causes ammonia concentrations to be in the AEGL-2 (disabling) and AEGL-3 (fatal) classifications over a larger area than the reference release. Since the AEGL-2 and AEGL-3 classifications are many times more costly than the AEGL-1 level, the maximum costs increase by between two and thirteen times, depending on the release height and atmospheric stability conditions.

6.0 Failure Risk and Cost of System Failure

Now that the consequent cost of various ammonia releases has been calculated, the probability of the mitigation system failing and allowing a release must be determined. For the water diffusion tank, flare, and scrubber systems, a failure of any component or part in the system is assumed to cause a release. For the Emergency Pressure Control System (EPCS), a failure will lead to one of the other mitigation systems. For the direct discharge to atmosphere, any time ammonia is released from the refrigeration system through the relief vents, it will be discharged to the atmosphere.

Failure rate information reported in *Nonelectronic Parts Reliability Data 2011* (Denson 2011) was used to obtain component failure rates. In addition to the cost of replacing a failed part, a failure of the ammonia mitigation method will lead to some sort of unmitigated or partially mitigated ammonia release. If a component is redundant in the system, it is assumed to replace the original component avoiding system failure. Therefore, failure of both redundant components during the same event fails the system resulting in an unmitigated release. Similar to an electrical circuit diagram, failure rates of redundant parts are calculated in parallel with each other, and separate parts are calculated in series.

$$f_{system} = f_A + f_B + f_C + (f_D * f_E) \tag{7}$$

Since all of the failure rates are necessarily less than one, Equation 7 clearly shows that the failure rate can be significantly reduced if redundant parts are introduced for the least reliable parts of the system.

Nonelectronic Parts Reliability Data 2011 (Denson 2011) gives the failure rate of parts in terms of failure number per million hours based on field data. For this application, lower failure rates result from good maintenance practices and from intermittent operation. If a part was found to be defective or damaged during regular maintenance, it could be repaired or replaced during the absence of an overpressure event so there would be no ammonia release. As a result, the failure rates listed below may probably be overestimated for what would cause a failure of the system during time of operation, and therefore, conservative. All systems are treated uniformly making the results consistent. However, feedback from the industry suggests that these systems are not always well maintained therefore implying that the failure rates used in the predictions here are reasonable.

6.1 Failure Risk: Discharge to Atmosphere

The discharge to atmosphere is the simplest system, and thus the most reliable. There are very few parts involved that have the potential to fail; however, ammonia is always released, so the failure rate does not end up being used in the calculations (Figure 17).

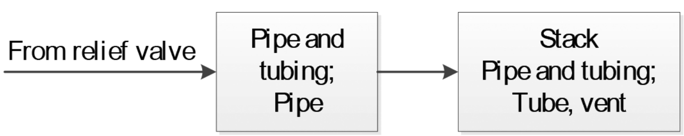

Figure 17. Failure path diagram for discharge to atmosphere

Discharge to atmosphere		
page	Parts	Failures per million hours
2-632	Pipe and tubing, pipe	2.477463
2-633	Stack - Pipe and Tubing, tube, vent	0.575243
	Total failures per million hours:	**3.05**

Table 8: Failure rates for discharge to atmosphere

6.2 Failure Risk: Water Diffusion Tank

The water diffusion tank has eight parts that could fail and cause a release. The parts that are most likely to fail are the tank itself and the manway. People in the industry have expressed concern about the rupture disk being the main source of problems, but according to the failure rate data, it is only the third most likely to fail. Neglected in the failure risk calculation is the disposal of the ammonia water mixture from the facility.

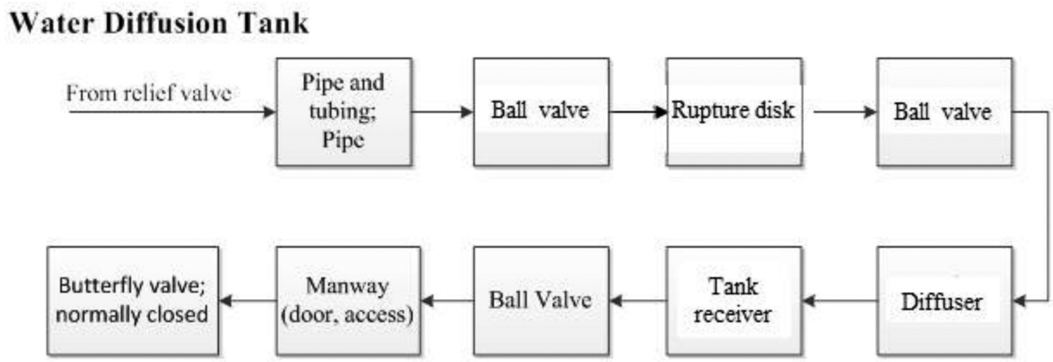

Figure 18. Failure Path Diagram for Water Diffusion Tank

Water diffusion tank		
Page	Parts	Failures per million hours
2-632	Pipe and tubing, pipe	2.477463
2-285	Diffuser	2.632306
2-289	Rupture Disk	4.289581
2-923	Tank, Receiver	13.991493
2-979	Butterfly Valve; Normally closed	0.448059
2-977	Ball Valve	1.505089
2-297	Manway (door, access)	20.89821
2-977	Ball Valve	1.585089
	Total failures per million hours:	**47.83**

Table 9: Failure rates for water diffusion tank system parts

6.3 Failure Risk: Scrubber

The scrubber is a more complicated system, with fifteen parts that are essential to the function of the system. It requires electric power to operate, and so must have a battery backup system in place. The pump is the most likely to fail out of all of its parts, and there are a relatively large number of components with a relatively high failure rate. Not surprisingly, since it is more complex, the scrubber is significantly more likely to fail than the water diffusion tank. The resulting failure rate for a simple scrubber without redundant components is relatively high at 128 failures per million hours.

A modified scrubber failure path diagram is shown in Figure 19 with added redundancy. A backup pump and backup liquid level switches are added. The added pump significantly improves the robustness of the system as that component was responsible for 28% of the failures of the original system. With the redundant pump installed, the chance of both pumps failing at the same time is so small that the pump is responsible for less than 1% of the system failures. The failure rate of the single pump failing is 36.1 failures per one million hours, but with the redundant pump installed, the rate of failure for that branch becomes much less than one failure per one million hours. The chance of both pumps failing is so small that the pumps go from being the main source of failure to a very minute portion. The redundant switches do not have nearly as great an impact, but they are relatively inexpensive and easy to install, so it is a worthwhile modification.

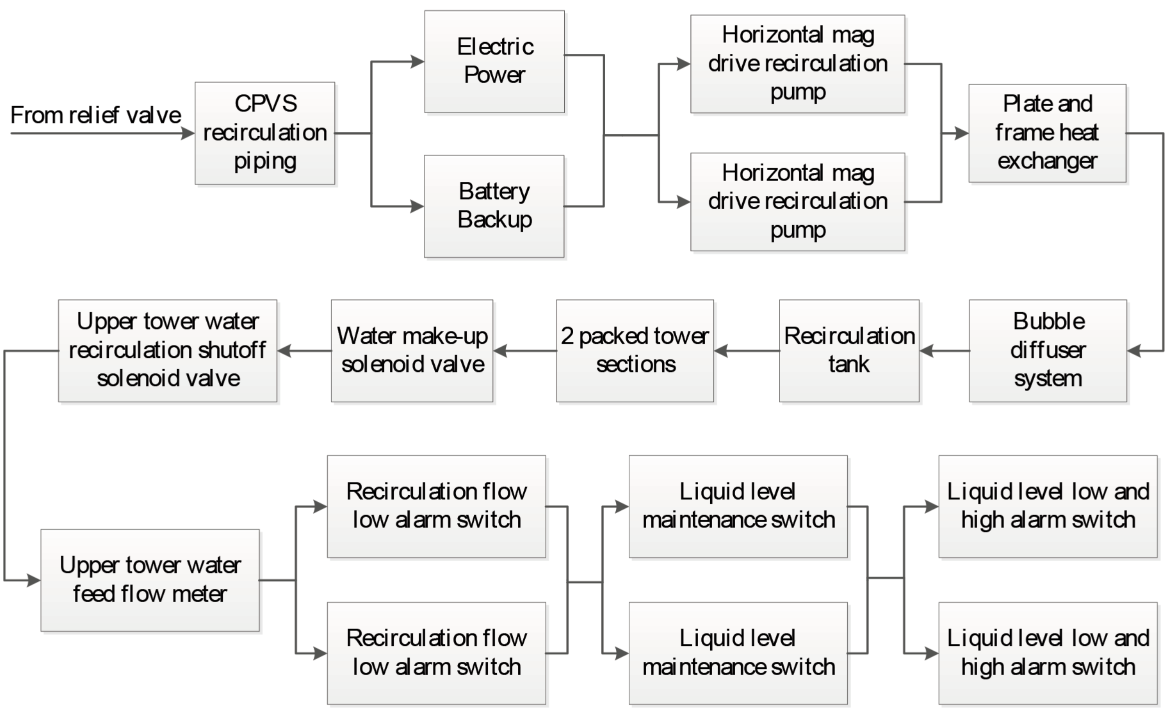

Figure 19. Failure path diagram for scrubber

Scrubber		
page	Parts	Failures per million hours
2-285	Bubble diffuser system	2.632306
2-923	Recirculation tank	13.991493
2-683	horizontal mag drive recirculation pump 7.5 hp	36.054515
2-683	horizontal mag drive recirculation pump 7.5 hp	36.054515
2-443	plate and frame heat exchanger	14.307564
2-632	CPVS recirc piping schedule 80	0.575243
2-894	1 recirculation flow low alarm switch	12.728835
2-895	liquid level maintenance switch	3.133598
2-895	liquid level maintenance switch	3.133598
2-895	liquid level low alarm switch	3.133598
2-895	liquid level low alarm switch	3.133598
2-895	liquid level high alarm switch	3.133598
2-895	liquid level high alarm switch	3.133598
2-225	water make-up solenoid valve	11.352988
2-556	upper tower water feed flow meter	15.574868
2-225	upper tower water recirculation shutoff solenoid valve	11.352988
2-878	power supply	13.991493
2-533	battery backup	20.486154
	Total failures per million hours:	**82.52**

Table 11. Failure rates for scrubber system parts

6.4 Failure Risk: Flare

The flare is the most complicated of all the systems, it has eighteen parts that could fail and cause a release. The least reliable parts are the two valve position controls that control the valves for the gas leading to the pilot flame and the main gas line for the incinerator. These valves regulate the amount of gas necessary based on the ammonia flow rate. These two parts alone account for over half of the failure rate for the flare.

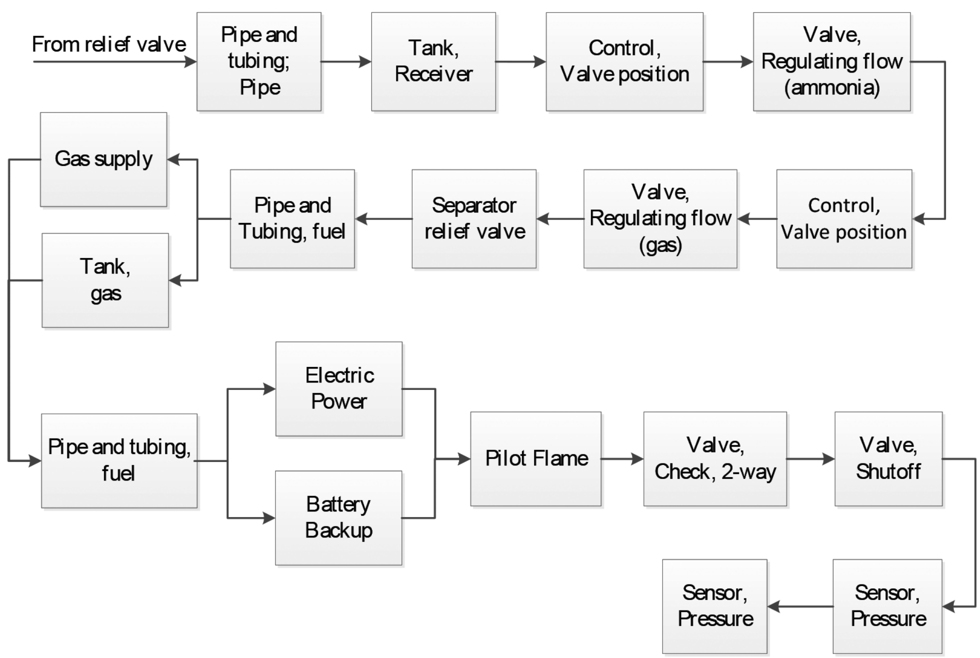

Figure 20. Failure path diagram for flare

Flare		
page	Parts	Failures per million hours
2-923	Tank, Receiver	13.991493
2-994	Valve, regulating, flow	4.120517
2-994	Valve, regulating, flow	4.120517
2-634	Pipe and tubing - fuel (for natural gas line)	2.272727
2-388	Gas supply	10.078525
2-921	tank, gas	5.995914
2-995	Separator Relief Valve	11.450611
2-473	Pilot Flame	3.922117
2-794	Sensor, Pressure	2.394713
2-794	Sensor, Pressure	2.394713
2-226	Control, Valve Position	46.724605
2-226	Control, Valve Position	46.724605
2-994	Valve, check, two-way	4.289581
2-994	Valve, shutoff (ISV-2)	17.396594
2-632	Pipe and tubing, pipe	2.477463
2-878	power supply	13.991493
2-533	battery backup	20.486154
	Total failures per million hours:	**162.281**

Table 10: Failure rates for flare system parts

6.5 Failure Risk: Emergency Pressure Control System

The Emergency Pressure Control System is a fairly simple system, with only 5 parts; however the two pressure regulating valves have a high failure rate, and so the overall system failure rate is comparable to the scrubber and flare.

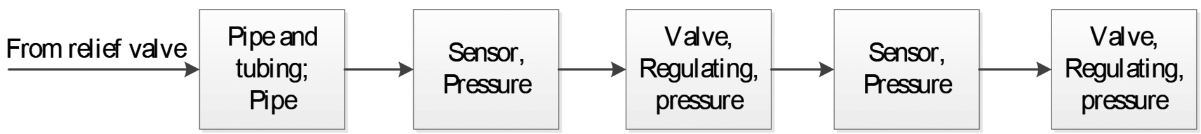

Figure 21. Parts for Emergency Pressure Control System

Emergency Pressure Control System		
Page	Parts	Failures per million hours
2-632	Pipe and tubing, pipe	2.477463
2-994	Valve, regulating, fluid pressure	51.704197
2-994	Valve, regulating, fluid pressure	51.704197
2-794	Sensor, Pressure	2.394713
2-794	Sensor, Pressure	2.394713
	Total failures per million hours:	**110.68**

Table 11: Failure rates for emergency pressure control system parts

6.6 Failure Risk: System Comparison

Table 12 shows the failure rates for all mitigation systems examined in this study. For the EPCS, a failure will result in a release that will go to one of the other mitigation systems, while for the four remaining systems, a failure will result in an unmitigated release to atmosphere. Note that the direct discharge to atmosphere will always result in a release, so its failure rate is set at 1,000,000 / 1,000,000 or 1, even though the system is not actually failing to do what it is designed to do.

Release Mitgation System	Failures / Million Hours	Failures / Year	Failure Release Stack Height (ft)
Discharge to atmosphere	1,000,000	8760	30
Scubber	82.5	0.72	20
Flare	162.3	1.42	20
Water diffusion tank	47.8	0.42	20
EPCS	110.7	0.97	(Goes to other mitigation)

Table 12: Failure rates for each mitigation system

The stack height for the three mitigation systems is 20 ft (6.10 m) while the direct discharge system has a stack height of 30 ft (9.14 m) in the comparisons. Also, in order to compare the four systems, it is important to know a relative failure rate for each system, and a corresponding relative cost of failure for each. To find a relative cost of failure, the average cost of failure for all atmosphere stability classes for the associated release height was determined. To find the overall relative cost, the relative failure rate was multiplied by the relative cost. The water diffusion tank was taken as the baseline for comparison. The EPCS was not included because it will be used in conjunction with another mitigation system, and will serve to greatly reduce the risk of a release. Tables 13, 14, and 15 show the results where the reference release, the double reference release, and the half reference release are shown, respectively. The costs shown are based on a population density of 1000 people per square mile.

Release Mitigation System	Relative Failure Rate	Cost of a Release	Relative cost of a Release	Relative Cost
Discharge to atmosphere	20,909	$ 772	0.011	230
Flare	3.39	$ 70,635	1	3.39
Scrubber	1.73	$ 70,635	1	1.73
Water diffusion tank	1	$ 70,635	1	1

Table 13: Relative cost of release by mitigation system—reference release

Release Mitigation System	Relative Failure Rate	Cost of a Release	Relative cost of a Release	Relative Cost
Discharge to atmosphere	20,909	$ 3,605	0.018	376
Flare	3.39	$ 201,184	1	3.39
Scrubber	1.73	$ 201,184	1	1.73
Water diffusion tank	1	$ 201,184	1	1

Table 14: Relative cost of release by mitigation system—double reference release

Release Mitigation System	Relative Failure Rate	Cost of a Release	Relative cost of a Release	Relative Cost
Discharge to atmosphere	20,909	$ 96	0.018	376
Flare	3.39	$ 25,328	1	3.39
Scrubber	1.73	$ 25,328	1	1.73
Water diffusion tank	1	$ 25,328	1	1

Table 15: Relative cost of release by mitigation system—half reference release

Tables 13, 14, and 15 show that the relative cost of direct discharge to atmosphere far exceeds that of the other systems. On the other hand, the cost of an individual release that is directly discharged to atmosphere at a height of thirty feet, instead of due to a failure in one of the other mitigation systems at a lower height, is relatively small. Note that while the "relative cost" of a release in Table 13 shows substantially higher values for discharge to the atmosphere compared to the flare, scrubber, and water diffusion tank, the "relative cost of a release" column clearly indicates a substantially lower cost by more than a factor of 50. In conjunction with EPCS, the relative failure rate is significantly reduced supporting the direct discharge to the atmosphere method. At the same time, other factors such as surrounding population density and topography may not favor the use of direct discharge.

Used in conjunction with an EPCS, direct discharge to atmosphere is a favorable option because there would very rarely be a release, and when there was, the impact would be minimized by the high elevation of discharge.

Recall that the mitigation systems examined are equivalent to each other in that each has a 20 ft (6.10 m) discharge stack height with the exception of direct discharge which has a 30 ft (9.14 m) height. The relative cost column is normalized using the diffusion tank at the 20 ft (6.10 m) height. The flare, scrubber, and diffusion tank can each be designed as an effective ammonia release mitigation system. Interestingly, if the scrubber did not have redundant pumps and controls, its relative failure rate would increase to about 4.1 from its 1.73 value in Tables 13, 14, and 15. Alternatively, if additional redundancy were added to the scrubber further reducing the failure rate from that computed for the proposed scrubber here, it is conceivable that the failure rate could be reduced to about 55.5 which are essentially the same as that of the water diffusion tank. This demonstrates that careful engineering of the scrubber and flare can result in similar risks regarding the mitigation of ammonia releases compared to that of the water diffusion tank.

Summarizing, the mitigation systems analyzed all reduce the consequences of an ammonia release to the surrounding population. Direct discharge does this by diluting the ammonia with air at a high elevation. The eater diffusion tank, scrubber, and flare accomplish this by treating the ammonia so that it is not released. The EPCS achieves this same result by directing the ammonia that would be released to a lower pressure vessel in the refrigeration system. In this study, the impact of a selected quantity of ammonia released to a surrounding population has been determined and reduced to an equivalent damage to health cost. This cost in conjunction with the expected failure rate of a particular mitigation system gives the cost impact of that particular mitigation system. Thus, the system with lower relative cost has the lesser risk. This study did not examine a specific plant and its surroundings, but rather, assumed typical features that were maintained constant in order to make consistent comparisons involving the mitigation systems. Therefore, designers may use the methods and results of this study to assist in the determination of a mitigation system's expected failure rate, and along with a plant's particular characteristics (surrounding population density, topography, etc.) develop a mitigation system that provides an acceptable failure frequency resulting in an acceptable consequent cost associated with an ammonia release of interest.

The EPCS is different from the other mitigation systems because the ammonia that would be released is contained within the refrigeration system. Its expected failure rate is on the order of the other three mitigation methods and so its performance in mitigating an ammonia release is comparable too. The EPCS coupled with a direct discharge of sufficient height (ammonia plume dispersion modeling is needed to determine this) can achieve the same performance as the other mitigation systems. Obviously, for the conditions of this study, a 30 ft (9.1 m) high discharge coupled with any of the three mitigation systems, or the EPCS, would yield approximately the same impact resulting from the same ammonia release.

7.0 Conclusions

The objective of this study was to determine the effectiveness of different methods mitigating ammonia releases due to the opening of pressure relief devices in an ammonia refrigeration system. The methods investigated were: water diffusion tank, scrubber, combustion flare, and direct discharge to the atmosphere. A quantitative risk analysis (QRA) was conducted for each of these methods. The analysis involved the use of the dispersion model SLAB (2012) that predicted downwind concentrations in the ammonia vapor plume. The terrain was assumed perfectly flat with roughness appropriate for a suburban area. It is realized that wind direction and speed is influenced by the local topography where the facility is located. Consequently, an actual ammonia refrigeration facility is not examined here, but rather a typical industrial refrigeration facility using ammonia where the refrigeration load was 362 tons (1270 kW) and ammonia charge was 11,590 lbm (5,300 kg). The impact of the ammonia plume was assessed by determining the consequent medical costs associated with the exposure to the population.

Three reference ammonia release was defined as 35.3 lb/min (16 kg/min) for a duration of one hour. Release rates double and half the reference rate were also examined in this study. Failure analysis performed on the water diffusion tank, scrubber, and flare resulted in 48, 83, and 162 predicted failures per million hours operation, respectively. The water diffusion tank serving as the method to which the other systems were compared, gave the relative failure rate as 1, 1.8, and 3.4, respectively. These failure rates are comparable to one another suggesting that these three mitigation systems are approximately equivalent in their effectiveness. The EPCS system's predicted failure rate was 111 failures per million hours which is the same level as the diffusion tank, scrubber, and flare. Therefore, it is reasonable to conclude that each of these ammonia release mitigation systems examined, water diffusion tank, scrubber, flare, and EPCS may be engineered to an equivalent level of risk with the approach in used in this study.

Direct discharge of ammonia to the atmosphere is a different approach to mitigating the release of ammonia – the ammonia is released from the facility and diluted by the atmosphere to lower concentrations. While the water diffusion tank, scrubber, and flare were assumed to release at a height of 20 ft (6.1 m) above ground, the direct discharge method in this study released at height of 30 ft (9.14 m) above the ground. As a result of the lower downwind concentrations, the downwind health impact of the ammonia was significantly reduced. The analysis done in this study indicates, under the assumed conditions, the relative impact (cost) of a release at 30 ft (9.14 m) is less than 2% of the impact from the other mitigation methods examined.

Any of the three mitigation systems – diffusion tank, scrubber, or flare – may be used in conjunction with discharge to the atmosphere. Doing so will obviously decrease impact of the ammonia being released. However, the EPCS has similar performance to diffusion tank, scrubber, and flare and so would also produce the same reduction. Consequently, the EPCS coupled with direct discharge to the atmosphere is an effective approach to mitigating the impact of an ammonia release. However, the surrounding population density, topography and other factors may cause the direct discharge method to be unworkable if used alone.

An ammonia release size double the reference release (35.27 lbm NH3 per minute (16 kg/minute)) more than doubles the human cost of the reference release. This occurs due to the tiered nature of the Acute Exposure Guideline Levels and the health event costs, and so there is no linear relationship between the amount of ammonia released and its impact cost.

References

Advanced Air Technologies, Inc. 2012. Internet. http://www.aat.cc/store.asp?pid=26895

AERMOD. 2004. http://www.epa.gov/scram001/7thconf/aermod/aermod_mfd.pdf

Air Resources Board. 2006. “Quantification of the Health Impacts and Economic Valuation Of Air Pollution From Ports And Goods Movement In California”

ALOHA (Area Locations of Hazardous Atmospheres). 1999. US EPA, Chemical Emergency Preparedness and Prevention Office, Washington, DC.

Anon. 1996. *Guidelines for Use of Vapor cloud Dispersion Models, 2nd Edition*. American Institute of Chemical Engineers, New York, NY.

ANSI/IIAR 2-2010. “Equipment, Design and Installation of Closed-Circuit Ammonia Mechanical Refrigeration Systems.” International Institute of Ammonia Refrigeration (IIAR), Alexandria, VA,

Biondi, M. 2012. Private Communication. Advanced Air Technologies, Inc., Corunna, MI.

California Building Standards Commission. 2010. “2010 California Mechanical Code,” California Building Standards Commission, Sacramento, CA.

CalPuff. 2013. http://www.beeline-software.com/product/tabid/355/p-3-professional-calpuff.aspx

CDC (Centers for Disease Control and Prevention. 2012. Atlanta, Ga. http://www.cdc.gov/niosh/npg/npgd0028.htmlCHARM (Complex Hazardous Air Release Model). 2012. CHARM Software, Lometa, TX.

CHARM. 2013. http://www.charmmodel.com/charm.aspx

DEGADIS. 2012. Trinity Consultants, Inc. Dallas, TX. Kivama, Ryo and Shigeru Minomura. 1950. “Reaction Between Ammonia and Carbon Dioxide Under High Pressure.” The Review of Physical Chemistry of Japan. Vol. 21, No. 1.

Denson, W., Chandler, G., Crowell, W. Clark, A., Jaworski, P. 2011. *Nonelectronic Parts Reliability Data 2011*. Reliability Information Analysis Center, Rome, NY.

Ermak, D. 1990. *User’s Manual for SLAB: An Atmospheric Dispersion Model for Denser-Than-Air Releases*. Lawrence Livermore National Laboratory, Livermore, CA

Federal Register, Sept. 5, 1996, “Protection of Stratospheric Ozone.” Vol. 61, No. 173 (47012-47018).

Fenton, D. L., Noeth, A. F. and Gorton, R. L., "Evaluation of Water as an Ammonia Trap," Int'l. Inst. of Ammonia Refrig. 13th Annual Meeting, San Francisco, CA, March 24-27, 1991. (Invited)

Fenton, D. L., Noeth, A. F. and Gorton, R. L., "Absorption of Ammonia into Water," ASHRAE Transactions, Vol. 97, Part 1, pp. 204-211, 1991.

Fenton, D., Walenta, C., and Chapman, K., “Dispersion of Ammonia Into the Atmosphere”, ASHRAE Transactions 2001, V. 107, Pt. 1. Atlanta, GA.

Fenton, D.L, Chapman, K.S., Kelley, R.D., and Khan, A.S., ., "Operating Characteristics of a Flare/Oxidizer for the Disposal of Ammonia from an Industrial Refrigeration Facility," ASHRAE Transactions, V. 101, Pt. 2, Atlanta, GA., 1995.

Fenton, D.L., Khan, A.S., Kelley, R.D., Chapman, K.S. , "Combustion Characteristics of Ammonia-Air Mixtures," ASHRAE Transactions, V. 101, Pt. 2, Atlanta, GA., 1995.

Heil Process Equipment, Inc. 2012. Private Communication, Avon, OH.

Hodges, T. and D.L. Fenton. 2013. Comparison of various methods of mitigating over pressure induced release events involving ammonia refrigeration using quantitative risk analysis (QRA). Final Report. Int’l Inst. Of Ammonia Refrigeration, Alexandria, VA.

International Code Council. 2012. “2012 International Fire Code,” International Code Council, Country Club Hills, IL.

International Code Council. 2012. “2012 International Mechanical Code,” International Code Council, Country Club Hills, IL.

Kaiser, Geoffrey. “Identification and Modeling of Worst-Case Scenarios for Ammonia Refrigeration Systems” Int'l. Inst. of Ammonia Refrig. 18th Annual Meeting, Atlanta, GA, March 3-6, 1996.

Khan, A. S., Kelley, R. E., Chapman, K. S., and Fenton, D. L., "Flammability Limits of Ammonia/Air Mixtures," ASHRAE Transactions, V. 101, Pt. 2, Atlanta, GA., 1995.

Lindborg, Anders. “Risk Assessment on a Large Industrial Ammonia Refrigeration System in Central Copenhagen, Denmark.” Int'l. Inst. of Ammonia Refrig. 28th Annual Meeting, Reno, NV, March 19-22, 2006.

National Research Council of the National Academies 2007. “Acute Exposure Guideline Levels for Selected Airborne Chemicals, Volume 6,” The National Academies Press, Washington, DC.

SLAB. 2012. Lakes Environmental Software, Waterloo, Ontario, Canada.

Shepherd, James. ”Ammonia Flares: Costs, Codes, Installation and Design Considerations”, Int'l. Inst. of Ammonia Refrig. 12th Annual Meeting, Memphis, TN, March 4-7, 1990.

Shepherd, James. ”Ammonia Flares: Incinerators-Oxidizers – A Proven Safe and Readily Used Method for Disposing of Ammonia in Industrial Applications”, Int'l. Inst. of Ammonia Refrig. 10th Annual Meeting, Savannah, GA, March 6-9, 1988.

Stoecker, W. F. *Handbook of Industrial Refrigeration1998*. McGraw-Hill Book Company, New York, NY.

Turner, D. B. “Workbook of Atmospheric Dispersion Estimates” U.S. Department of Health, Education, and Welfare; Public Health Service Publication No. 999-AP-26. 1970.

User’s Guide for the Industrial Source Complex (ISC2) Dispersion Models, Vol. 1 – User’s Instructions. 1992. U. S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

Notes: