

COMPARISON OF VARIOUS METHODS OF MITIGATING OVER PRESSURE INDUCED
RELEASE EVENTS INVOLVING AMMONIA REFRIGERATION USING QUANTITATIVE
RISK ANALYSIS (QRA)

by

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B.S., Kansas State University, 2010

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering
College of Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2013

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Abstract

This project was done to determine the effectiveness of different methods of mitigating the effects of an ammonia release through a pressure relief device in an ammonia refrigeration system. Several methods were considered, and five were selected for further study. The methods chosen for further study were 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. Discharge into a tank containing standing water is the most common method in existence today but several people in the ammonia refrigeration industry have questioned its reliability. The methods were compared based on a quantitative risk analysis, combining failure rates of each system with ammonia dispersion modeling and the monetized health effects of a system's failure to contain an ammonia release.

It was determined that the release height had a greater influence on the downwind cost impact than any other variable, including weather conditions and release from multiple sources. The discharge into a tank containing standing water was determined to have the lowest failure rate, while the flare system was found to be the most effective in terms of relative overall release consequent cost. The emergency pressure control system is now required by the codes, and any of the other mitigation systems would be very effective when used in conjunction with the emergency pressure control system.

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Phase 1

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 cause 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 capture 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 captured, 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.

The objective of Phase 1 of this project is to determine the methods that are employed to capture ammonia released from pressure relieving devices at a refrigerating facility. The pressure relief

valves are installed with a set pressure so that they prevent the vessels storing ammonia – high, intermediate and low pressure receivers, flash tanks, and others – from structurally failing due to high pressure. In cooperation with the IIAR Project Monitoring Committee, several of these methods have been selected for further study and are analyzed on the basis of a quantitative risk analysis in Phase 2 of the project. Ammonia may be released from a refrigeration plant by other means than through a pressure relief valve system. These include: leaks through rotating seals, piping 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 capturing 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. This is so because of the evaporative cooling lowering the pressure in the vessel, which, in turn, reduces the mass flow of ammonia from the vessel. Once a safe pressure level is achieved inside the vessel, the pressure relief valve will close, shutting off the ammonia flow, with some ammonia still remaining in the vessel. If the vessel is allowed to vent sufficiently long to achieve an internal pressure equal to atmospheric pressure, the liquid temperature would be -28°F and the vapor flow rate from the vessel would be limited to that caused by evaporation driven by heat transfer into the vessel. This project is associated with only ammonia releases that occur with the opening of pressure relief valves. Other ammonia releases from the refrigeration equipment occurring from mechanical failure are outside the operating

conditions of an ammonia capturing system designed to operate in conjunction with a system's pressure relief valves.

For the purposes of this study, a conservative assumption will be 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 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 ft³ (9.0 m³). 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 Equation 1 is applied.

Equation 1:

$$C = fDL$$

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 (NH₃) (16.0 kg) per minute. The equation is designed for the flow rate of air in lbm/minute because of the units of the flow factor f , so the value for C must be converted from lbm (air)/min to lbm (NH₃) based on the ratio of their molecular weights. 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 NH₃ (959.8 kg).

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

3.0 Application of Codes

ANSI/ASHRAE Standard 15-2010 Safety Standard for Refrigeration Systems establishes many requirements relating to the safe operation of a refrigerating facility. An important code that supports Standard 15 is the ASME Boiler and Pressure Vessel Code – 2010, which addresses vessels and piping in particular. Another code required only by ammonia refrigeration systems is ANSI/IIAR 2-2008 published and maintained by the International Institute of Ammonia Refrigeration (IIAR) and by its Appendix K presents information useful for “Emergency

Pressure Control Systems.” ANSI/IIAR 2-2008 refers to and draws on information given in ANSI/ASHRAE Standard 15. At the local Authority Having Jurisdiction that enforces compliance with the applicable codes, the International Fire Code – 2012 or other mechanical code can be applied to an individual facility in its design and installation. These codes also reference information from the ASME Boiler and Pressure Vessel Codes, ANSI/ASHRAE Standard 15, and IIAR 2. The refrigeration system must be compliant with all applicable codes before it is permitted to operate.

ANSI/ASHRAE Standard 15, IIAR 2, and the International Fire Code – 2012 have provisions requiring, to a varying extent, the capture 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 capture 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 606.12.4, 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 captured 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 using a sufficiently high stack.

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 Capturing Methods

For this study, several different ammonia capturing methods are being considered. Some of these methods are used more than others. The most commonly used capture method is discharging the ammonia into a water diffusion tank where it is absorbed. 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 being used for this application in industry, is a scrubber system. For plants that are already using a cascade refrigeration system with both carbon dioxide and ammonia, there is a possibility of using carbon dioxide as the scrubbing agent instead of water. Other chemical solutions can be used in conjunction with water as the scrubbing agent to improve effectiveness. In some cases, the ammonia may be released directly to atmosphere through a sufficiently tall stack 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 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, and that ammonia is naturally occurring in air.

By section 9.7.8 of 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 minimum 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 capturing equipment for emergency releases of chemicals such as ammonia.

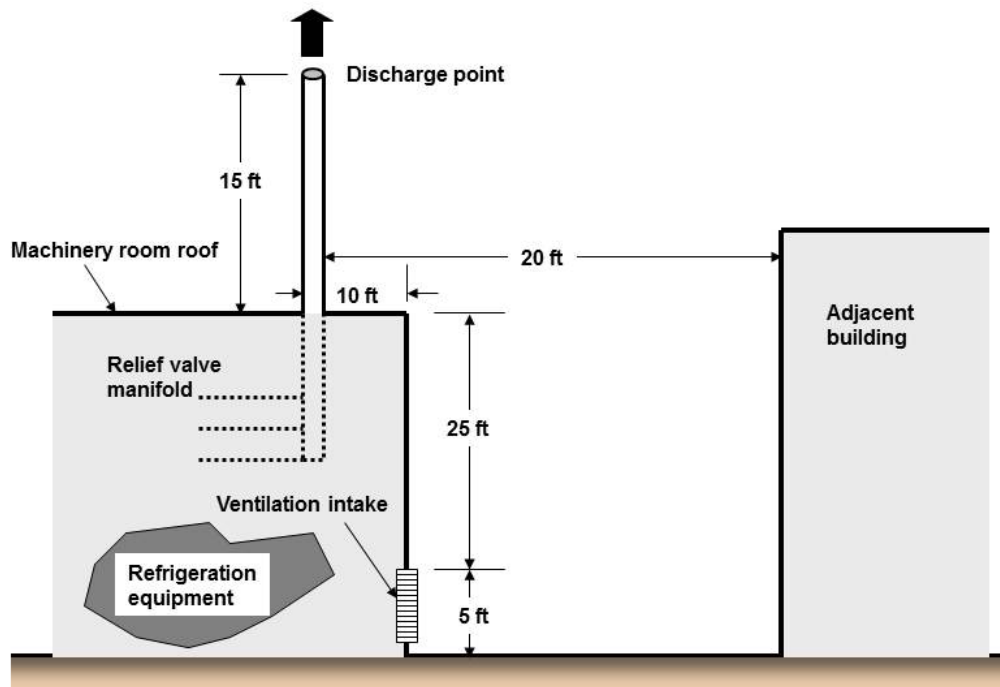


Figure 1: Schematic diagram of an ammonia discharge stack at a refrigeration facility showing minimum stack height above and adjacent to building structures.

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. Stoecker (1998) reports that stack height and upward discharge velocity reduce downwind ground level

ammonia concentrations based on dispersion model predictions. For the conditions that he investigated, a release rate of 20 lbm/min (0.15 kg/s), peak ground level concentrations were reduced by a factor of more than two by increasing the upward velocity by a factor of four (obtained by decreasing the stack inside diameter by a factor of two) where the stack height was 20 ft (6 m). Additionally, by doubling the stack height (from 20 ft (6 m) to 40 ft (12 m)), the peak ground level concentration was reduced by 60%. In all situations, the peak ground level concentrations were measured at a distance less than 330 ft (100 m) from the stack position.

Fenton et al. (2001) completed a study for ASHRAE measuring the concentration of ammonia vapor downstream from more than 80 controlled releases, over varying weather stability classes, at two discharge heights: 6 ft (1.8 m) and 26.5 ft (8.1 m) above the ground, and 80 ft (24 m), 160 ft (49 m), and 320 ft (98 m) downstream. The objective of this research was to determine the influence of stack height, discharge upward velocity, and the ammonia concentration on the downwind dispersion of ammonia. Release velocities were 32.8 ft/s (10 m/s) and 164 ft/s (50 m/s). Elevations were 6.5 ft (2.0 m) and 26.5 ft (8.1 m). Concentrations of the ammonia vapor in air were 100% and 1% by volume. All the ammonia releases were simulated using the then available EPA ISCST2 atmospheric dispersion model (1992). The experimental data, supported by the ISCST2 predictions, showed that ground level ammonia concentrations were influenced the most by the discharge height. As an example, Figure 2 shows measured downwind ammonia vapor concentrations from experiment HLL_5 (high ammonia vapor concentration source (pure ammonia vapor), low elevation (6 ft (1.8 m) above ground), and low velocity (33 ft/sec (10 m/s))). The ISCST2 model does adequately predict the general trend of the release for the six detector locations. For the lower elevation detector locations, the ISCST2 predicts that the concentration of ammonia vapor decreases as the plume moves downwind. This trend was

matched by the detector readings, although the values between the two were not an exact match. For the upper elevation detector locations, the model predicts that the concentration increases as the plume moves downwind, but that concentrations are low and under 10 ppm (v/v).

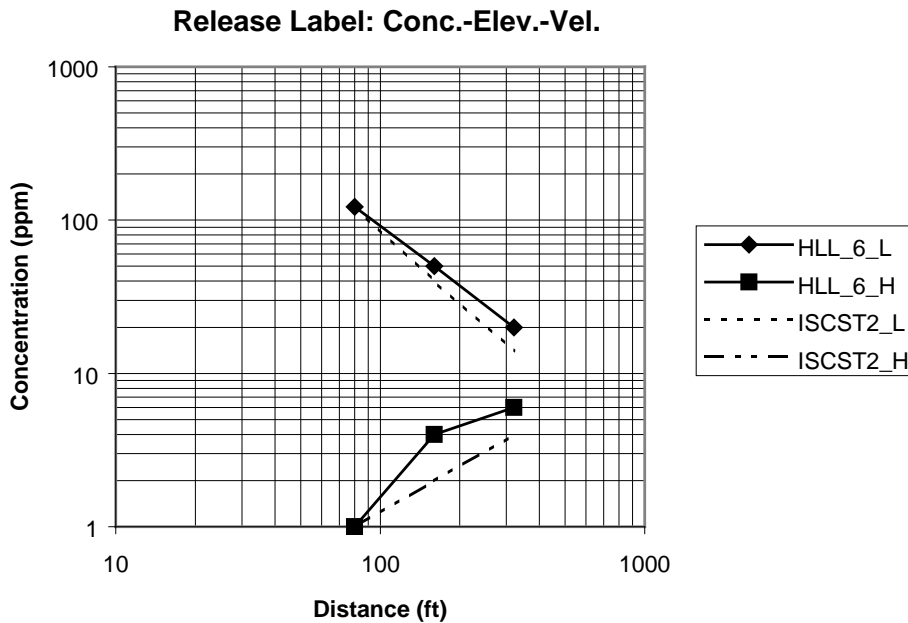


Figure 2: Comparison of measured and predicted downwind ammonia vapor concentration for release HLL_6 (pure ammonia source, 6.5 ft elevation above ground, 33 ft.sec upward velocity) (Fenton et.al. 2001).

The experimental data collected by Fenton et al. (2001) indicated that increasing the elevation of the release, decreasing the ammonia concentration, and increasing the upward velocity at the source all individually reduce the downwind ammonia concentrations at ground level. However, the data also shows that the plume rose, increasing the ammonia concentration at the detectors located at the high elevation. The three ground level measurements showed approximately an 80% reduction in concentration from the low to the high release elevation. The next most effective source characteristic in reducing ground level concentration was the ammonia vapor

concentration, reducing the concentration by 50%. 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. Also, the Fenton et al. (2001) release data suggested that the combined effect of decreasing source ammonia vapor concentration and increasing upward velocity have about the same effect as just increasing the source elevation. Note these generalizations are based on the Fenton et al. (2001) experimental data and so are restricted to the specific changes made in the source characteristics for their project.

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)."

In summary, the dispersion model predictions made by Stoeker (1998) regarding downwind ammonia vapor concentrations are supported by the experiments and ISCST2 dispersion model predictions conducted by Fenton et al. (2001). Deviations between these two studies are within the normal variations of air dispersion studies. According to Beychok (1995) a factor of 2 or 3 is an acceptable result. Consequently, air dispersion models predicting the downwind concentrations of ammonia vapor are valid. Depending on the amount of ammonia released,

whether the ammonia is an aerosol or a vapor, the weather conditions, and the surrounding topography, there are innumerable scenarios that can result from ammonia being discharged to the atmosphere.

The experiments conducted by Fenton et al. (2001) only considered vapor ammonia. From a casual survey conducted by Stoecker (1995), about half of the ammonia releases from relief valves contain liquid ammonia in the form of an aerosol. The ammonia from these discharges appeared similar to steam. Ammonia aerosol can be generated by a sudden pressure drop in a vessel containing ammonia liquid caused by the opening of a pressure relief valve. The ammonia liquid will boil in order to adjust to the pressure drop, forming vapor bubbles throughout the liquid. The consequent violent agitation of the liquid generates droplets which are entrained into the vapor flow stream from the vessel and into the pressure relief piping manifold. As the release of ammonia occurs, the aerosol leaves the stack at the point of discharge and enters the atmosphere, appearing as a “white” cloud (similar to steam). The aerosol is a two-phase mixture of ammonia liquid and vapor, with the liquid dispersed into a large number of small droplets. Because the ammonia liquid droplet is evaporating ammonia, the temperature of the ammonia droplet and the surrounding vapor is very cold (ammonia liquid at atmospheric pressure is nearly -28°F). As a result, the density of the ammonia cloud greater than that of the ambient air. The ammonia cloud descends to the ground level and remains there until it's fully mixed with the ambient air. The ammonia concentrations in the cold aerosol could be very high thus posing a dangerous hazard to all humans and animals that may come in contact with it. The local topography and prevailing wind conditions are very important as it directs the movement of the cold aerosol cloud.

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 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 (2012), DEGADIS (2012), and SLAB (2012). Application of software capable of predicting ammonia aerosol cloud behavior is outside the scope of this project.

Wewers and Fenton (2011) have proposed a simple device that separates ammonia liquid from vapor in a discharge line. Preliminary tests conducted by the Ammonia Safety and Training Institute (ASTI) (Smith 2011) have shown that the device, named "Ammonia Liquidator" does indeed capture a large fraction of the liquid portion of the ammonia vapor mixture before it enters the atmosphere. A device like this, inserted in the pressure relief manifold upstream from the discharge point, has the potential of trapping the liquid phase of the ammonia released, therefore reducing the liquid phase of an aerosol cloud. The trapped ammonia liquid may be either reclaimed or disposed of by a procedure acceptable to the authority having jurisdiction.

An alternative approach for the dispersion of ammonia has been uncovered – namely moving the point of discharge to the top of an evaporative condenser. This idea seems to have merit by the fact that the velocity of the air exiting the evaporative condenser is always upward and that the droplets in the airstream will absorb the ammonia, thereby reducing the ammonia concentration.

With careful review of this idea, several important safety issues remain. The first is that the ammonia is still present in the evaporator's plume and so as the water droplets evaporate, ammonia will also evaporate and become vapor. This will increase the vapor concentration of the ammonia. The ammonia flow rate during a release could overwhelm the evaporative condenser plume's ability to handle it. Further, when the ambient air's relative humidity is high, evaporation will slow down, causing the ammonia-water droplets to settle out from the plume where the pH of the droplets will be approximately 12. At this pH level, the droplets would have several negative effects upon settling, including damage to automobile paint finishes and human health hazards due to inhalation. Conceivably, the evaporative condenser's plume under high RH levels could migrate for considerable distances, exacerbated by low temperatures caused by the ammonia. Second, the top of an evaporative condenser may not be in a position satisfying Standard 15's criteria for location of the discharge point.

4.2 Ammonia Absorption into Water Contained in a Tank

This concept's general requirements originate with ASHRAE Standard 15 (ASHRAE 2010) paragraph 9.7.8.2.b which states that if a water dilution tank is used, the water and ammonia quantities used 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 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. The study found that at ratios of one gallon of water to one pound of ammonia, the water was 90% effective at trapping ammonia vapor and 100% effective at trapping ammonia liquid. The effectiveness of trapping ammonia vapor approaches 100% if the ratio of water to ammonia is increased.

Figure 3 shows experimental results for the ammonia to water ratio given in Standard 15. It shows that as the ammonia concentration reaches its maximum while being trapped in water, the ammonia to water ratio is very near the 1 lbm NH₃ 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.

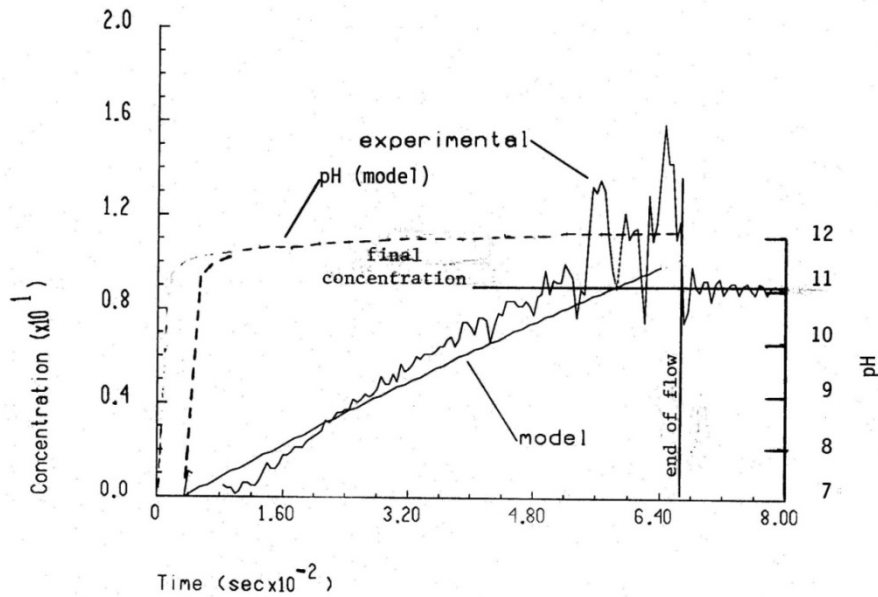


Figure 3: Experimental results and model predictions of ammonia concentration in water for ammonia absorption into water ending at 1 pound of ammonia per gallon of water (Fenton et al. 1991).

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 prevents the migration of moisture into the relief piping, preventing failure of the pressure relief valve caused by rust. A schematic diagram of a water diffusion system is shown in Figure 4 where the basic components are shown. 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. Figure 5 shows a "generic" water diffusion system as it would appear installed at a refrigeration plant.

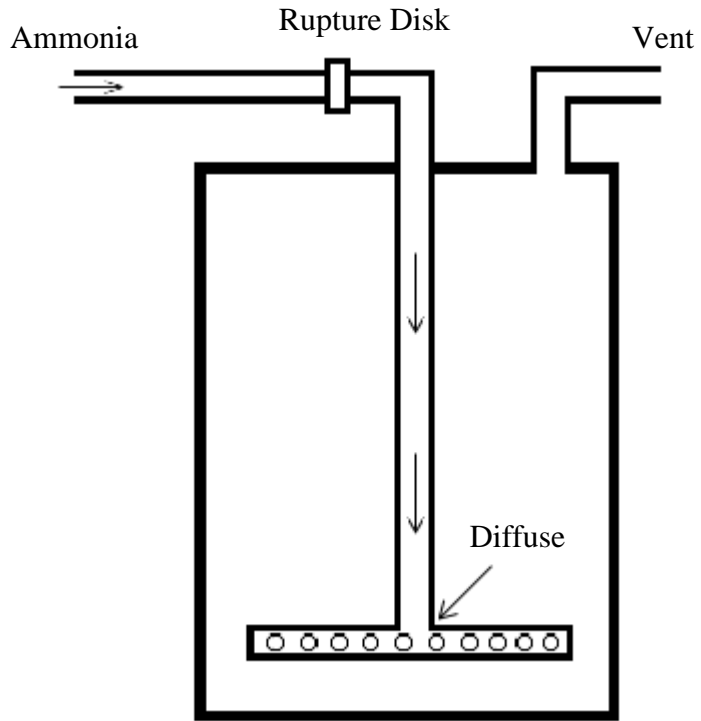


Figure 4: Schematic diagram of a water diffusion tank for the absorption of ammonia into standing water.

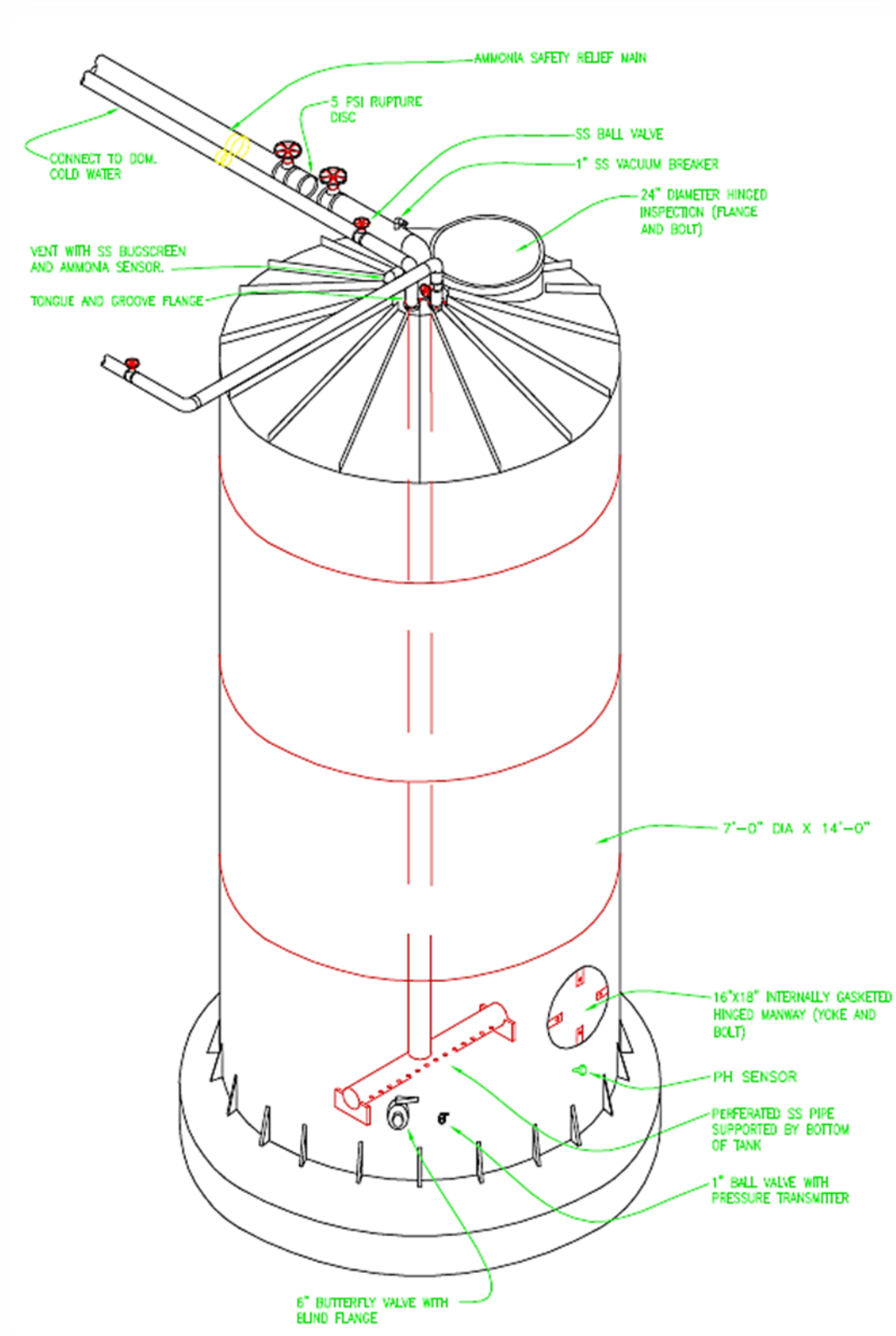


Figure 5: A generic water diffusion tank system as installed (Chapp 2012)

After the system is used, something must be done with the ammonia-water solution. Stoecker (1998) suggests a few different methods for dealing with the leftover ammonia-water solution. Combining this information and the information obtained with several personal communications, several alternative approaches were discovered for the disposal of ammonia-water mixtures. Depending on the local Authority Having Jurisdiction (AHJ), it can be forbidden to dump the ammonia-water mixture into the storm water drain for environmental reasons which include potential harm to marine life. Methods that may be acceptable are discussed below.

1. Employ licensed hazardous waste transporters to remove and dispose the ammonia – water mixture. In some instances, it may be possible to reclaim the ammonia in the mixture and re-use it in the refrigeration plant. Depending on the local AHJ, the ammonia-water mixture may be applied as an agricultural fertilizer when it is free of contaminants.
2. If allowed and approved by the local AHJ, the ammonia-water mixture may be added (possibly diluted with water) to the sewer provided that ammonia quantities and concentration limits are adhered to. A permit may need to be obtained to accomplish this.
3. If the refrigeration plant has internal provisions to handle the ammonia-water mixture, its facilities can be used to hold the mixture in separate holding tanks and slowly drain to the on-site water treatment plant.
4. Mixing the ammonia-water mixture with an acid such as citric acid or sulfuric acid, using appropriate concentrations may be useful. The chemical reaction that occurs with the acid will neutralize the ammonia-water solution leaving an ammonium salt which is non-hazardous and easily disposed.

5. The ammonia-water mixture could be distributed over an empty parking lot located several hundred feet from the closest neighbors. The parking lot must not contain any drains leading to the storm water drains and local foot and vehicular traffic must be limited to a safe distance. A caution is in order here, the ammonia mass leaving the plant facility cannot exceed 100 lb (45 kg) NH_3 per 24 hour period.
6. The ammonia-water mixture could be left open to the atmosphere. Desorption of ammonia from the ammonia-water mixture occurs due to the relatively high vapor pressure of ammonia over water. Fenton et al. (1991) performed experiments using 55 gal drums open to the atmosphere to estimate the desorption rate of ammonia. Using several drums as controls containing only water, several other drums containing ammonia-water mixtures at the initial ammonia concentration of 10.1% were filled from about half to two-thirds of the drum's internal volume. The drums were stored outside for 50 days over the summer where the ammonia concentration dropped to 50-60% of the initial value. Importantly, in practice the ammonia-water mixture must be drained after a release and replenished with fresh water so that the water diffusion tank may capture a subsequent ammonia release. Draining to holding tanks provides for a means to replenish and may allow desorption to occur. Must check with the local AHJ for approval and take steps to ensure that not more than 100 lbs (45 kg) of ammonia vapor enters the atmosphere per 24 hour period.

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 ammonia would be captured, the water volume is

increased to 2500 gal (9.5 m³). 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 m³).

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 of flares to refrigeration plants was in 1970 (Shepard 1988). 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 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, any liquid ammonia must be removed from the relief system before it gets to the flare. Ammonia droplets evaporate slowly due to the liquid’s high latent heat, and they may pass through the flare without fully evaporating. By 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 6.

Flaring systems have been used for decades in ammonia manufacturing plants, but there are notable differences in applying them to refrigeration systems. The flare would not be used often, only operating when there is a release through the pressure relief valves of the refrigeration system. In other flaring systems, the flare is used continuously. The system must be able to lie dormant for long periods but be able to work immediately and effectively when challenged with ammonia. It also must be able to handle a wide variety of flow rates of ammonia. In an emergency release, the ammonia flow rate could be small or large. Shepherd (1988) indicates that the turndown ratio (ratio between maximum and minimum fuel flow rate) of a flare system must be around 30,000 to 1. In Shepherd’s diagram of the flaring system in Figure 6, a pressure controller on the phase separator controls the flow control valve on the natural gas line to regulate the amount of pilot gas supplying the flare. To burn the ammonia efficiently, the ammonia and natural gas needs to be within a specific range of ratios. The gas velocities at the flare tip usually range between 40 and 50 ft/s (12 and 15.2 m/s) and are shielded from the wind

by a shroud (Shepherd 1990). Further, the location of the flare system must be outside of the facility buildings allowing it to be accessed by emergency personnel.

AMMONIA ELEVATED OPEN FLARE

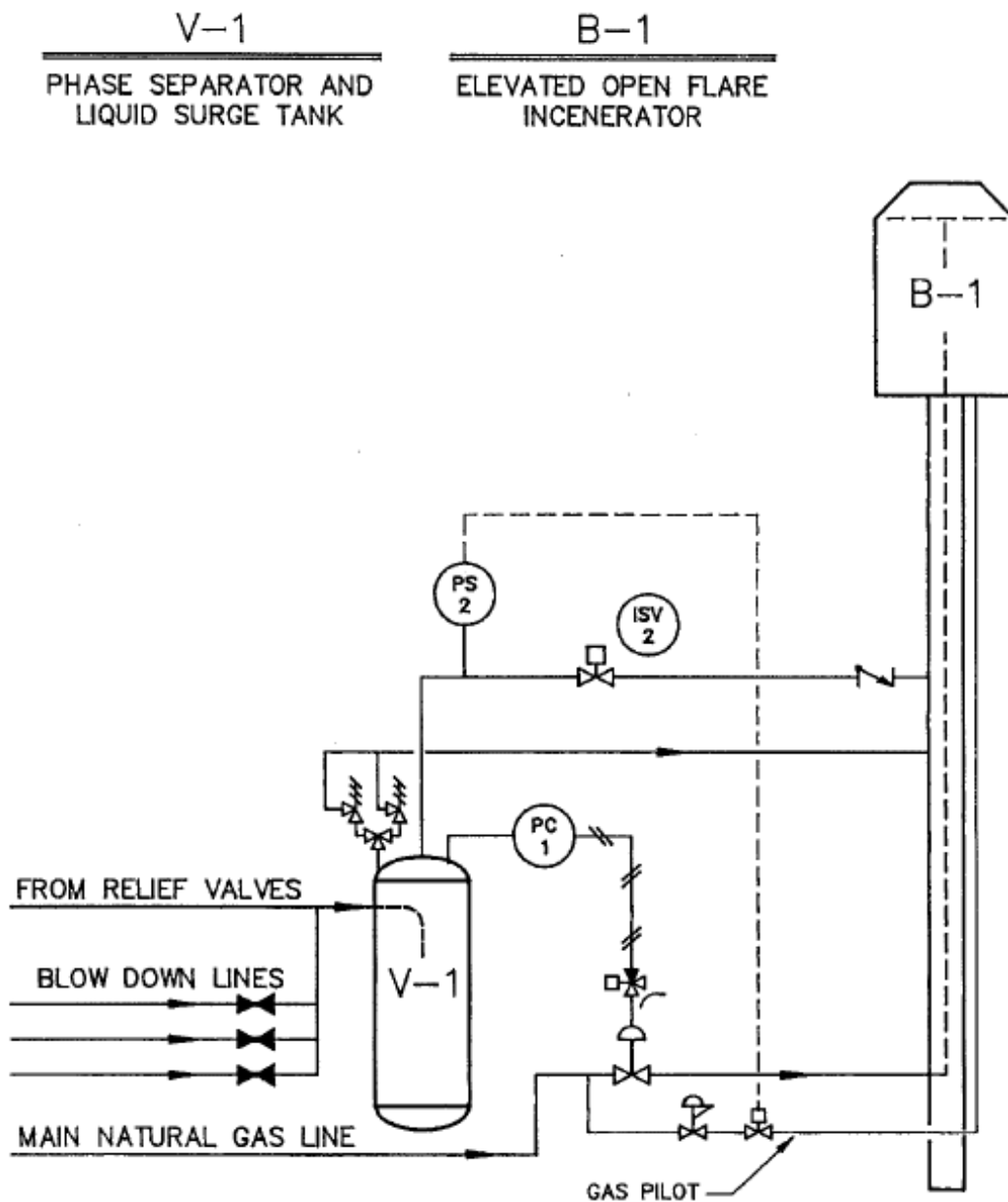


Figure 6: Ammonia elevated open flare diagram (Shepherd 1990).

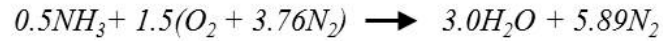
Figure 6 shows a diagram of an elevated stack flare, but other types of flares include: enclosed, horizontal, and pit (Shepherd 1988). At the present time the efficiency of flares burning ammonia are reported to be greater than 98% according to two flare manufacturers (JohnZink Co. 2012, National Air Oil Burner Co. 2012).

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.

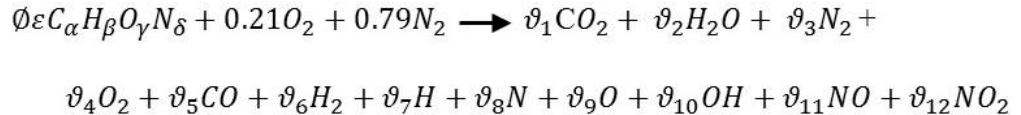
The possibility that ammonia could be burned in a process steam boiler that was already operating on site is one potential way to reduce cost (Shepherd 1990). No instances of on-site combustion boilers burning released ammonia were found. One end user with four plants in California has installed combustion flares to burn the ammonia that may be released at the refrigeration plant (Faust 2012). In these installations, the use of water diffusion tanks was avoided at the request of the owner. The installation costs of the flare systems were somewhat greater than that of suitable water diffusion systems but operation and maintenance costs appear to be less. The flares used in these four plants all use a pilot flame to initiate combustion in the event of an ammonia release. Routine emissions testing of these ammonia flare systems is not required as they are not a continuous source. While combustion flare systems are rare with

ammonia refrigeration plants serving the food industry, they are common in the ammonia production and petrochemical industries.

As already mentioned, a pilot flame is needed to ignite the ammonia-air mixture and sustain the combustion in the flare. The simple complete combustion reaction of ammonia in air is:



where the combustion products are H_2O and unreacted N_2 . With the use of a hydrocarbon pilot fuel, the chemical reaction is complicated by the presence of the carbon. Combining the ammonia and hydrocarbon fuel into a generic fuel molecule, the oxidation reaction becomes the combustion product species identified with unknown mole numbers



where ϕ is the fuel-air equivalence ratio, ε is the H/C atom ratio in the fuel molecule, and ϑ_i are the product mole numbers. All the shown product species appear during the combustion reaction at some point as chemical equilibrium is attained. To the extent that oxygen is available, the reaction will produce CO and CO_2 , and due to the dissociation of nitrogen, NO_2 will form in small quantities. The other product species are intermediate and contribute to the final product mole numbers. A literature review by Fenton et al. (1995) found that as temperature increases, the lower flammability limit decreases and the upper flammability limit increases, widening the range where ammonia is flammable. By contrast, increased humidity narrows the flammability range. The normal flammability limits of ammonia are reported as 15.2% and 27.4% in dry air at room temperature. By contrast, Khan et al (1995) measured the ammonia air flammability limits

as 16% and 26.6% at 100% RH. Lubricating oils in the ammonia-air mixture can lower the flammability limits as much as 50% (Fenton 1995).

Fenton et al. (1995) developed a laboratory sized ammonia flare system in the shape of a venturi where immediately downstream of the throat was placed a flame holder. 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 consisting of 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 fuel-air supply mixture was near stoichiometric conditions with lower temperatures coming when the fuels and ammonia supplies are unbalanced. Emissions were measured downstream from the combustion zone including: NH_3 , CO , CO_2 , NO_x , and total hydrocarbons (HC). Oxygen was also measured downstream from the combustion zone. Figure 7, Figure 8, Figure 9, Figure 10, Figure 11, and Figure 12 show the measured downstream concentrations of O_2 , NH_3 , CO , CO_2 , NO_x , and HCs, respectively.

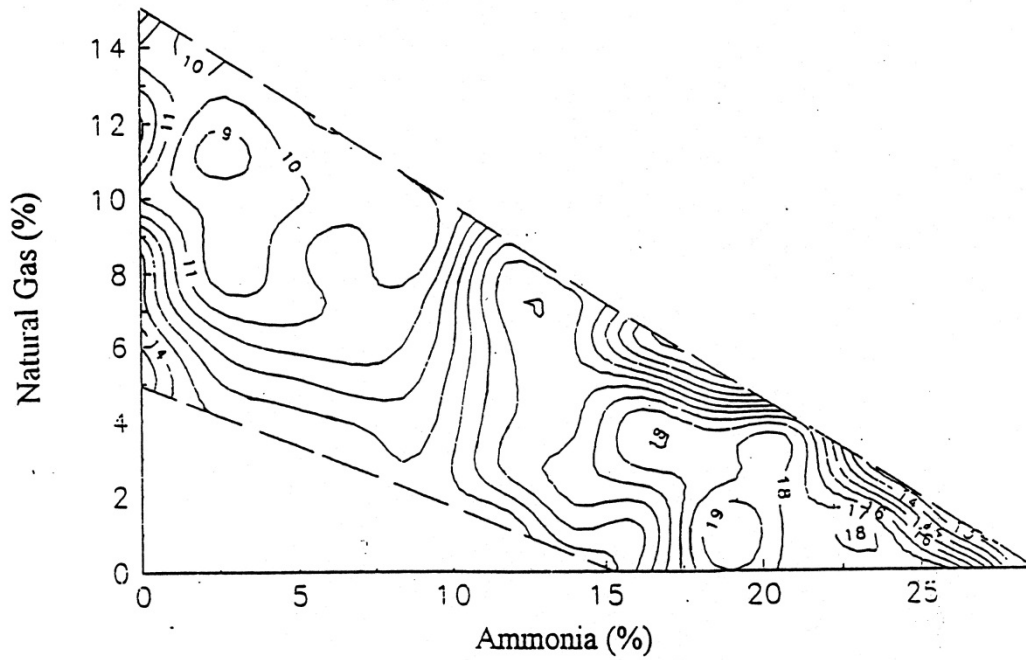


Figure 7: Variation of oxygen concentration (%) measured downstream from the combustion zone as a function of the fuel mixture (Fenton et al. 1995).

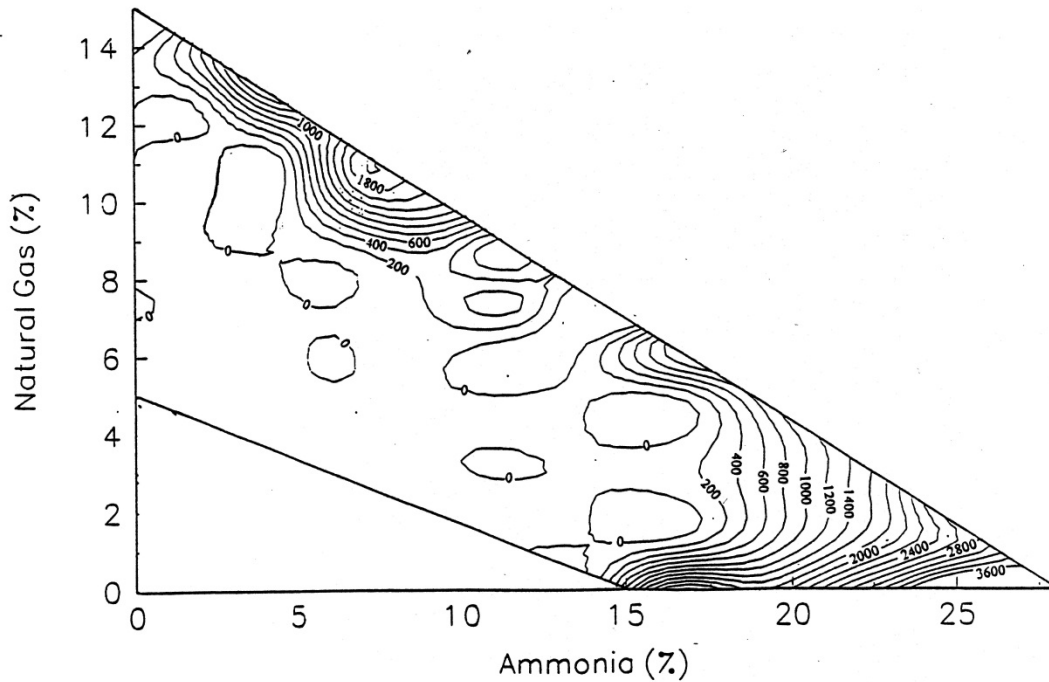


Figure 8: Variation of ammonia (ppm, v/v) measured downstream from the combustion zone as a function of the fuel mixture (Fenton et al. 1995).

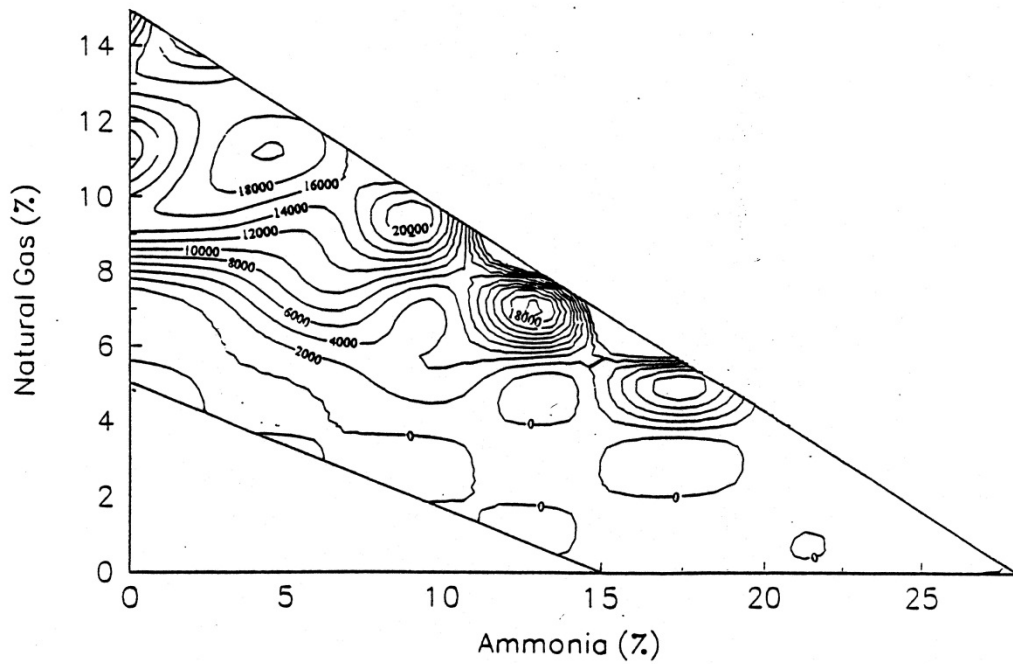


Figure 9: Variation of carbon monoxide (ppm, v/v) measured downstream from the combustion zone as a function of the fuel mixture (Fenton et al. 1995).

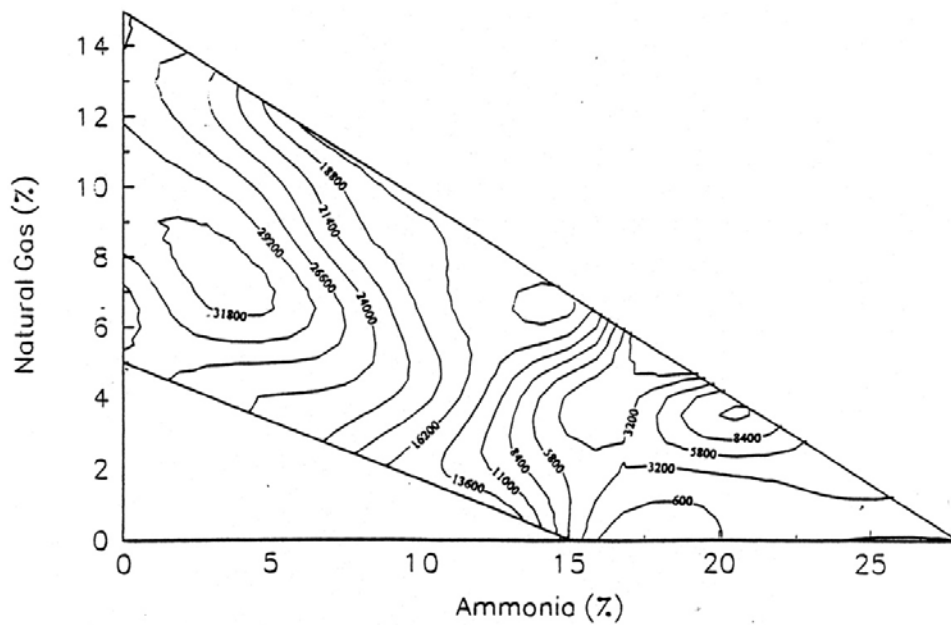


Figure 10: Variation of carbon dioxide (ppm, v/v) measured downstream from the combustion zone as a function of the fuel mixture (Fenton et al. 1995).

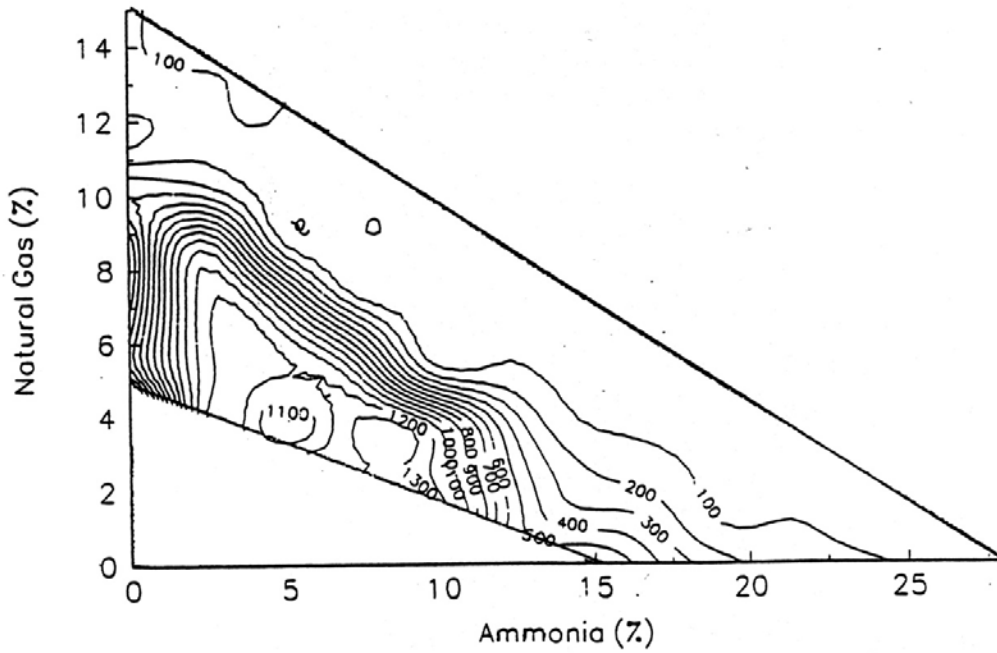


Figure 11: Variation of nitrous oxides (NOx) (ppm, v/v) measured downstream from the combustion zone as a function of the fuel mixture (Fenton et al. 1995).

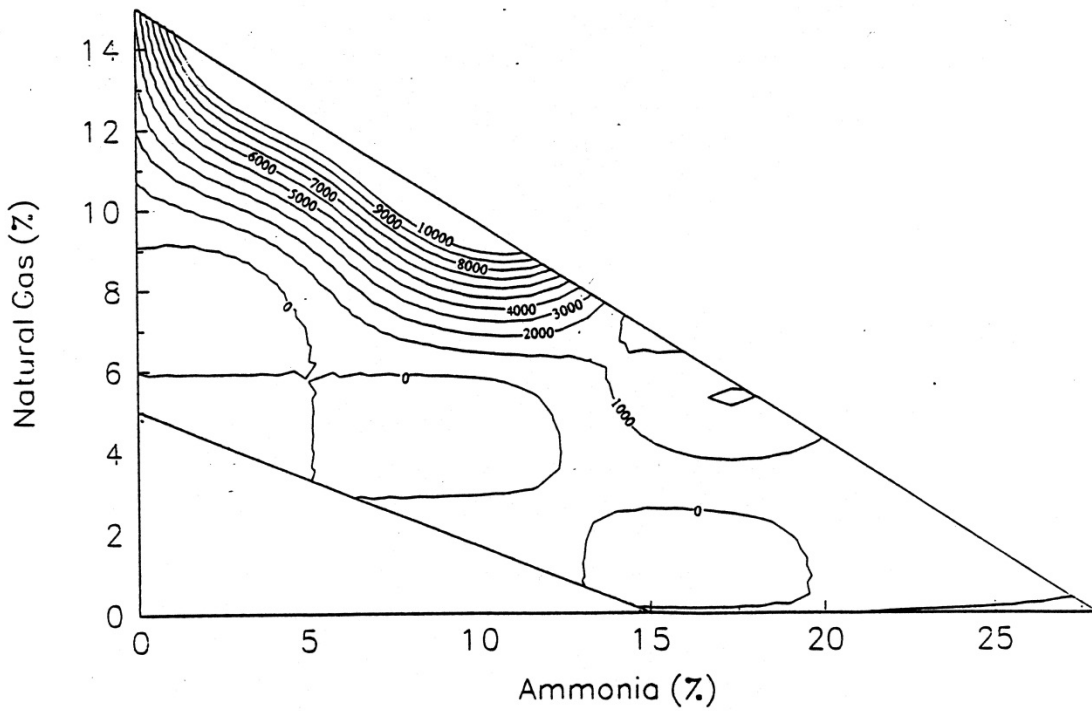


Figure 12: Variation of total hydrocarbons (HC) (ppm, v/v) measured downstream from the combustion zone as a function of the fuel mixture (Fenton et al. 1995).

NO_x emissions were greater than 1200 ppm (v/v) when the fuel supply mixture was lean and below 12%. Oxygen emissions decreased with increasing concentrations of natural gas and ammonia. It was observed that the oxygen concentration was highest when the natural gas concentration was below 2% and the ammonia concentration was below 20% providing for lean combustion. As the flame became rich and oxygen became scarce, CO_2 concentrations decreased and CO concentrations increased, under some conditions greater than 16000 (ppm v/v). Importantly, the ammonia and total hydrocarbon concentrations remained low until the fuel mixture approached the upper flammability limit.

The experimental flare was also challenged with liquid ammonia (Fenton et al. 1995). When the combustion flame is operating at stoichiometric conditions, the addition of liquid ammonia pushes the concentration of the fuel mixture into the rich region. The quantity of ammonia liquid could be great enough to exceed the concentration of the upper flammability limit thus quenching the flame. It was observed that injecting liquid ammonia into a near stoichiometric air-natural gas pilot flame at an ammonia-to-natural gas mass ratios less than 0.5 gave ammonia exhaust concentrations less than 5 ppm (v/v). However, as the mass ratio increased, the ammonia concentration in the exhaust stream increased to over 6000 ppm (v/v) before the flame quenched or extinguished.

Fenton et al. (1995) also measured the influence of lubricating oils on the flammability limits of the ammonia air mixture. Four oil types were tested and all significantly decreased the lower flammability limit while only slightly decreasing the upper flammability limit. Measurements indicated that mineral, paraffinic, and other oils decreased the lower flammability limit to 12%

for the ammonia air mixture when the oil concentration in the ammonia was 20% by weight. Polyester oils were measured to decrease the lower flammability limit of the ammonia air mixture to 9.5%.

Reference Release: The stack height flare offers several advantages when applied to refrigeration plants. The flaring combustor does not require warming to maintain a standby temperature, 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 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.

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 tank, rather than the water standing in the tank. In the event of a release, the end product is the same ammonia-water solution as in the water diffusion tank. In Fenton et al. (1991) it was 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 that was 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.

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). 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. Some commercial scrubbing systems use a “packed bed” system, as shown in Figure 13 to “provide intimate contacting of the upward flowing vapor and the downward flowing liquid (Beychok 2010).”

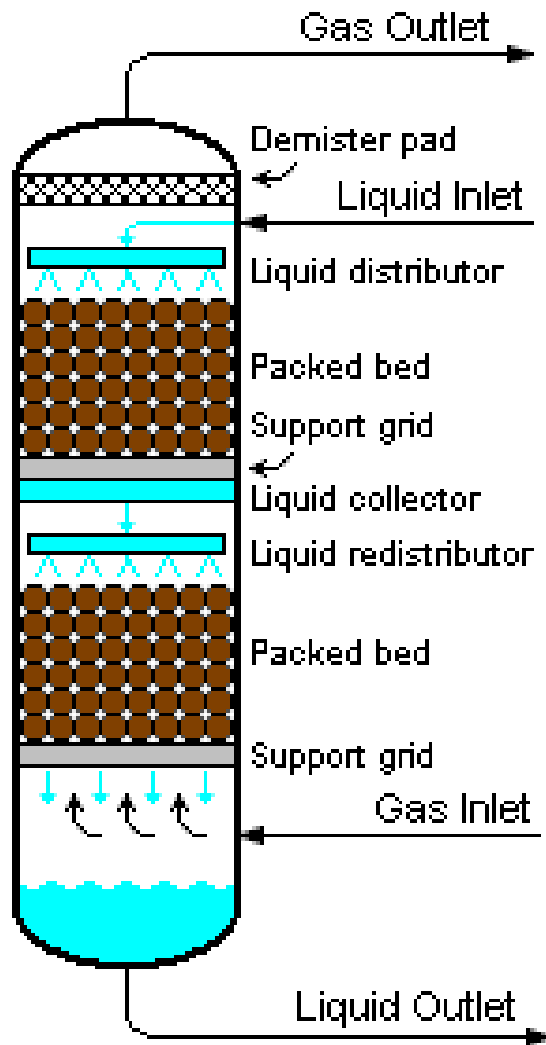


Figure 13: Diagram of a packed bed absorption column scrubber (Beychok 2010).

The emergency scrubber may, or may not, need dilution air to operate depending on its configuration. In addition to the packed bed scrubber shown in Figure 13, spray chambers and water jets may also be suitable scrubber configurations for emergency service (Heil 2012).

Figure 14 is a schematic diagram of a simple vertical packed-bed counterflow scrubber.

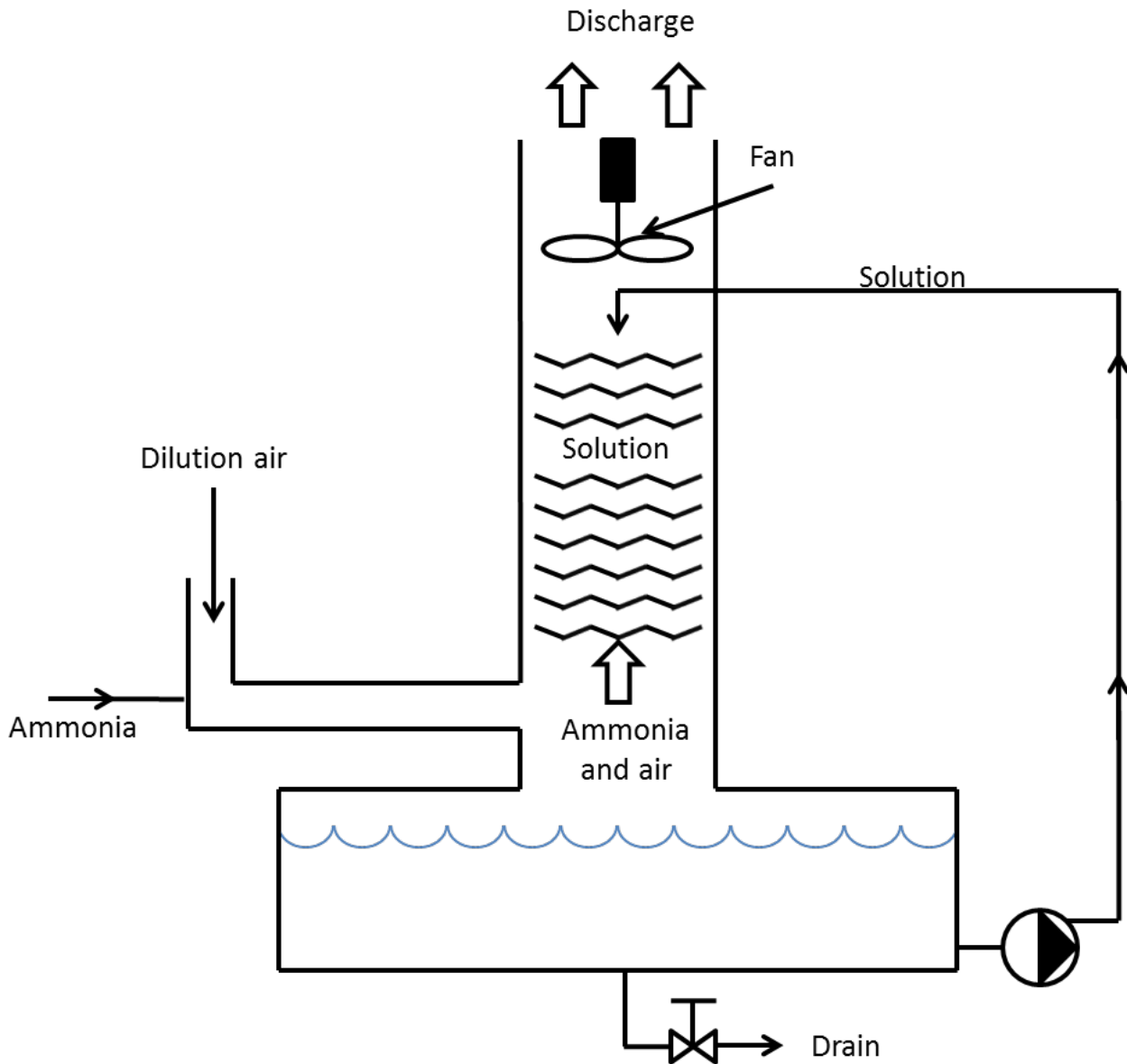
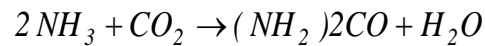


Figure 14: Schematic diagram of an emergency scrubber suitable for capturing ammonia.

A unique opportunity may exist with industrial refrigeration systems that incorporate carbon dioxide and ammonia as refrigerants. It is known that ammonia chemically reacts with carbon dioxide producing water and a substance that appears as a white powder or “snow.” The chemical reaction is:



where the $(NH_2)_2CO$ is ammonium carbamate (Minami 2012). This reaction was explored with varying pressure, temperature and water concentrations with vapor reactants by Kivama and Minomura (1950). With the stoichiometric ratio of ammonia and carbon dioxide (2-to-1), reactant temperatures below 264°F (129°C), and reactant pressures near one atm (14.7 psi), chemical reaction results in the formation of the powder ammonium carbamate. When temperatures are greater than about 264°F (129°C), the above reaction begins to form urea, which has a chemical formula of $CO(NH_2)_2$ – the extent of which depends on the temperature and pressure. It was also noted that water vapor concentrations greatly influenced this chemical reaction.

With ammonia-carbon dioxide cascade refrigeration systems that utilize an interconnecting “cascade” heat exchanger, pressure transducers are placed in both the ammonia and carbon dioxide sides to trigger the occurrence of a leak causing the carbon dioxide to mix with the ammonia (Andrews 2012). The above reaction occurs, forming the solid ammonium carbamate, thereby disrupting operation. No cascade systems were discovered that utilize carbon dioxide as a means of trapping an ammonia release. Despite this, the concept appears to have merit because both the ammonium carbamate and water are harmless and convenient to dispose of.

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 recommended concentration of the reference relief.

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. The idea behind relieving pressure to another vessel, is to have the ammonia go from a higher pressure vessel to a lower pressure vessel and prevent it from needing to be released from the system.

Because ECPS 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 pressures 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 capturing system. In the case of a major plant fire affecting all, or a large

enough portion, of the pressure vessels in the system, the EPCS could be overwhelmed, causing a failure of the system.

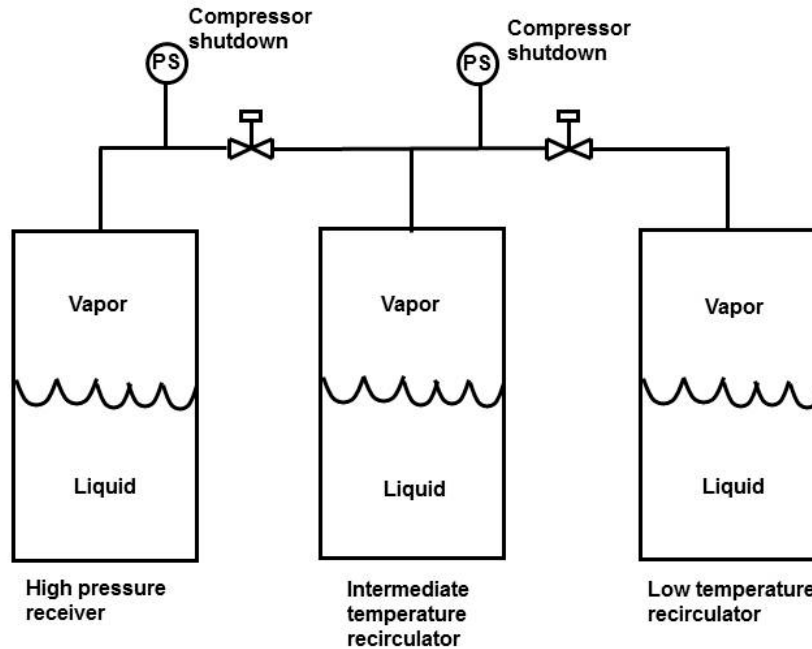


Figure 15: Diagram showing the basic components of an ECPS internal pressure relief system (stop valves, flow strainers, and pressure gauges not shown.)

5.0 Phase 1 Conclusions

It is recommended that the ammonia capture methods to be examined further in Phase 2 include:

1. Discharge into a tank containing standing water (absorption).
2. Discharge into the atmosphere.
3. Discharge into a flare (combustion).
4. Discharge into a wet scrubber.
5. Emergency Pressure Control System

As discussed above in the text of Phase 1, other ammonia capturing schemes have been explored, but either they have not been evaluated or implemented in the refrigeration industry, or they may have questionable technical merit.

Phase 2

6.0 Phase 2 Introduction

Phase two of this project is the quantitative risk analyses of the ammonia capturing methods defined in phase one. The components of the quantitative risk analysis include modeling the downwind ammonia concentration from releases under various conditions, determining the cost associated with the downwind concentrations, determining a failure rate for each ammonia capturing method, and finding the relative cost of a release with each capture method. Several different ammonia releases were modeled, including releases from three different heights, six different sets of atmospheric conditions, both the reference release rate and double the reference release rate, and split releases from two separate release points.

7.0 Ammonia Dispersion Modeling

In order to determine the off-site consequences of the ammonia release, the dispersion of the ammonia must be modeled. Initially, the model selected was the model outlined in *Workbook of Atmospheric Dispersion Estimates* (Turner 1970). This model allows the calculation based on a relatively simple and broad set of inputs. Turner's method allows modeling to be done using the stability classes developed by Pasquill (Pasquill 1961), based on broader weather characteristics. The major inputs required to use this model are the weather stability class, release rate, wind speed, and the stack height. From this, the ammonia concentration can be calculated at any location downwind. After testing this model in comparison to the results of "Dispersion of Ammonia Into the Atmosphere" (Fenton 2001), it was found to be an inadequate simulation. The results of the study did not match up very well with the results of the model. The main cause for this is thought to be the Turner model's inability to account for the properties of the

pollutant. It treats all pollutants the same, and does not account for ammonia being a dense gas when released at cold temperatures.

The model that was finally chosen was SLAB, which is specifically designed as a dense gas dispersion model. SLAB requires many of the same inputs as Turner's model, but also requires the properties of the pollutant, the ambient and source temperatures and pressures, and other parameters. The requirements for the input file will be described in detail in the next section. In contrast to more complex models, such as CALPUFF PRO and AERMOD, SLAB does not require the surrounding terrain or the specific weather patterns to be modeled. For the terrain, it uses a surface roughness parameter and for the weather, it uses Pasquill's atmospheric stability classes. CALPUFF PRO and AERMOD are the two models recommended by the 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. 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 come up with a more precise QRA for that site. CALPUFF PRO and AERMOD also are not designed for use with dense gases.

The SLAB model did a much better job than Turner's model of replicating the measured results of Fenton's dispersion study. Figure 16 shows that the Turner model overestimates the concentrations at the 8.1 meter receptor height for the low velocity ammonia release by a factor of about 10. At the 2 meter receptor height, the Turner model estimates that there would be no ammonia at the given distances downwind. The SLAB model follows the experimental data

rather closely at the 8.1 meter receptor, and slightly underestimates the concentrations at the 2 meter receptors. For the high velocity release shown in Figure 17, the Turner model does not follow the actual profile at all for either the 8.1 meter or the 2 meter receptors. The SLAB model slightly overestimates for the 8.1 meter receptor again, but follows very closely at the 2 meter receptor.

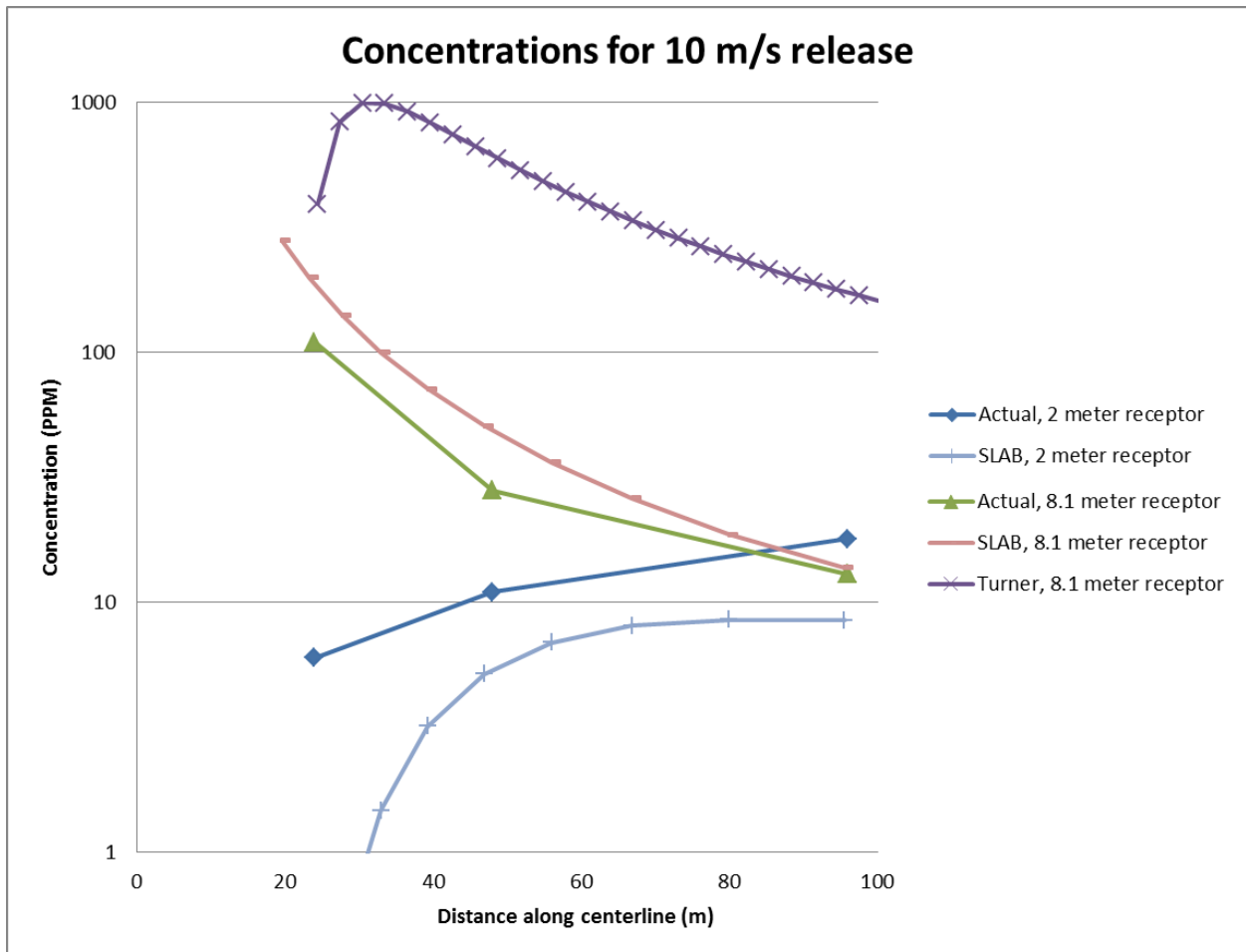


Figure 16: Model comparisons to Fenton’s study, low velocity release

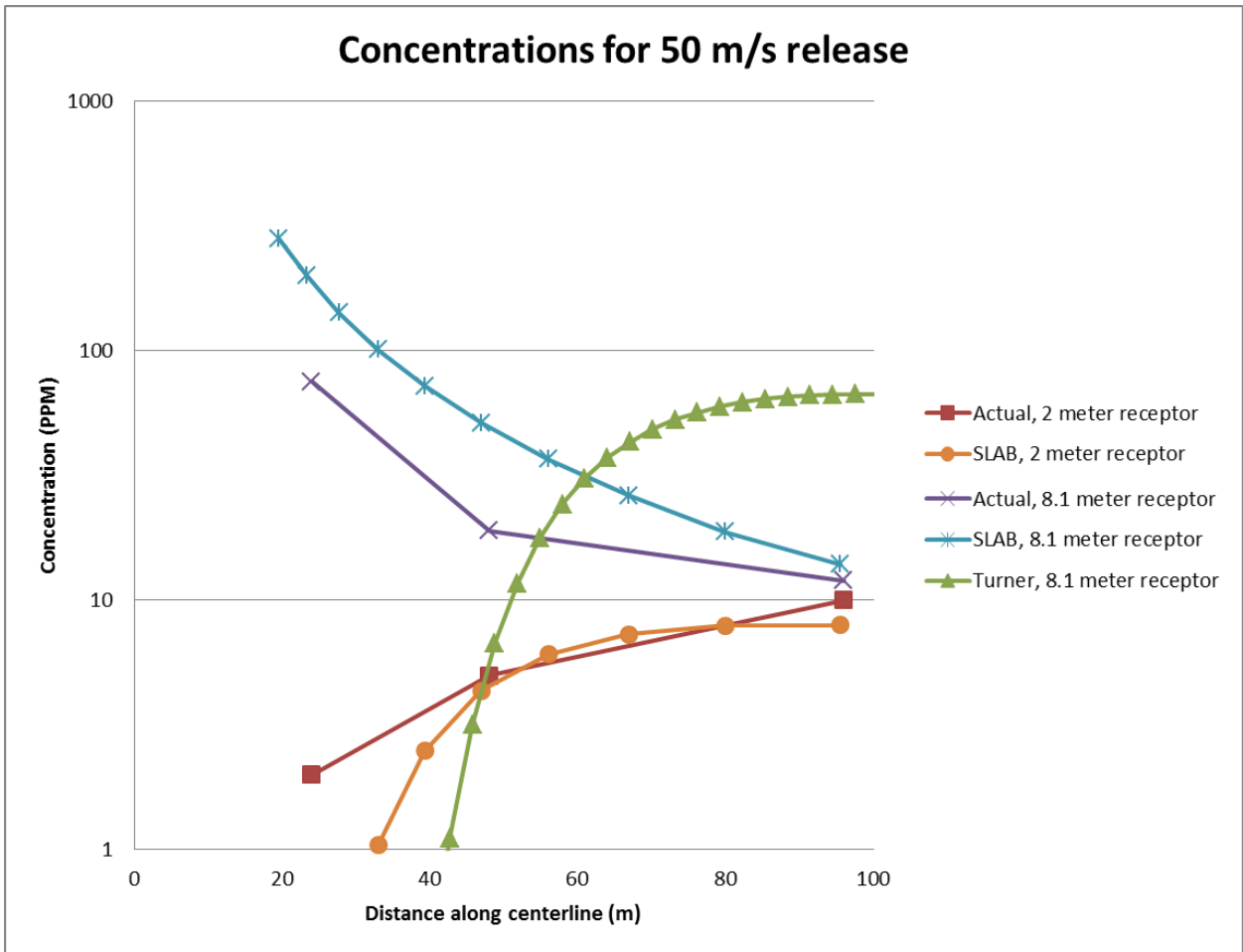


Figure 17: Model comparisons to Fenton’s study, high velocity release

7.1 Model Input File

Figure 18 comes from *User’s Manual for SLAB: An Atmospheric Dispersion Model for Denser-than-air Releases* (Ermak 1990), and shows the definitions of each of the input variables for the model. The model is a FORTRAN program and uses a text input file. Note that all of the measurements are in imperial units, rather than English units.

Figure 19 shows an example input file. The 1st line is the spill source type, which is always ‘3’ for this project, representing a vertical jet or stack release. The 2nd line is the numerical substep parameter, which determines the number of substeps during the program’s calculations. 1 is the

recommended value for computational stability, while 3 triples the number of substeps. With modern computer processors, the run time of the program is insignificant so 3 was chosen for all simulations. The next 7 lines are source properties of the pollutant. These values can be looked up in a table provided in the user's manual (Ermak 1990). The next two lines are the saturation pressure constants, which the program will calculate on its own if the values are left at their defaults of -1.0 for line 10 and 0.0 for line 11.

Source Type and Numerical Substep Parameter

- IDSPL Spill source type
 - 1—evaporating pool release
 - 2—horizontal jet release
 - 3—vertical jet or stack release
 - 4—instantaneous or short duration evaporating pool release
- NCALC Numerical substep parameter

Source Properties

- WMS Molecular weight of source material (KG)
- CPS Vapor heat capacity at constant pressure (J/KG-°K)
- TBP Boiling point temperature (°K).
- CMEDO Initial liquid mass fraction
- DHE Heat of vaporization (J/KG)
- CPSL Liquid heat capacity (J/KG-°K)
- RHOSL Liquid density of source material (KG/M3)
- SPB Saturation pressure constant (Default: SPB = -1.0)
- SPC Saturation pressure constant (Default: SPC = 0.0)

Spill Parameters

- TS Temperature of source material (°K)
- QS Mass source rate (KG/S)
- AS Source area (M2)
- TSD Continuous source duration (S)
- QTIS Instantaneous source mass (KG)
- HS Source height (M)

Field Parameters

- TAV Concentration averaging time (S)
- XFFM Maximum downwind distance (M)
- ZP(i) Heights of concentration calculation (M); I = 1, 4

Meteorological Parameters

- ZO Surface roughness height (M)
- ZA Ambient measurement height (M)
- UA Ambient wind speed (M/S)
- TA Ambient temperature (°K)
- RH Relative humidity (percent)
- STAB Stability class values

| Class | Value | Description |
|----------|---------|---------------------------|
| A-F | 1.0-6.0 | Unstable-Stable |
| Default: | 0.0 | Input "ALA" for stability |
- ALA Inverse Monin-Obukhov length (1/M)
(ALA is an input parameter only when STAB = 0.0)

Figure 18: Input variable definitions

```
3
3
.017031
2170.
239.72
.0
1370840.
4294.
682.8
-1.0
0.0
190.9528
.2583
3.866309
3600.
0.
9.14
600.
10000.
10.
5.
2.
0.04
1.0
2.00
2.0
293.2
35.0
1.
-1.
0
```

Figure 19: Sample input file

Lines 12 through 17 are the spill parameters. All of these except the source height will remain the same for all of the simulations in this project. The source temperature is not input as the temperature of the ammonia while it is in the pressurized tank, but rather as the properties after it has fully expanded. The source area is also treated as such. Equation 2 and Equation 3, respectively, show how the source temperature and source area are calculated.

Equation 2:

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

Equation 3:

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

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)

(Ermak 1990)

It is important to note that if the calculated source temperature is less than the boiling point temperature, the program 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 (input as 0.2583 kg/s). The instantaneous source mass is 0 for any jet or stack release. The source height will be varied between 30 feet (9.14 m) for the direct release to the atmosphere, 20 feet (6.10 m) for the flare, and 10 feet (3.05 m) for the scrubber and diffusion tank. Line 18 is the averaging time for the ammonia concentrations. This is important because the EPA has different limits on concentrations based on exposure time. For this project, concentration averaging times of 10 minutes (input as 600 s)

and 1 hour (input as 3600 s) were simulated. The next line sets the limit for downwind distance in the simulation, which was 6.21 miles (10,000 m). The four lines of the input file following are the detector heights where the downwind concentrations are measured. For these simulations, heights of 16.4 ft (5 m), 6.56 ft (2 m), and 0.13 ft (0.04 m) were selected to cover a range of heights that humans would typically live at.

Line 24 sets the 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. Line 25 sets the height for ambient wind speed measurement, and was set at 6.56 ft (2 m). The ambient temperature and relative humidity are set in lines 27 and 28. They were maintained at 68°F (293.15 K) and 35% RH for all simulations. Lines 26 and 29 control the wind speed and the Pasquill stability class. The stability classes have a range of wind speeds and weather conditions they represent, and shows how they were paired in the simulations. Some of the stability classes share a wind speed, but have different dispersion characteristics. The stability classes go 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. The final line of the program is just a negative number that tells the program that the input file has terminated.

Table 1: Stability and Wind Speed Relation

| 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) |

7.2 Simulation Inputs

A simulation was run for each combination of stability class, release height, and concentration averaging time for a total of 36 different simulations. The combinations are listed below in .

The rest of the input variables remained constant across all of the simulations, and are listed in .

Note that in and the imperial units are shown first, with English units in parentheses, because the SLAB program requires the input to be in imperial units. The release is characterized by the release rate calculated in section 1.1 of 2,116 lbm (959.8 kg) of ammonia released over the course 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. The program automatically resets the source temperature to be the boiling point temperature in this case.

Table 2: Dispersion Modeling Simulation Combinations

| Combination Number | Release Height | Concentration avg. time | Stability Class |
|---------------------------|-----------------------|--------------------------------|------------------------|
| 1 | 9.14 m (30 ft) | 3600 s (1 hour) | Class A |
| 2 | 9.14 m (30 ft) | 3600 s (1 hour) | Class B |
| 3 | 9.14 m (30 ft) | 3600 s (1 hour) | Class C |
| 4 | 9.14 m (30 ft) | 3600 s (1 hour) | Class D |
| 5 | 9.14 m (30 ft) | 3600 s (1 hour) | Class E |
| 6 | 9.14 m (30 ft) | 3600 s (1 hour) | Class F |
| 7 | 9.14 m (30 ft) | 600 s (10 minutes) | Class A |
| 8 | 9.14 m (30 ft) | 600 s (10 minutes) | Class B |
| 9 | 9.14 m (30 ft) | 600 s (10 minutes) | Class C |
| 10 | 9.14 m (30 ft) | 600 s (10 minutes) | Class D |
| 11 | 9.14 m (30 ft) | 600 s (10 minutes) | Class E |
| 12 | 9.14 m (30 ft) | 600 s (10 minutes) | Class F |
| 13 | 6.10 m (20 ft) | 3600 s (1 hour) | Class A |
| 14 | 6.10 m (20 ft) | 3600 s (1 hour) | Class B |
| 15 | 6.10 m (20 ft) | 3600 s (1 hour) | Class C |
| 16 | 6.10 m (20 ft) | 3600 s (1 hour) | Class D |
| 17 | 6.10 m (20 ft) | 3600 s (1 hour) | Class E |
| 18 | 6.10 m (20 ft) | 3600 s (1 hour) | Class F |
| 19 | 6.10 m (20 ft) | 600 s (10 minutes) | Class A |
| 20 | 6.10 m (20 ft) | 600 s (10 minutes) | Class B |
| 21 | 6.10 m (20 ft) | 600 s (10 minutes) | Class C |
| 22 | 6.10 m (20 ft) | 600 s (10 minutes) | Class D |
| 23 | 6.10 m (20 ft) | 600 s (10 minutes) | Class E |
| 24 | 6.10 m (20 ft) | 600 s (10 minutes) | Class F |
| 25 | 3.05 m (10 ft) | 3600 s (1 hour) | Class A |
| 26 | 3.05 m (10 ft) | 3600 s (1 hour) | Class B |
| 27 | 3.05 m (10 ft) | 3600 s (1 hour) | Class C |
| 28 | 3.05 m (10 ft) | 3600 s (1 hour) | Class D |
| 29 | 3.05 m (10 ft) | 3600 s (1 hour) | Class E |
| 30 | 3.05 m (10 ft) | 3600 s (1 hour) | Class F |
| 31 | 3.05 m (10 ft) | 600 s (10 minutes) | Class A |
| 32 | 3.05 m (10 ft) | 600 s (10 minutes) | Class B |
| 33 | 3.05 m (10 ft) | 600 s (10 minutes) | Class C |
| 34 | 3.05 m (10 ft) | 600 s (10 minutes) | Class D |
| 35 | 3.05 m (10 ft) | 600 s (10 minutes) | Class E |
| 36 | 3.05 m (10 ft) | 600 s (10 minutes) | Class F |

Table 3: Inputs that remain constant across all simulations

| Variable | Variable Description | Value |
|-----------------|---|-----------------------------------|
| IDSPL | Spill source type | 3 – Vertical jet or stack release |
| NCALC | Numerical substep parameter | 3 |
| WMS | Molecular weight of source material (kg) | 0.017031 |
| CPS | Vapor heat capacity at constant pressure (J/kg-K) | 2170 |
| TBP | Boiling point temperature (K) | 239.72 (-28.17°F) |
| CMEDO | Initial liquid mass fraction | 0.0 |
| DHE | Heat of vaporization (J/kg) | 1370840 |
| CPSL | Liquid heat capacity (J/kg-K) | 4294 |
| RHOSL | Liquid density of source material (kg/m ³) | 682.8 |
| SPB | Saturation pressure constant | -1.0 (default for program calc) |
| SPC | Saturation pressure constant | 0.0 (default for program calc) |
| TS | Temperature of source material (K) | 190.9528 (-115.96°F) |
| QS | Mass source rate (kg/s) | 0.2666 (0.5878 lbm/s) |
| AS | Source area (m ²) | 3.86631 (12.687 ft ²) |
| TSD | Continuous source duration (s) | 3600 (1 hour) |
| QTIS | Instantaneous source mass (kg) | 0 |
| XFFM | Maximum downwind distance (m) | 10000 (32808 ft) |
| ZP(1) | Height of concentration calculation (m) | 10 (32.81 ft) |
| ZP(2) | Height of concentration calculation (m) | 5 (16.40 ft) |
| ZP(3) | Height of concentration calculation (m) | 2 (6.56 ft) |
| ZP(4) | Height of concentration calculation (m) | 0.04 (0.13 ft) |
| ZO | Surface roughness height (m) | 1 (3.28 ft) |
| ZA | Ambient measurement height (m) | 2 (6.56 ft) |
| TA | Ambient temperature (K) | 293.2 (68°F) |
| RH | Relative humidity (%) | 35 |
| P _{st} | Storage pressure (atm) | 17.01 (250 psi) |
| P _a | Ambient pressure (atm) | 1 (14.7 psi) |
| T _{st} | Storage temperature (K) | 245.15 (-18.4°F) |
| A _r | Actual area of opening (m ²) | 0.3048 (1 ft) |
| γ | Ratio of specific heats (C _p /C _v) | 1.307 |

7.3 Dispersion Modeling Output

An example of the output file produced by SLAB is contained in Appendix A, and a description of all that is included can be found in the user's manual (Ermak 1990). The important part of the output file is the time-averaged volume concentrations, at the specified measurement heights. For each downwind distance, the model 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, 2.5) of this effective half-width. This gives specifically defined concentrations at the x-y coordinates that are along those lines. Figure 20 shows these lines and demonstrates that further downwind, as the plume spreads, the distance between calculated coordinates increases. Figure 21 shows the points at which there are actual calculated concentrations.

In order to make use of the ammonia concentration data, and relate it to a population density, an area must be defined to be represented by each point. To make it possible to superimpose multiple releases from different points, a linear interpolation was done in both the downwind and crosswind directions. The result of the interpolations gave values for the ammonia concentration at intervals of 3.28 feet (1 m) for the entire footprint of the ammonia plume. As a result, the defined area for each point is the same and is 10.76 ft^2 (1 m^2). The reason for doing this is the irregularity of the locations for which the program output gives an explicit result makes it impossible to superimpose two releases from separate release points to get single concentration value. Equation 4 shows how the interpolation was done in the crosswind direction, and Equation 5 shows how it was done in the downwind direction. Note that the downwind interpolations were done using the concentrations calculated by the crosswind direction.

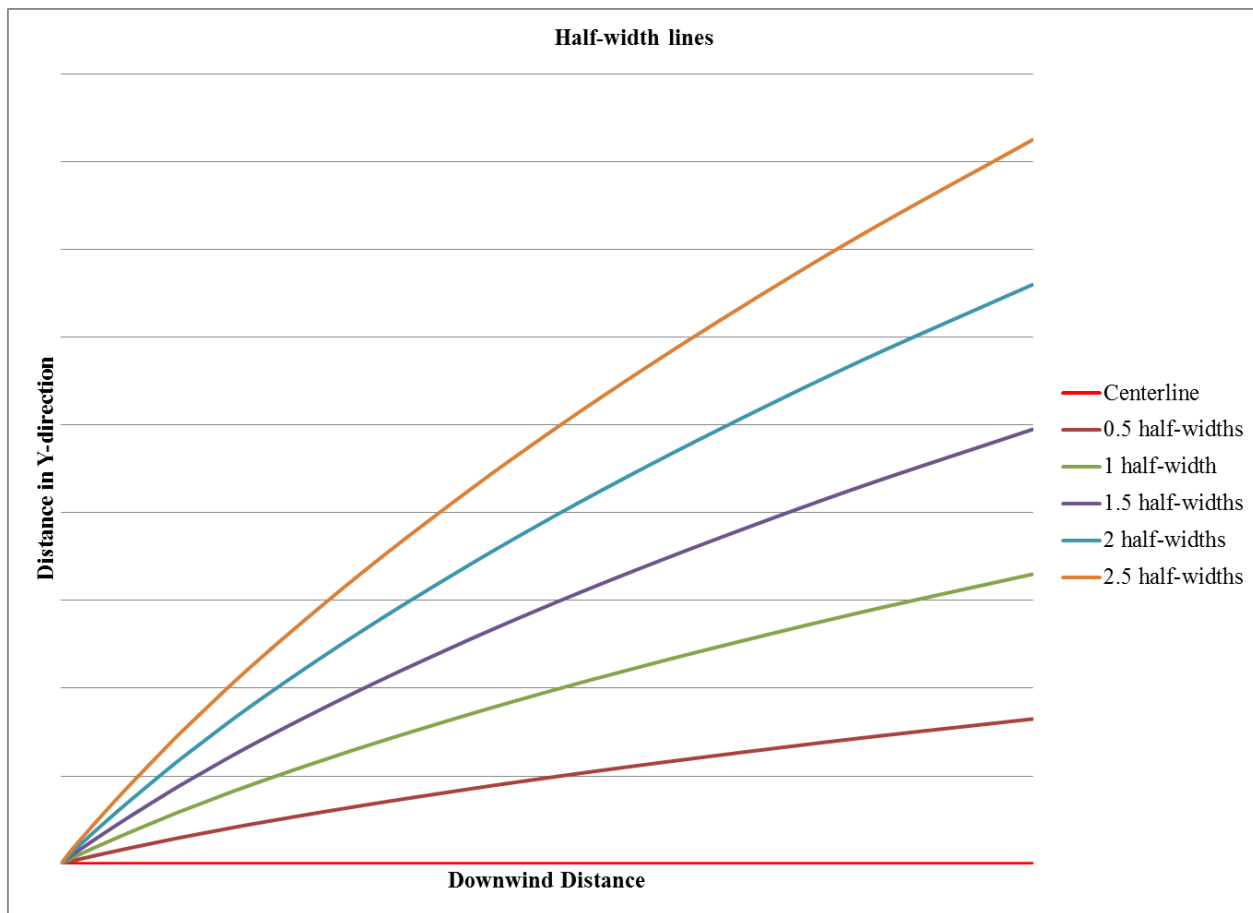


Figure 20: Lines of calculated concentration

Equation 4:

$$C(y) = \frac{y - y_{low}}{y_{high} - y_{low}} * [C(y_{high}) - C(y_{low})] + C(y_{low})$$

C = Ammonia Concentration

y = new crosswind location

y_{low} = nearest crosswind location closer to centerline in program output

y_{high} = nearest crosswind location further from centerline in program output

Equation 5:

$$C(x) = \frac{x - x_{low}}{x_{high} - x_{low}} * [C(x_{high}) - C(x_{low})] + C(x_{low})$$

C = Ammonia Concentration

x = new downwind location

x_{low} = nearest downwind location closer to source in program output

x_{high} = nearest downwind location further from source in program output

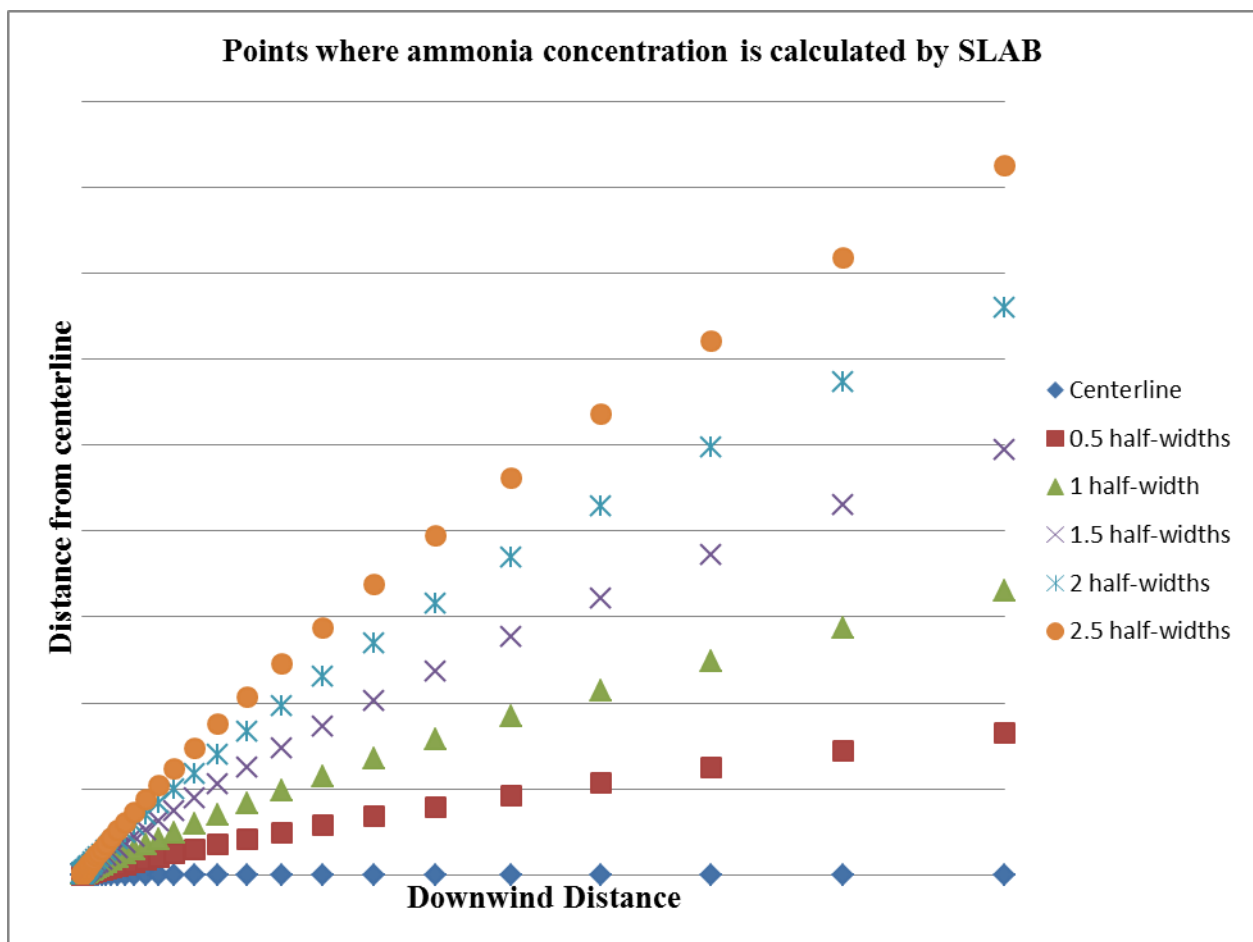


Figure 21: Locations of actual ammonia concentration calculations

7.4 Ammonia Dispersion Model Results

Figure 22 is an example of the dispersion model output after converting the raw program output, which gives the concentration in volume fraction, to concentration in parts per million. This is for the 16.4 foot detector for the 30 foot release under stability Class A. To fit it on one page, it has been truncated after concentration begins to drop off. Figure 23 is the graph that shows the data from Figure 22. Figure 24 and Figure 25 show the data for the 6.28 foot (2 m) and the 0.13 foot (0.04 m) detectors. As the detector heights get shorter, the concentration peaks further downwind, and the concentrations are lower.

| Downwind Distance x (ft) | Plume half-width bbc (ft) | average concentration (Parts per million) at (x,y,z) | | | | | |
|--------------------------------|---------------------------------|--|--------|--------|--------|--------|--------|
| | | y/bbc= | y/bbc= | y/bbc= | y/bbc= | y/bbc= | y/bbc= |
| | | 0 | 0.5 | 1 | 1.5 | 2 | 2.5 |
| 3.3 | 3.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3.3 | 3.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3.4 | 3.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3.5 | 3.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3.6 | 3.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3.7 | 3.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3.8 | 3.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 4.0 | 3.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 4.2 | 3.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 4.4 | 3.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 4.7 | 3.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 5.0 | 3.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 5.3 | 3.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 5.7 | 4.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 6.3 | 4.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 6.9 | 4.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 7.5 | 4.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 8.4 | 5.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 9.4 | 6.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 10.5 | 6.9 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| 11.8 | 7.9 | 1.0 | 0.7 | 0.2 | 0.0 | 0.0 | 0.0 |
| 13.5 | 9.1 | 5.2 | 3.6 | 1.2 | 0.2 | 0.0 | 0.0 |
| 15.4 | 10.5 | 18.6 | 12.8 | 4.2 | 0.6 | 0.0 | 0.0 |
| 17.6 | 12.2 | 48.4 | 33.3 | 10.8 | 1.7 | 0.1 | 0.0 |
| 20.2 | 14.1 | 97.5 | 67.0 | 21.8 | 3.3 | 0.2 | 0.0 |
| 23.3 | 16.4 | 159.0 | 109.0 | 35.4 | 5.4 | 0.4 | 0.0 |
| 26.9 | 19.1 | 218.0 | 150.0 | 48.7 | 7.5 | 0.5 | 0.0 |
| 31.2 | 22.1 | 261.0 | 180.0 | 58.4 | 9.0 | 0.6 | 0.0 |
| 36.4 | 25.8 | 282.0 | 193.0 | 62.8 | 9.6 | 0.7 | 0.0 |
| 42.3 | 30.0 | 279.0 | 192.0 | 62.2 | 9.5 | 0.7 | 0.0 |
| 49.2 | 34.8 | 258.0 | 178.0 | 57.7 | 8.8 | 0.6 | 0.0 |
| 57.7 | 40.7 | 228.0 | 157.0 | 50.9 | 7.8 | 0.6 | 0.0 |
| 67.6 | 47.2 | 195.0 | 134.0 | 43.5 | 6.7 | 0.5 | 0.0 |
| 79.1 | 55.1 | 163.0 | 112.0 | 36.4 | 5.6 | 0.4 | 0.0 |
| 92.8 | 64.0 | 135.0 | 92.8 | 30.1 | 4.6 | 0.3 | 0.0 |
| 108.9 | 74.1 | 110.0 | 75.5 | 24.5 | 3.8 | 0.3 | 0.0 |
| 128.0 | 86.3 | 88.9 | 61.1 | 19.8 | 3.0 | 0.2 | 0.0 |
| 150.3 | 100.7 | 70.9 | 48.7 | 15.8 | 2.4 | 0.2 | 0.0 |
| 176.8 | 117.5 | 55.6 | 38.2 | 12.4 | 1.9 | 0.1 | 0.0 |
| 208.0 | 137.5 | 42.8 | 29.4 | 9.6 | 1.5 | 0.1 | 0.0 |
| 244.8 | 161.1 | 32.4 | 22.3 | 7.2 | 1.1 | 0.1 | 0.0 |

Figure 22: Ammonia dispersion modeling concentration data

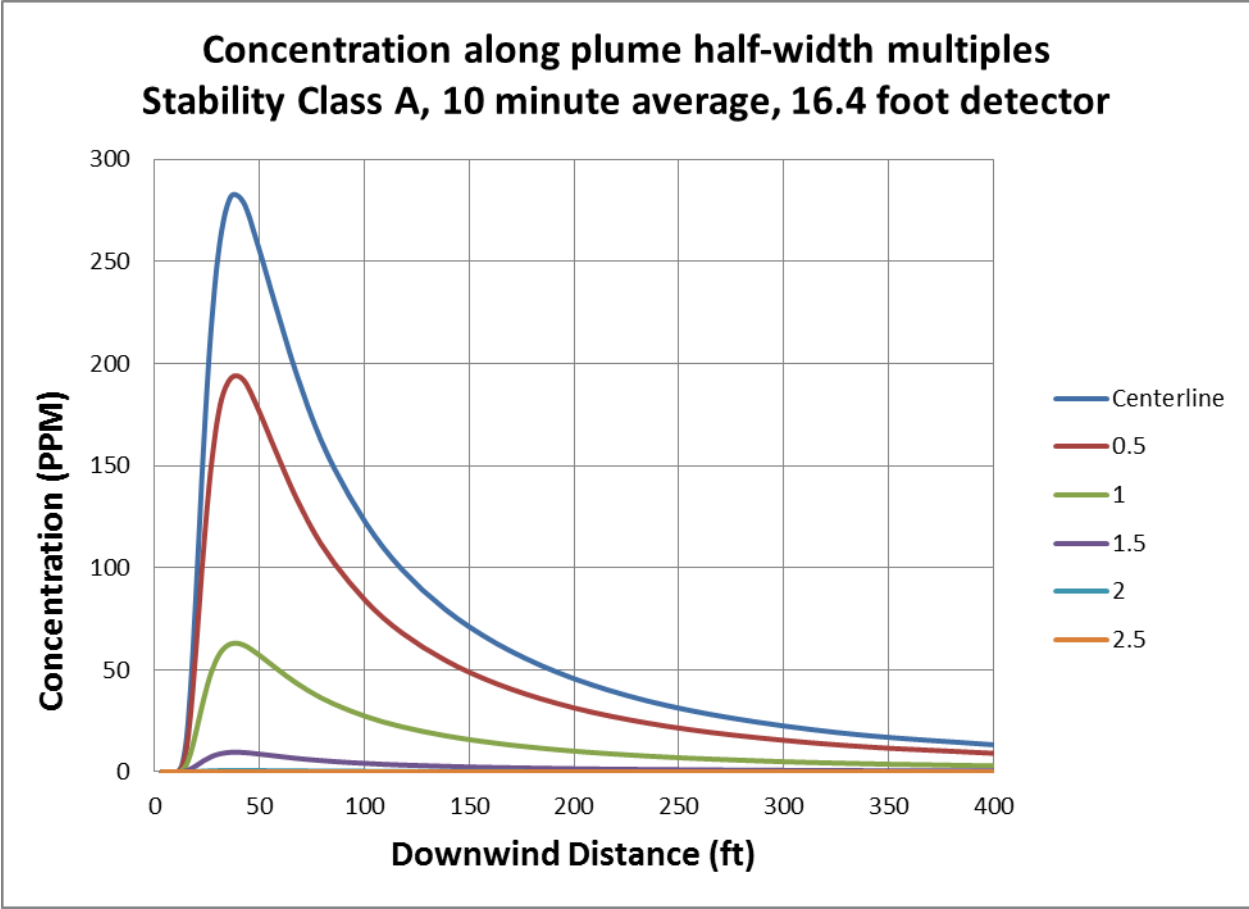


Figure 23: Concentration along plume half-width multiples, 30 foot release, 16.4 foot detector

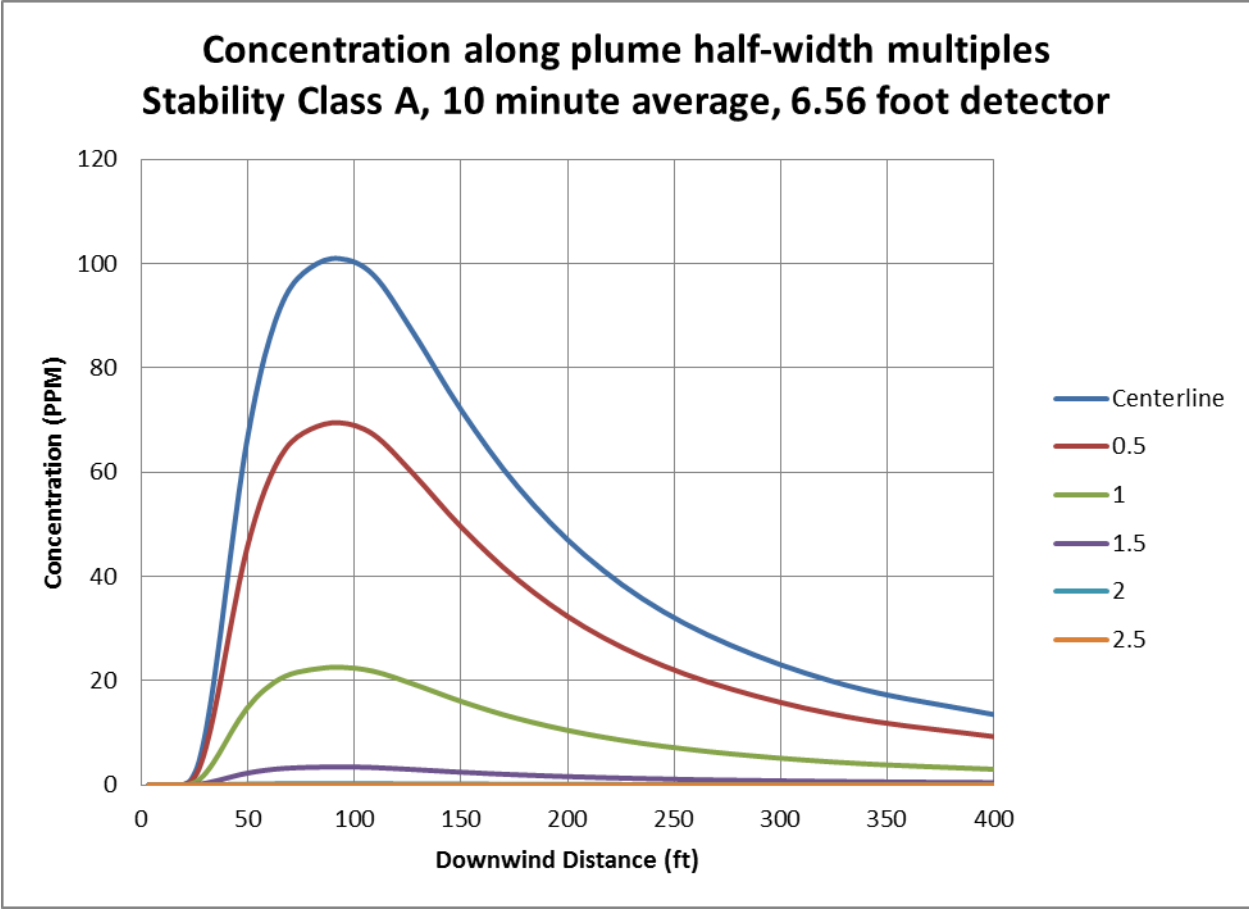


Figure 24: Concentration along plume half-width multiples, 30 foot release, 6.56 foot detector

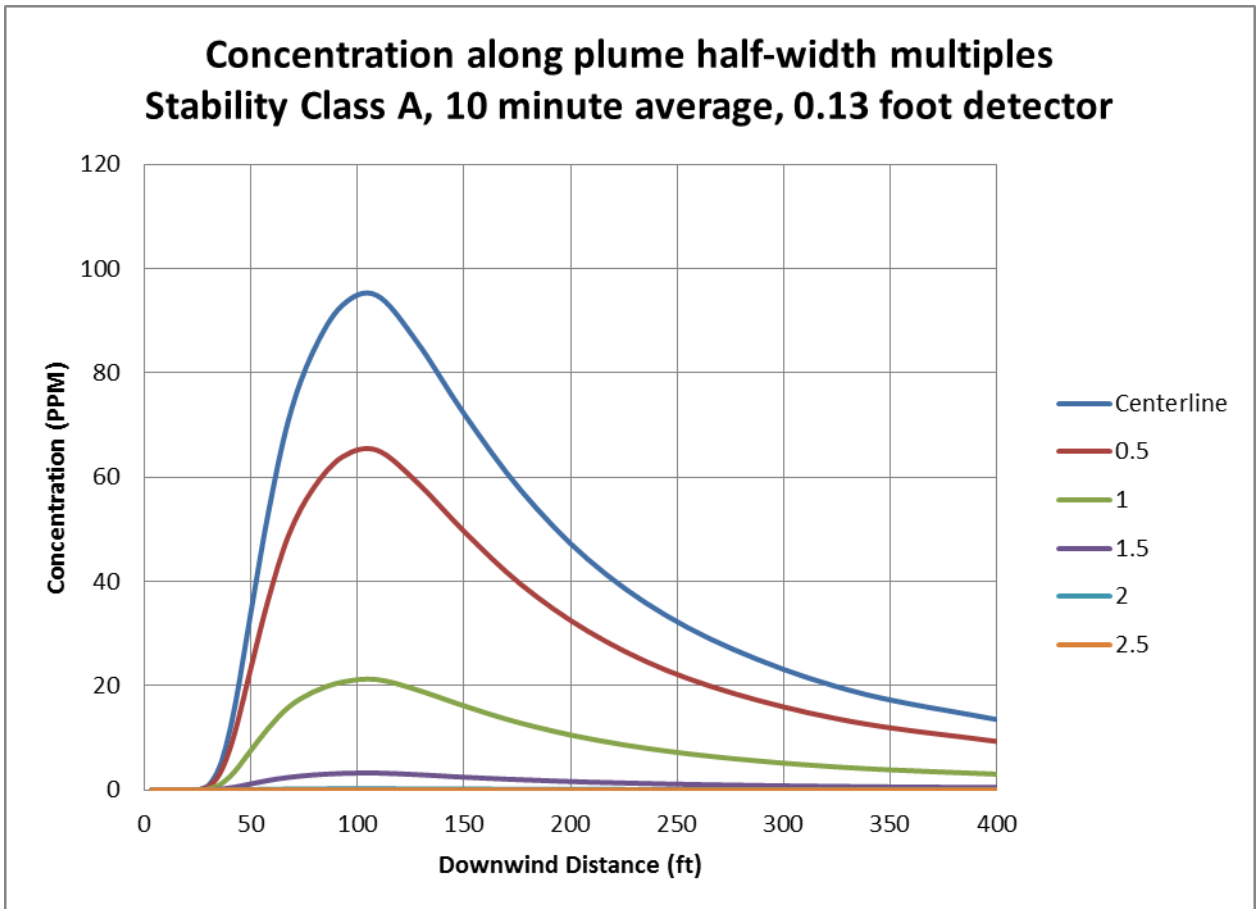


Figure 25: Concentration along plume half-width multiples, 30 foot release, 0.13 foot detector

The difference made by the different atmospheric stability classes is shown in Figure 26, Figure 27, and Figure 28. These are graphs of the centerline concentrations for the 6 stability classes at each detector height for the 30 foot release. The major trends are that the least stable classes, A and B, have higher concentration peaks, but they occur over a shorter distance, while the most stable classes, E and F, have smaller peaks, but persist for a much longer distance.

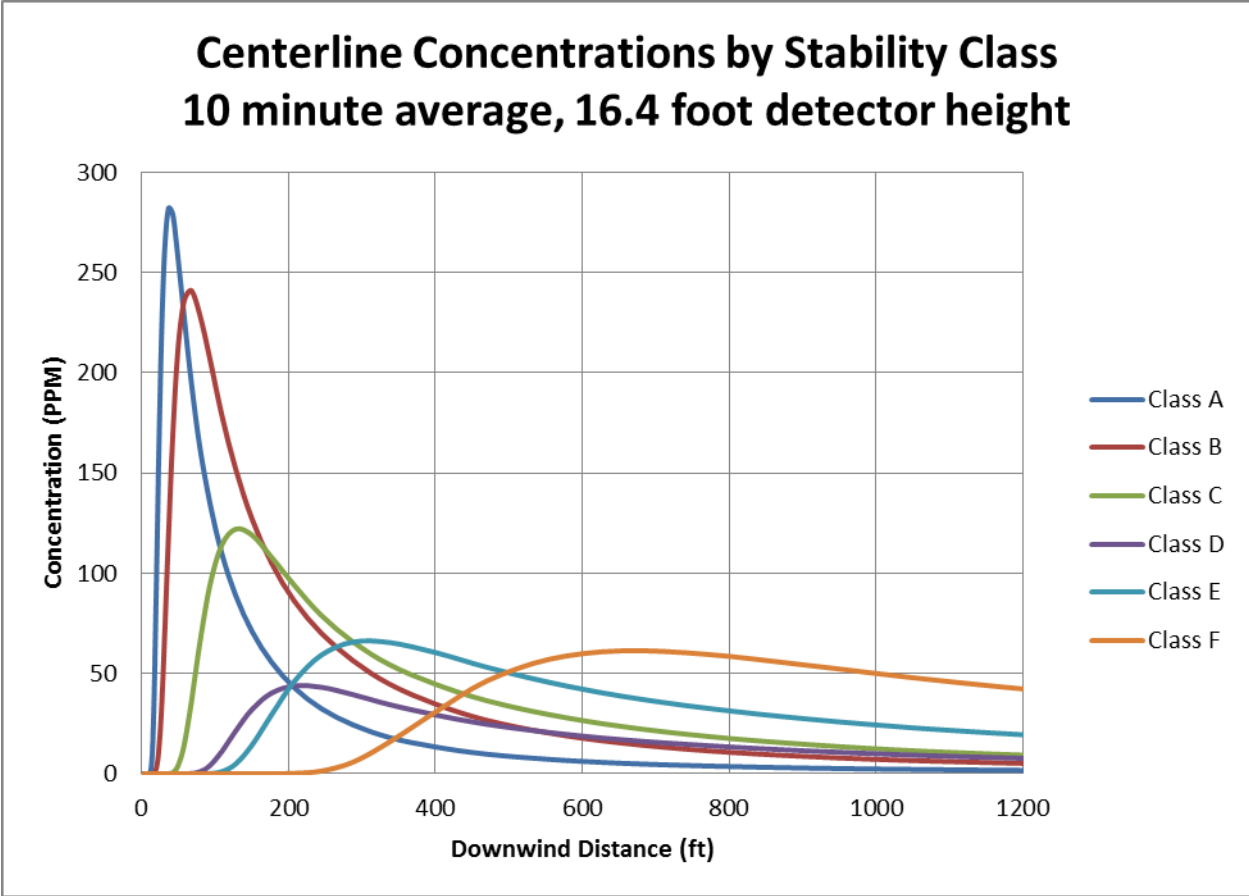


Figure 26: Centerline concentrations by stability class, 30 foot release

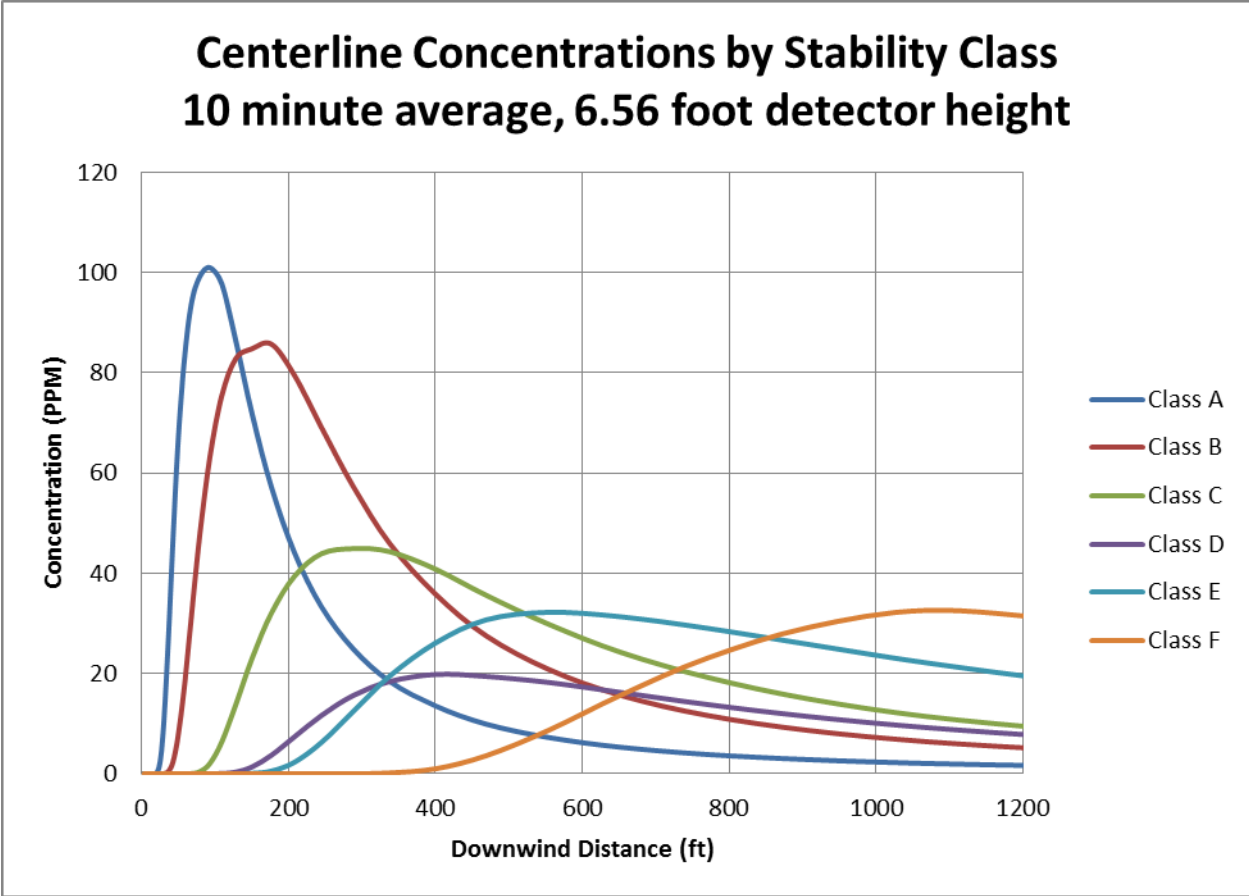


Figure 27: Centerline concentrations by stability class, 20 foot release

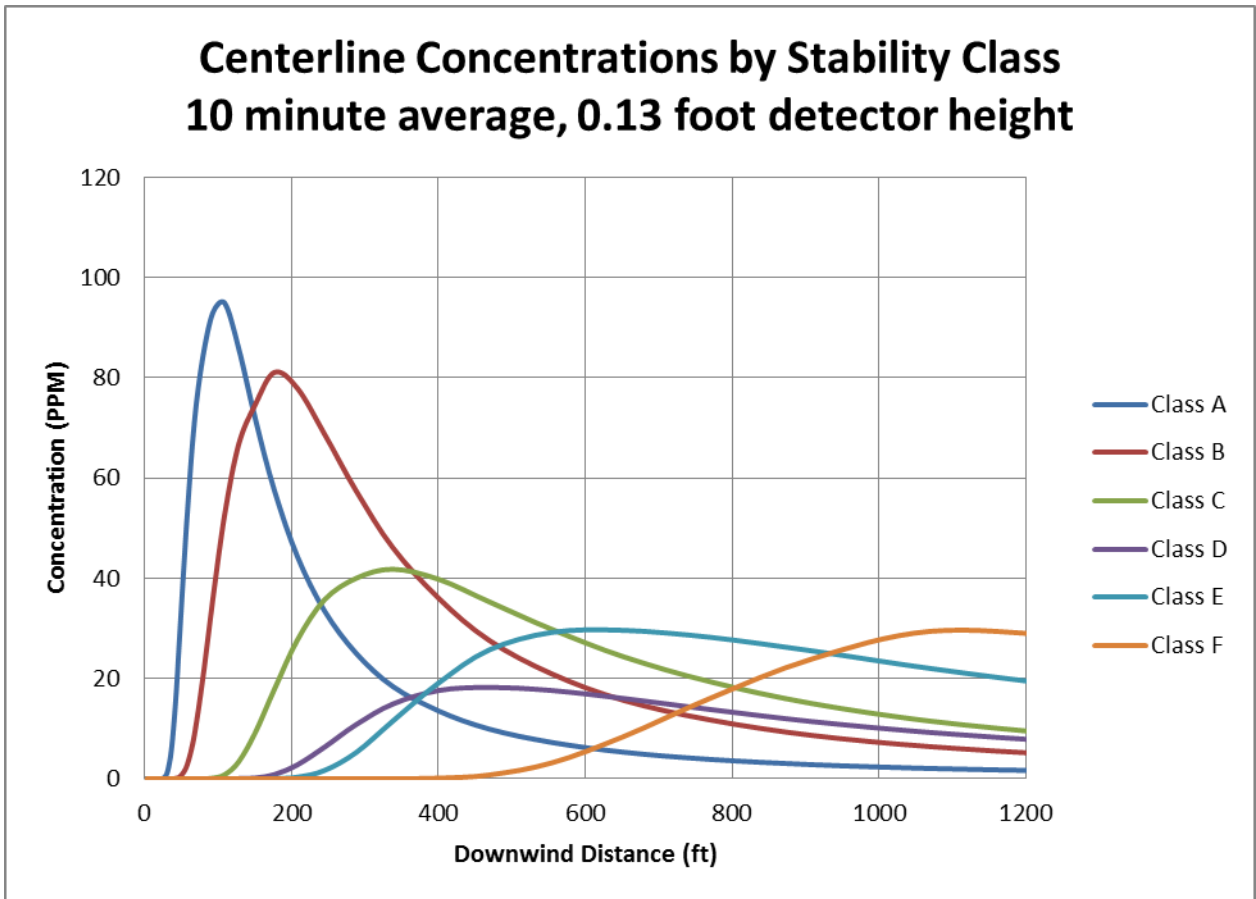


Figure 28: Centerline concentrations by stability class, 10 foot release

One important result of the dispersion modeling is that it shows much higher ammonia concentrations for the lower elevation releases. This is a major design consideration. In order to minimize the concentration of ammonia that people may be exposed to after a release, the higher above ground that the release occurs, the better. Figure 29 and Figure 30 show a comparison of centerline concentrations for releases under stability Class B and a detector height of 6.56 feet (2 m).

| Distance x (ft) | Centerline Concentration (PPM) | | |
|--------------------|--------------------------------|-----------------|-----------------|
| | 30 foot release | 20 foot release | 10 foot release |
| 3.28 | 0.0 | 0.0 | 0.0 |
| 3.35 | 0.0 | 0.0 | 0.0 |
| 3.41 | 0.0 | 0.0 | 0.0 |
| 3.48 | 0.0 | 0.0 | 0.0 |
| 3.58 | 0.0 | 0.0 | 0.0 |
| 3.71 | 0.0 | 0.0 | 0.0 |
| 3.84 | 0.0 | 0.0 | 0.0 |
| 4.00 | 0.0 | 0.0 | 0.0 |
| 4.17 | 0.0 | 0.0 | 0.4 |
| 4.40 | 0.0 | 0.0 | 16.8 |
| 4.66 | 0.0 | 0.0 | 178.0 |
| 4.95 | 0.0 | 0.0 | 816.0 |
| 5.31 | 0.0 | 0.0 | 2210.0 |
| 5.74 | 0.0 | 0.0 | 4230.0 |
| 6.27 | 0.0 | 0.0 | 6330.0 |
| 6.86 | 0.0 | 0.0 | 7270.0 |
| 7.55 | 0.0 | 0.0 | 7870.0 |
| 8.37 | 0.0 | 0.0 | 8080.0 |
| 9.35 | 0.0 | 0.0 | 7930.0 |
| 10.5 | 0.0 | 0.0 | 7490.0 |
| 11.8 | 0.0 | 0.0 | 6850.0 |
| 13.5 | 0.0 | 0.3 | 6090.0 |
| 15.4 | 0.0 | 1.7 | 5290.0 |
| 17.6 | 0.0 | 7.1 | 4510.0 |
| 20.2 | 0.0 | 22.1 | 3790.0 |
| 23.3 | 0.0 | 52.9 | 3150.0 |
| 26.9 | 0.0 | 101.0 | 2650.0 |
| 31.2 | 0.1 | 161.0 | 2210.0 |
| 36.4 | 0.5 | 221.0 | 1850.0 |
| 42.3 | 2.2 | 269.0 | 1530.0 |
| 49.2 | 7.2 | 299.0 | 1270.0 |
| 57.7 | 17.0 | 310.0 | 1040.0 |
| 67.6 | 31.3 | 307.0 | 835.0 |
| 79.1 | 47.7 | 293.0 | 663.0 |
| 92.8 | 63.2 | 279.0 | 519.0 |
| 108.9 | 75.4 | 253.0 | 401.0 |
| 128.0 | 82.8 | 220.0 | 306.0 |
| 150.3 | 84.8 | 183.0 | 231.0 |
| 176.8 | 85.7 | 148.0 | 173.0 |
| 208.0 | 79.5 | 117.0 | 129.0 |
| 244.8 | 69.1 | 90.1 | 95.7 |
| 288.1 | 57.3 | 68.6 | 70.9 |
| 337.9 | 45.9 | 51.7 | 52.3 |
| 400.3 | 35.8 | 38.7 | 38.6 |

Figure 29: Comparison of releases under the same conditions at different release heights (table)

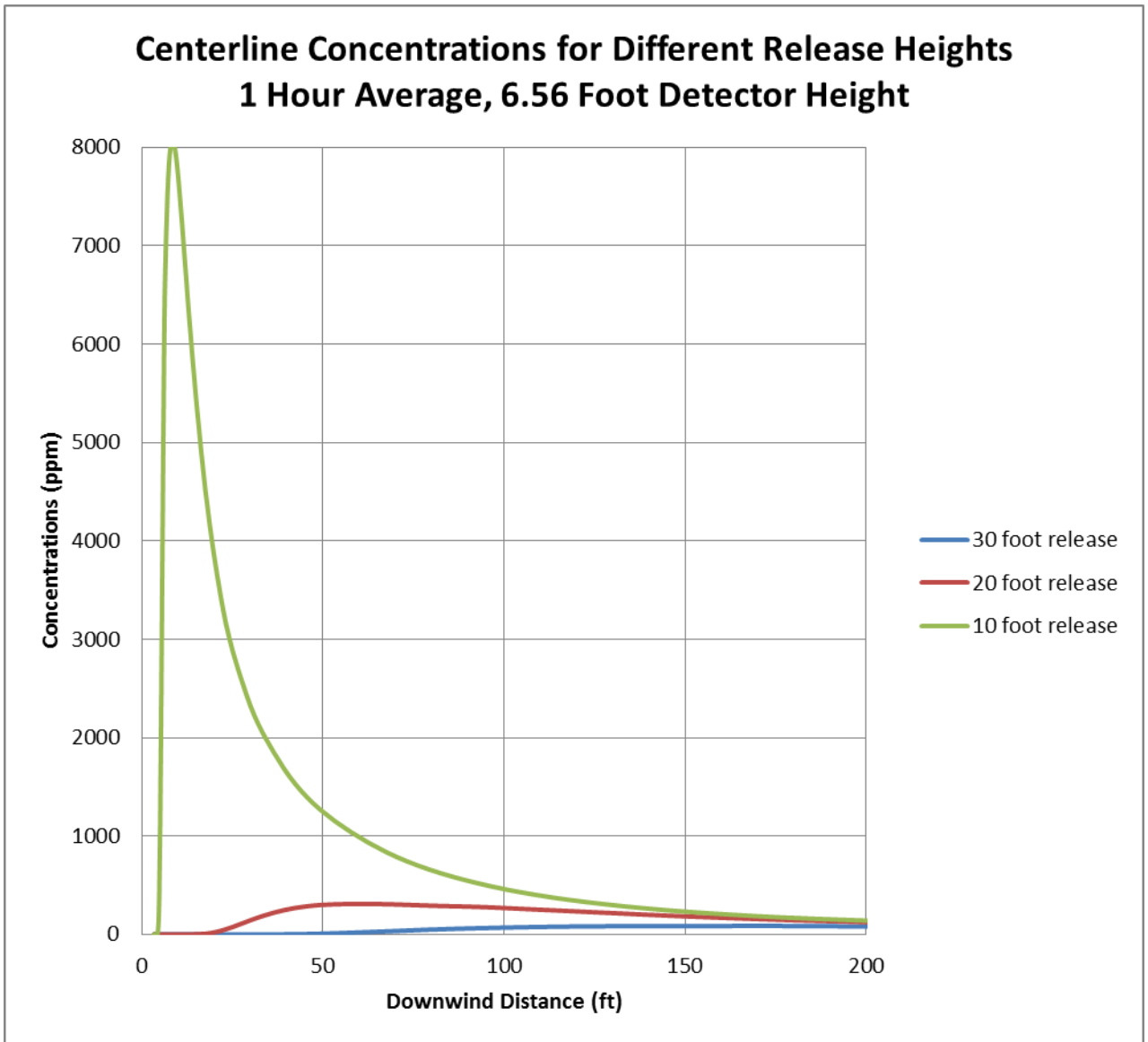


Figure 30: Comparison of releases under the same conditions at different release heights (graph)

7.5 Correlating Ammonia Exposure with Health Cost

The California Air Resources Board has a document that shows the financial cost associated with health effects caused by air contaminants (Air Resources Board 2006). The table in Figure 31 details these costs. Combined with the data from an EPA publication outlining the Acute Exposure Guideline Levels (AEGL) for ammonia (National Research Council of the National

Academies 2007), shown in Figure 32, a cost associated with an exposure to a certain concentration of ammonia has been defined. defines which AEGL Classification is associated with each health event, and shows the average cost for the health events associated with each of the AEGL Classifications. The overall human health cost is calculated by Equation 6.

| 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 31: 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 (non-disabling) | 30 ppm (21 mg/m ³) | 30 ppm (21 mg/m ³) | 30 ppm (21 mg/m ³) | 30 ppm (21 mg/m ³) | 30 ppm (21 mg/m ³) | 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/m ³) | 110 ppm (77 mg/m ³) | 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/m ³) | 390 ppm (273 mg/m ³) | Lethality (Kapeghian et al. 1982; MacEwen and Vernot 1972) |

Figure 32: Summary of AEGL Values for Ammonia (National Research Council of the National Academies 2007)

Table 4: Table 4: Health Events Related to Ammonia Exposure Classification

| Health Event | Associated Cost | AEGL Classification |
|-----------------------------------|-----------------|------------------------|
| Acute Bronchitis | \$440 | AEGL-1 (non-disabling) |
| Lower Respiratory Symptoms | \$19 | AEGL-1 (non-disabling) |
| Work Loss Day | \$195 | AEGL-1 (non-disabling) |
| Minor Restricted Activity Day | \$62 | AEGL-1 (non-disabling) |
| School Absence Day | \$95 | AEGL-1 (non-disabling) |
| 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 5: Average Cost by AEGL Classification

| AEGL Classification | Average Cost |
|------------------------|--------------|
| AEGL-1 (non-disabling) | \$162 |
| AEGL-2 (disabling) | \$40,000 |
| AEGL-3 (lethal) | \$8,100,000 |

Equation 6:

$$\text{Human Cost} = \sum_i RA_i * C_{AEGL,i} * P_{dens}$$

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 the program output. This was done in order to later overlap releases from different release points. The original program 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 will give a conservative estimate. shows the calculated costs for each detector height for the 30 foot releases, and and do the same for the 20 foot and 10 foot releases, respectively. shows the maximum costs for each type of release.

Table 6: Human health costs for 30 foot ammonia releases

| 30 Feet Atmospheric Stability | 16.4 feet (5 m) | | 6.28 feet (2 m) | | 0.13 feet (0.04 m) | | Maximum Cost |
|----------------------------------|-----------------|----------|-----------------|--------|--------------------|--------|-----------------|
| | 10 min | 1 hour | 10 min | 1 hour | 10 min | 1 hour | |
| 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 7: Human health costs for 20 foot ammonia releases

| 20 Feet Atmospheric Stability | 16.4 feet (5 m) | | 6.28 feet (2 m) | | 0.13 feet (0.04 m) | | Maximum Cost |
|----------------------------------|-----------------|------------|-----------------|----------|--------------------|----------|-----------------|
| | 10 min | 1 hour | 10 min | 1 hour | 10 min | 1 hour | |
| 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 8: Human health costs for 10 foot ammonia releases

| 10 feet Atmospheric Stability | 16.4 feet (5 m) | | 6.28 feet (2 m) | | 0.13 feet (0.04 m) | | Maximum Cost |
|----------------------------------|-----------------|--------------|-----------------|------------|--------------------|-----------|-----------------|
| | 10 min | 1 hour | 10 min | 1 hour | 10 min | 1 hour | |
| 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 9: Maximum cost for each release height

| Atmospheric Stability | 10 feet Cost | 20 Feet Cost | 30 Feet 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 |

7.6 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° offset. This is shown in Figure 33. Note that only one of the additional release points is used at one time.

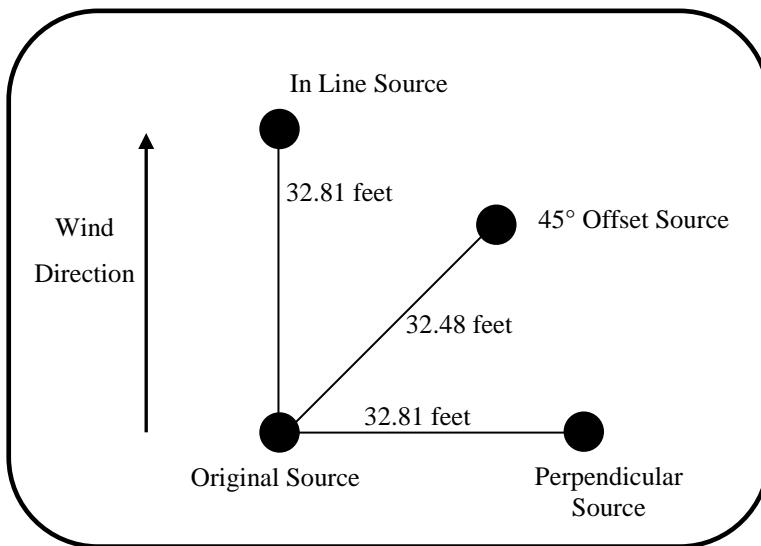


Figure 33: Orientation of Multiple Release Points

The results of the dispersion model were superimposed over each other with an origin offset determined by the orientation of the release points. The output of the model calculates the maximum concentration for a ten minute period so for different points, the maximum concentration happens at different times. In superimposing the results from the two release points, 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 used.

, , and show the maximum ammonia concentrations for each release type. In most cases, splitting the release into two sources reduces the maximum concentration, although for more stable atmospheric conditions, the model indicates that the maximum concentration could actually be increased for the releases from greater elevation.

In every case, the maximum concentrations of the split releases were from the inline release, while the perpendicular release has the lowest concentration. This is a result of the inline release causing more overlapping in the downwind ammonia concentrations than the release points oriented perpendicular to the wind or at a 45 degree offset.

Table 10: Maximum concentrations comparing split to single release, 30 foot release

| 30 foot release Atmospheric Stability | Maximum Concentration (PPM) for Various Release Types | | | |
|--|---|--------|---------------|------------|
| | Single Release Pt. | Inline | Perpendicular | 45° Offset |
| Class A | 282 | 313 | 204 | 259 |
| Class B | 241 | 229 | 135 | 169 |
| Class C | 122 | 124 | 75 | 91 |
| Class D | 44 | 68 | 47 | 53 |
| Class E | 66 | 110 | 78 | 88 |
| Class F | 61 | 110 | 85 | 92 |

Table 11: Maximum concentrations comparing split to single release, 20 foot release

| 20 foot release Atmospheric Stability | Maximum Concentration (PPM) for Various Release Types | | | |
|--|---|--------|---------------|------------|
| | Single Release Pt. | Inline | Perpendicular | 45° Offset |
| Class A | 5460 | 3899 | 3449 | 3556 |
| Class B | 4920 | 3264 | 2656 | 2677 |
| Class C | 2290 | 1904 | 1301 | 1302 |
| Class D | 423 | 684 | 382 | 388 |
| Class E | 512 | 956 | 505 | 523 |
| Class F | 410 | 902 | 453 | 501 |

Table 12: Maximum concentrations comparing split to single release, 10 foot release

| 10 foot release Atmospheric Stability | Maximum Concentration (PPM) for Various Release Types | | | |
|--|---|--------|---------------|------------|
| | Single Release Pt. | Inline | Perpendicular | 45° Offset |
| Class A | 8980 | 6362 | 5680 | 5787 |
| Class B | 8080 | 4963 | 4191 | 4215 |
| Class C | 4100 | 3065 | 2313 | 2316 |
| Class D | 4910 | 3253 | 2502 | 2503 |
| Class E | 7160 | 5722 | 4097 | 4098 |
| Class F | 7610 | 6436 | 3757 | 3757 |

, , and

show the cost for each release type. It turns out to be quite a bit higher in several cases. This happens because although the average ammonia concentration may be reduced, a greater area could have a concentration exceeding the AEGL threshold values. For example, if an area has an ammonia concentration of 500 PPM over a 10 minute period, it is classified as AEGL-2 and if another area has a concentration of 1500 PPM over a 10 minute period, it is also classified as AEGL-2. Since they are the same AEGL classification, they each have the same associated cost, despite one having three times the concentration level. Many of the split releases reach the threshold concentration values over a larger area than the corresponding single point releases, and therefore have higher costs than the reference release. Splitting the release is only effective

in cases where the concentration is lowered enough to drop the AEGL classification over a significant portion of the affected area.

Table 13: Maximum costs of various release types, 30 foot release

| 30 foot release | Maximum Cost for Various Release Types | | | |
|-----------------------|--|----------|---------------|------------|
| Atmospheric Stability | Single Release Pt. | Inline | Perpendicular | 45° Offset |
| Class A | \$ 2,687 | \$ 2,200 | \$ 1,675 | \$ 1,812 |
| Class B | \$ 508 | \$ 419 | \$ 204 | \$ 201 |
| Class C | \$ 164 | \$ 167 | \$ 162 | \$ 161 |
| Class D | \$ 86 | \$ 111 | \$ 89 | \$ 97 |
| Class E | \$ 338 | \$ 439 | \$ 423 | \$ 425 |
| Class F | \$ 852 | \$ 1,218 | \$ 1,184 | \$ 1,178 |

Table 14: Maximum costs of various release types, 20 foot release

| 20 foot release | Maximum Cost for Various Release Types | | | |
|-----------------------|--|------------|---------------|------------|
| Atmospheric Stability | Single Release Pt. | Inline | Perpendicular | 45° Offset |
| Class A | \$ 169,212 | \$ 182,652 | \$ 126,311 | \$ 138,648 |
| Class B | \$ 144,870 | \$ 126,851 | \$ 52,211 | \$ 70,708 |
| Class C | \$ 44,698 | \$ 39,065 | \$ 7,858 | \$ 7,928 |
| Class D | \$ 6,919 | \$ 7,788 | \$ 7,073 | \$ 7,404 |
| Class E | \$ 17,231 | \$ 81,183 | \$ 19,739 | \$ 19,109 |
| Class F | \$ 40,876 | \$ 47,218 | \$ 48,869 | \$ 47,129 |

Table 15: Maximum costs of various release types, 10 foot release

| 10 foot release | Maximum Cost for Various Release Types | | | |
|-----------------------|--|--------------|---------------|--------------|
| Atmospheric Stability | Single Release Pt. | Inline | Perpendicular | 45° Offset |
| Class A | \$ 169,920 | \$ 240,679 | \$ 159,796 | \$ 184,413 |
| Class B | \$ 203,895 | \$ 223,157 | \$ 111,635 | \$ 129,763 |
| Class C | \$ 128,641 | \$ 148,179 | \$ 42,687 | \$ 45,405 |
| Class D | \$ 126,464 | \$ 168,646 | \$ 70,746 | \$ 69,726 |
| Class E | \$ 533,870 | \$ 502,856 | \$ 267,541 | \$ 282,024 |
| Class F | \$ 1,499,712 | \$ 1,426,486 | \$ 1,031,697 | \$ 1,274,687 |

7.7 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 NH₃ (8 kg) per minute. This could be useful in designing a mitigation system for a larger or smaller refrigeration system. , , and compare the maximum costs for the different release rates at each release height. Interestingly, in all cases, 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. Figure 34, Figure 35, and Figure 36 are graphical representations of this data. While the cost is not linearly related to the release rate, it is reasonable to expect that a release rate in between any of these measured releases would have a cost that falls somewhere in between as well. The lines are included between points on the graphs to easily connect the points simulated under the same atmospheric conditions and are not meant to indicate a linear relationship between the cost and release rate.

Table 16: Comparing costs of varied release rates, 30 foot release rates

| 30 foot release | Half 17.64 lbm | Reference 35.27 lbm | Double 70.54 lbm |
|-----------------|-------------------|------------------------|---------------------|
| Class A | \$ 77 | \$ 2,687 | \$ 10,118 |
| Class B | \$ 76 | \$ 508 | \$ 6,569 |
| Class C | \$ 47 | \$ 164 | \$ 820 |
| Class D | \$ 8 | \$ 86 | \$ 308 |
| Class E | \$ 103 | \$ 338 | \$ 1,035 |
| Class F | \$ 267 | \$ 852 | \$ 2,779 |

Table 17: Comparing costs of varied release rates, 20 foot release rates

| 20 foot release | Half 17.64 lbm | Reference 35.27 lbm | Double 70.54 lbm |
|-----------------|-------------------|------------------------|---------------------|
| Class A | \$ 78,162 | \$ 169,212 | \$ 370,781 |
| Class B | \$ 41,012 | \$ 144,870 | \$ 334,721 |
| Class C | \$ 3,386 | \$ 44,698 | \$ 227,553 |
| Class D | \$ 3,107 | \$ 6,919 | \$ 58,500 |
| Class E | \$ 7,855 | \$ 17,231 | \$ 119,892 |
| Class F | \$ 18,443 | \$ 40,876 | \$ 95,906 |

Table 18: Comparing costs of varied release rates, 10 foot release rates

| 10 foot release | Half 17.64 lbm | Reference 35.27 lbm | Double 70.54 lbm |
|-----------------|-------------------|------------------------|---------------------|
| Class A | \$ 98,076 | \$ 169,920 | \$ 504,361 |
| Class B | \$ 73,598 | \$ 203,895 | \$ 501,374 |
| Class C | \$ 35,828 | \$ 128,641 | \$ 410,995 |
| Class D | \$ 10,413 | \$ 126,464 | \$ 411,116 |
| Class E | \$ 178,068 | \$ 533,870 | \$ 1,243,062 |
| Class F | \$ 620,264 | \$ 1,499,712 | \$ 3,266,198 |

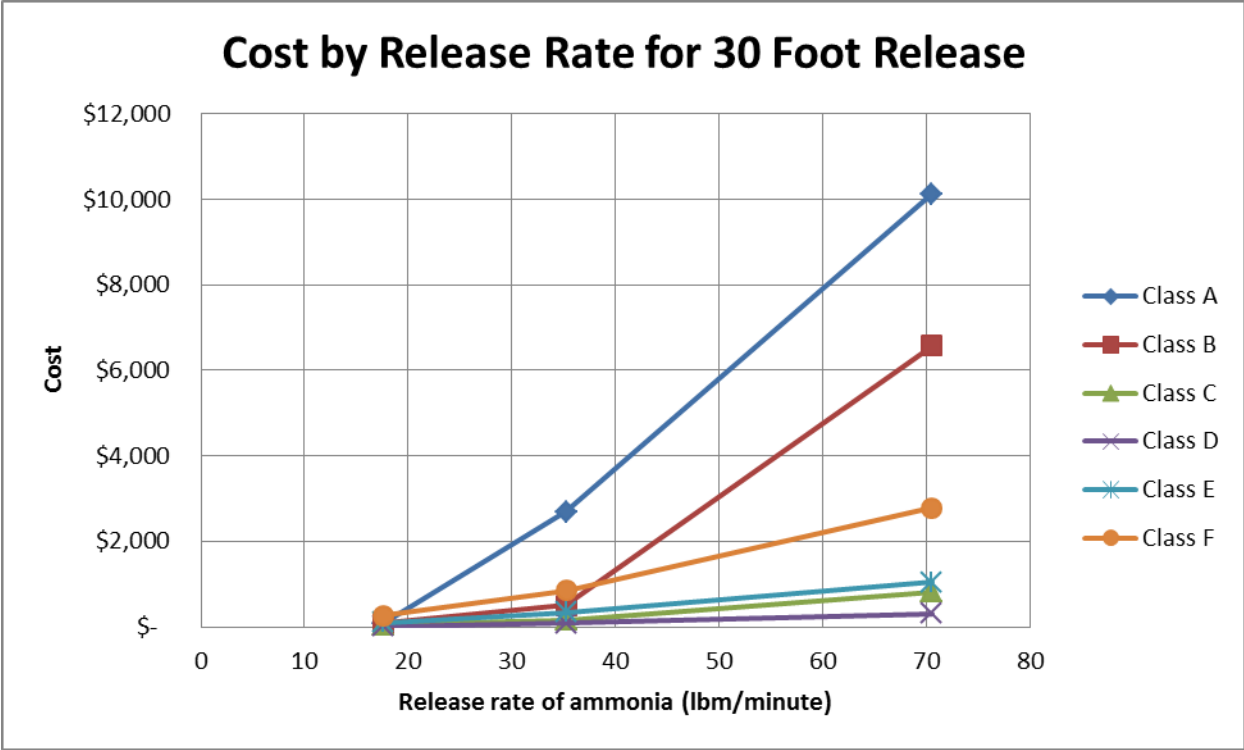


Figure 34: Comparing costs of varied release rates, 30 foot release

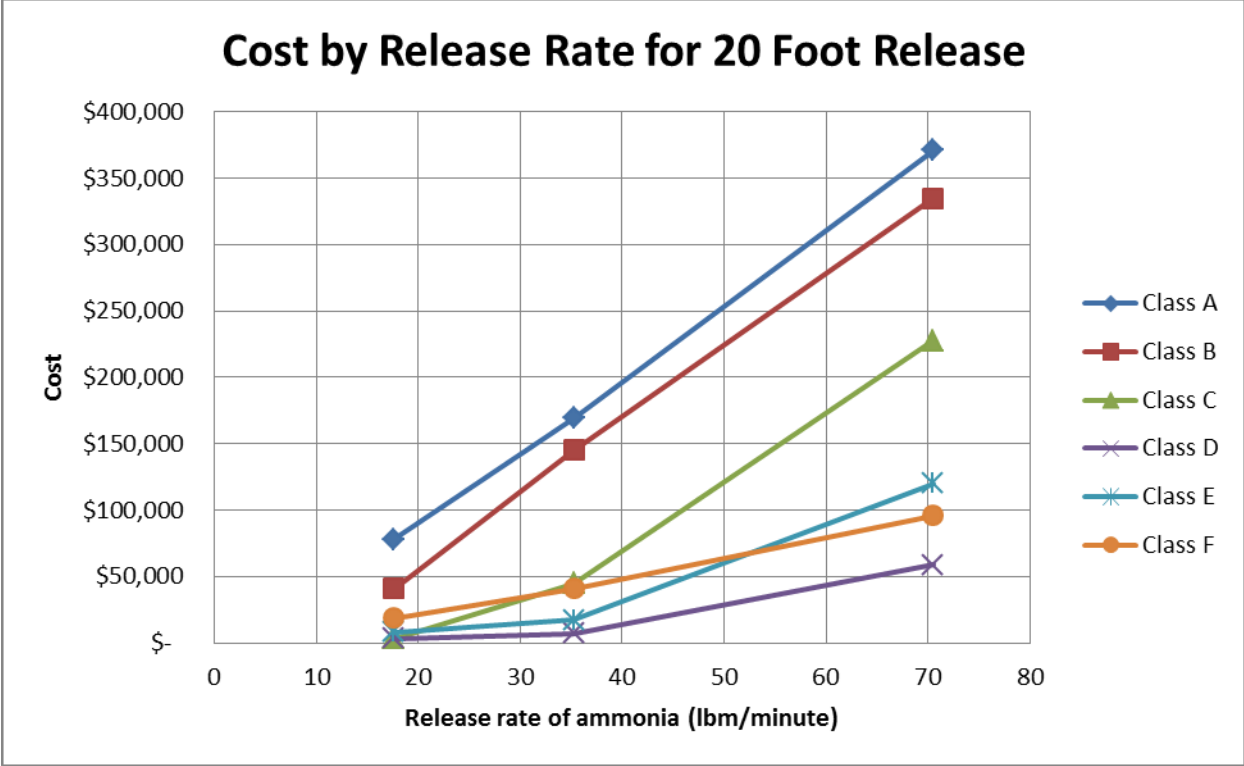


Figure 35: Comparing costs of varied release rates, 20 foot release

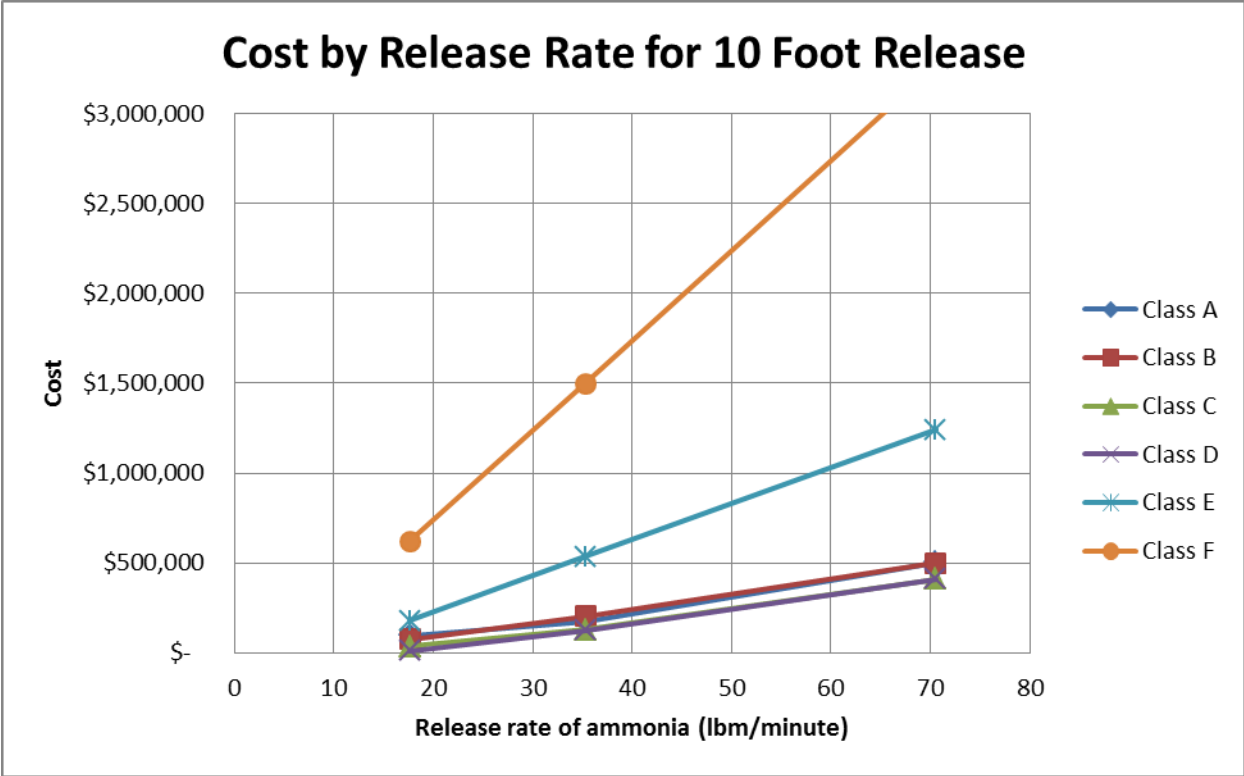


Figure 36: Comparing costs of varied release rates, 10 foot release

8.0 Failure Risk and Cost of System Failure

Now that the cost of various ammonia releases has been calculated, the chance of the mitigation system allowing a release must be calculated. For the water diffusion tank, flare, and scrubber systems, a failure of a part in the system will cause a release. For the Emergency Pressure Control System, 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.

To assess the risk of system failure, we will use *Nonelectronic Parts Reliability Data 2011* (Denson 2011). In addition to the cost of replacing a failed part, a failure of the ammonia capturing method will lead to some sort of unmitigated or partially mitigated ammonia release. For the purposes of this project it is assumed that a failure of an essential part of the release mitigation system will cause an unmitigated ammonia release. If a part has a redundant part that will take over the function in case of failure, then it will take both of those parts failing simultaneously to cause an unmitigated release. Similar to a circuit diagram, redundant parts are calculated in parallel with each other, and each part is calculated in series. For example, if there is a system with parts A, B, C that are independent, and D and E that are in parallel, with failure rates f_A , f_B , f_C , f_D , and f_E . Figure 37 shows a diagram of the system, and Equation 7 shows how the failure rate would be calculated.

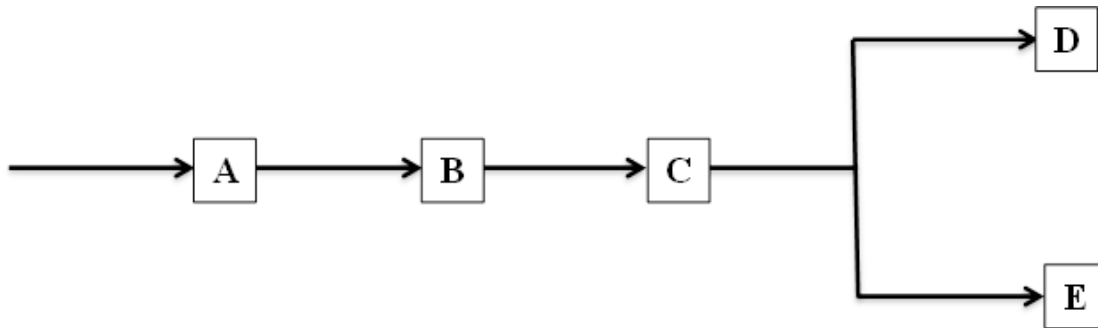


Figure 37: Example failure path diagram

Equation 7:

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

Since all of the failure rates are smaller than one, Equation 5 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 failures per million hours. For this application, a well maintained system could have a much lower failure rate because the system is used intermittently. If a part was found to be defective or damaged during regular maintenance, it could be repaired or replaced without an overpressure event occurring so there would be no ammonia release. As a result, the failure rates listed below probably are overestimated for what would cause a failure of the system in time of operation, but based on feedback from the industry, it is known that these systems are not always properly maintained. Figures 38 through 42 show the failure path diagrams and Tables 19 through 24 failure rates for the parts involved in the 5 different release mitigation systems.

8.1 Failure Risk: Discharge to Atmosphere

The discharge to atmosphere is the simplest system, and is 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.

Discharge to Atmosphere

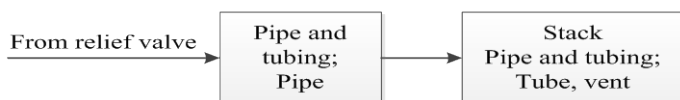


Figure 38: Failure path diagram for Discharge to Atmosphere

Table 19: Failure rates 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 |

8.2 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 data, it is only the third most likely to fail.

Water Diffusion Tank

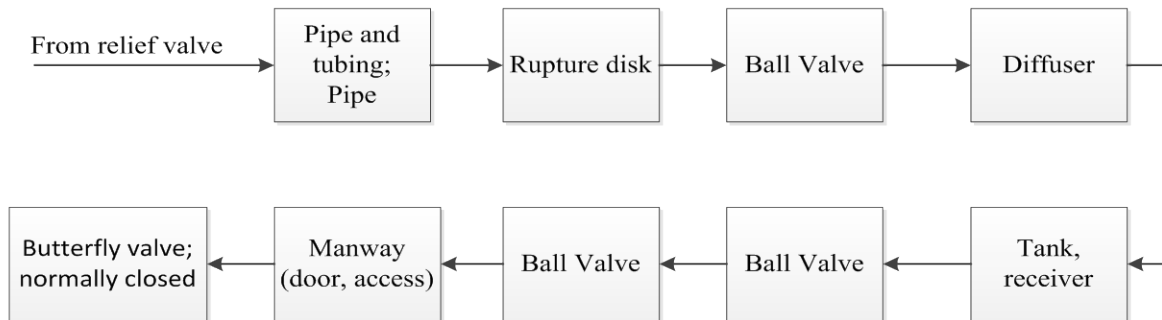


Figure 39: Failure Path Diagram for Water Diffusion Tank

Table 20: Failure rates for water diffusion tank system parts

| 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 |

8.3 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 must have a battery backup system in place. The pump is the most likely to fail out of all of its parts, but there are quite a few parts 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.

Scrubber

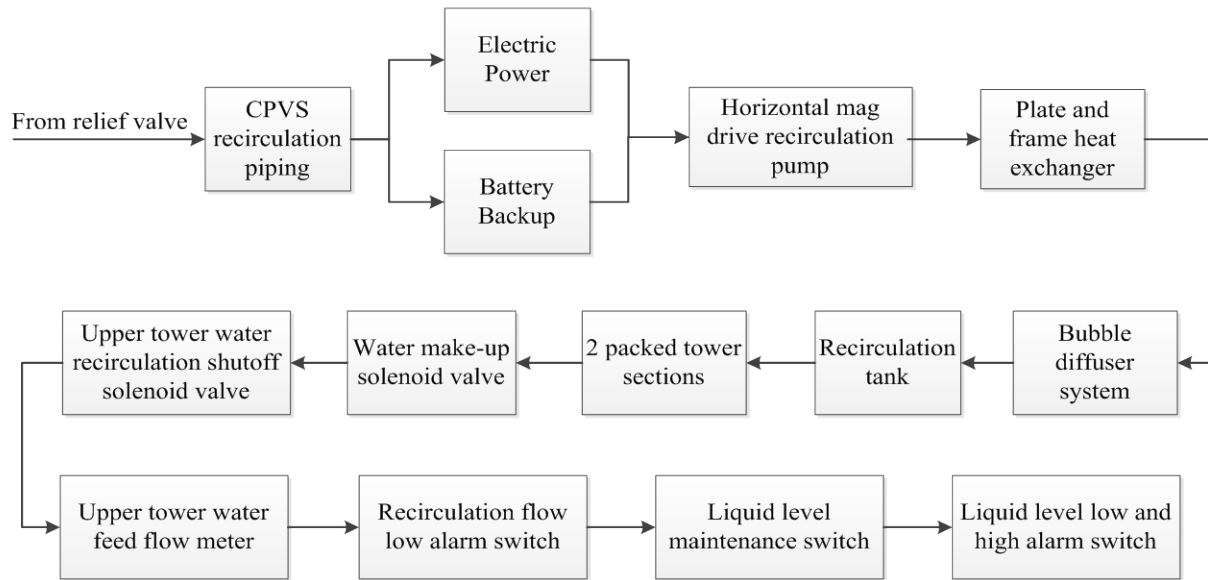


Figure 40: Failure path diagram for scrubber

Table 21: Failure rates for scrubber system parts

| 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 |
| 2-443 | 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 low 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: | | 127.97 |

8.4 Failure Risk: Flare

The flare is the most complicated of all the systems, and 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.

Flare

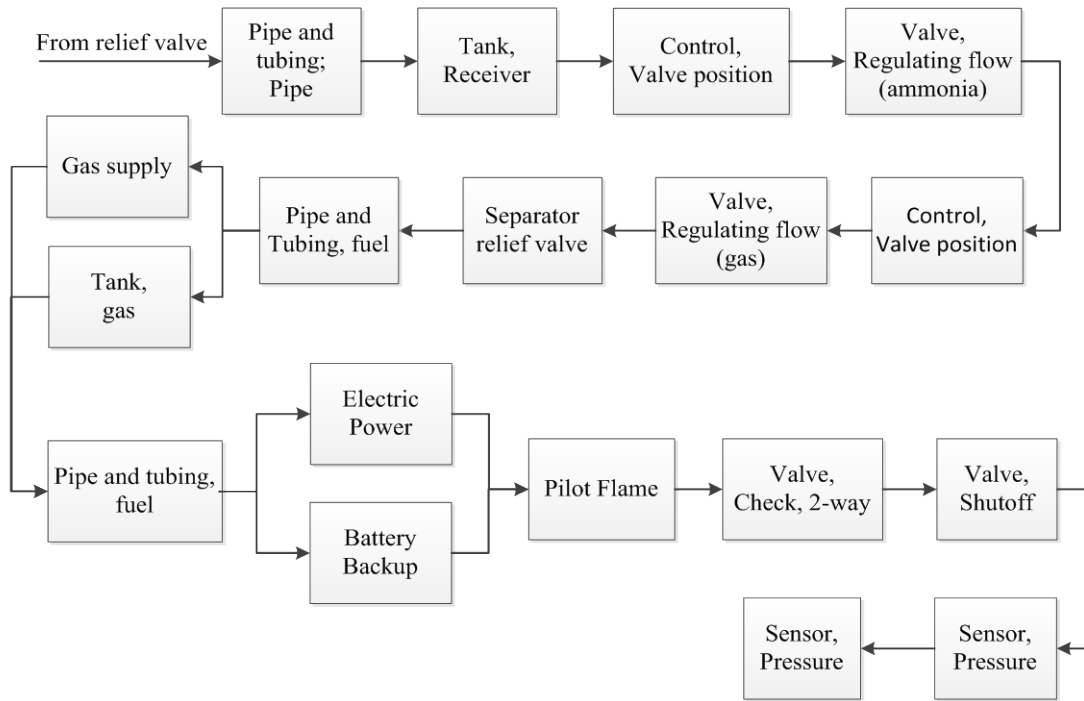


Figure 41: Failure path diagram for flare

Table 22: Failure rates for flare system parts

| 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 |

8.5 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, so the overall system failure rate is close to as high as the scrubber and flare.

Emergency Pressure Control System



Figure 42: Parts for Emergency Pressure Control System

Table 23: Failure rates for emergency pressure control system parts

| 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 |

8.6 Failure Risk: System Comparison

For each of these systems, all of the parts except the gas and power supplies are essential, and there are no redundant parts built in. In order to try to make some of the systems more reliable, some redundant parts will be added later. Figure 60 shows the combined failure rates for all of the systems and what the result of a failure is in terms of a release. 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 100%, even though the system is not actually failing to do what it was designed to do.

Table 24: Failure rates for each mitigation system

| Release Mitigation System | Failures / million | Failures / year | Failure release result |
|---------------------------|--------------------|-----------------|--------------------------|
| Discharge to atmosphere | 1000000 | 8760 | 30 foot release |
| Scrubber | 127.972 | 1.121 | 10 foot release |
| Flare | 162.281 | 1.422 | 20 foot release |
| Water diffusion tank | 47.827 | 0.419 | 10 foot release |
| EPCS | 110.675 | 0.970 | Goes to other mitigation |

In order to compare the five systems, it is important to know a relative failure rate for each system, and a relative cost of failure for each. To find a relative cost of failure for each, the

average cost of failure for all stability classes for the associated release height was compared. To find the overall relative cost, the relative failure rate was multiplied by the relative cost of release. 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. The results are tabulated in . For comparison, the results for double the reference release, and half the reference release were included as well in and . As before, the costs are based on a population density of 1000 people per square mile.

Table 25: 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 | \$ 772.37 | 0.0017 | 36.3925 |
| Scrubber | 2.68 | \$ 443,750.43 | 1.0000 | 2.6757 |
| Flare | 3.39 | \$ 70,634.56 | 0.1592 | 0.5401 |
| Water diffusion tank | 1.00 | \$ 443,750.43 | 1.0000 | 1.0000 |

Table 26: Relative cost of release by mitigation system—doubled reference release

| Release Mitigation System | Relative Failure Rate | Cost of a release | Relative cost of a release | Relative Cost |
|---------------------------|-----------------------|-------------------|----------------------------|---------------|
| Discharge to atmosphere | 20,909 | \$ 3,604.91 | 0.0034 | 71.3639 |
| Scrubber | 2.68 | \$ 1,056,184.32 | 1.0000 | 2.6757 |
| Flare | 3.39 | \$ 201,225.43 | 0.1905 | 0.6464 |
| Water diffusion tank | 1.00 | \$ 1,056,184.32 | 1.0000 | 1.0000 |

Table 27: Relative cost of release by mitigation system—half reference release

| Release Mitigation System | Relative Failure Rate | Cost of a Release | Relative Cost of a Release | Relative Cost |
|---------------------------|-----------------------|-------------------|----------------------------|---------------|
| Discharge to Atmosphere | 20909 | \$ 96 | 0.0006 | 4.54 |
| Water Diffusion Tank | 1.00 | \$ 169,375 | 1.0000 | 0.38 |
| Flare | 3.39 | \$ 25,328 | 0.1495 | 0.19 |
| Scrubber | 2.68 | \$ 169,375 | 1.0000 | 1.02 |

This shows 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 systems at a

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

The flare is the only mitigation system that performs better than the water diffusion tank in terms of relative cost. It has a slightly higher failure rate than either the scrubber or water diffusion tank, but the cost of a failure leading to release is significantly less than that of the other two methods. The relative cost for the flare is 54% of the water diffusion tank at for the reference release, while it is 65% for the doubled release. The scrubber does not perform as well as the flare or the water diffusion tank, but by installing redundant backup parts, the failure rate can be greatly reduced making the scrubber nearly equivalent to the others.

8.7 Release Mitigation System Modifications

Figure 43 and show the failure path diagram and the part failure rates for the modified scrubber system. To make the system more resistant to failure, a backup pump was installed, and backup liquid level switches were added. The added pump improves the robustness of the system significantly, 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 that great an impact, but they are relatively inexpensive and easy to install, so it is a worthwhile change.

Scrubber

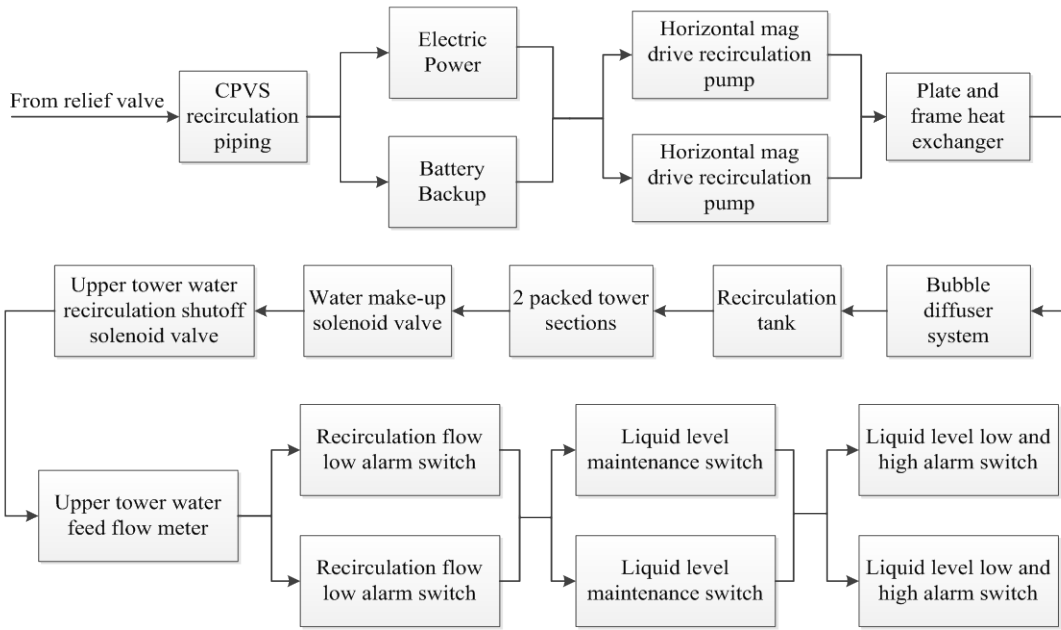


Figure 43: Modified Failure path diagram for scrubber

Table 28: Failure rates for scrubber system parts

| 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 |

The flare and water diffusion tank could be modified somewhat, but there are not any changes that would bring significant improvement that would also be reasonable modifications to the system. The failure rate of the scrubber was reduced to 65% of its original value, but because of the lower release height, the relative cost is still quite a bit larger than the flare or the water diffusion tank. With a stack added to the scrubber so that a release associated with a failure happened at 20 feet instead of the 10 feet, the relative cost is greatly improved. This also improves the cost for the water diffusion tank as well. Figure 44 is a plot of the relative costs of the systems for the reference release. shows the new relative costs including the modified scrubber system. and do the same for the doubled and half reference releases.

Table 29: 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 | 20909 | \$ 772 | 0.0017 | 36.39 |
| Water Diffusion Tank | 1.00 | \$ 443,750 | 1.0000 | 1.00 |
| Water Diffusion Tank, 20 Foot Stack | 1.00 | \$ 70,635 | 0.1592 | 0.16 |
| Flare | 3.39 | \$ 70,635 | 0.1592 | 0.54 |
| Scrubber | 2.68 | \$ 443,750 | 1.0000 | 2.68 |
| Modified Scrubber | 1.73 | \$ 443,750 | 1.0000 | 1.73 |
| Modified Scrubber, 20 Foot Stack | 1.73 | \$ 70,635 | 0.1592 | 0.28 |

Table 30: 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 | 20909 | \$ 3,605 | 0.0034 | 71.37 |
| Water Diffusion Tank | 1.00 | \$ 1,056,184 | 1.0000 | 1.00 |
| Water Diffusion Tank, 20 Foot Stack | 1.00 | \$ 201,225 | 0.1905 | 0.19 |
| Flare | 3.39 | \$ 201,225 | 0.1905 | 0.65 |
| Scrubber | 2.68 | \$ 1,056,184 | 1.0000 | 2.68 |
| Modified Scrubber | 1.73 | \$ 1,056,184 | 1.0000 | 1.73 |
| Modified Scrubber, 20 Foot Stack | 1.73 | \$ 201,225 | 0.1905 | 0.33 |

Table 31: Relative cost of release by mitigation system—half reference release

| Release Mitigation System | Relative Failure Rate | Cost of a Release | Relative Cost of a Release | Relative Cost |
|-------------------------------------|-----------------------|-------------------|----------------------------|---------------|
| Discharge to Atmosphere | 20909 | \$ 96 | 0.0006 | 11.89 |
| Water Diffusion Tank | 1.00 | \$ 169,375 | 1.0000 | 1.00 |
| Water Diffusion Tank, 20 Foot Stack | 1.00 | \$ 25,328 | 0.1495 | 0.15 |
| Flare | 3.39 | \$ 25,328 | 0.1495 | 0.51 |
| Scrubber | 2.68 | \$ 169,375 | 1.0000 | 2.68 |
| Modified Scrubber | 1.73 | \$ 169,375 | 1.0000 | 1.73 |
| Modified Scrubber, 20 Foot Stack | 1.73 | \$ 25,328 | 0.1495 | 0.26 |

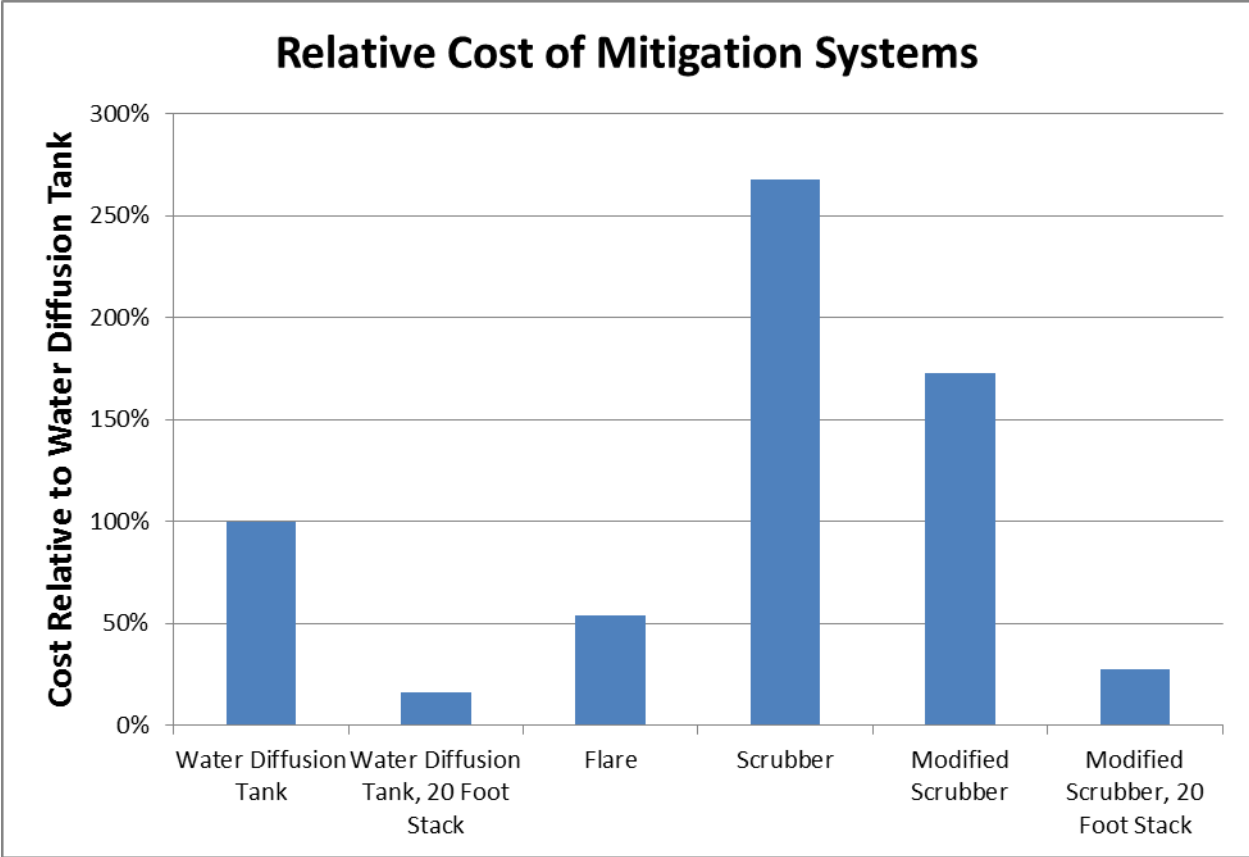


Figure 44: Relative cost of release by mitigation system—reference release

Conclusions

The dispersion modeling showed that the most effective way of decreasing the impact of an ammonia release is by increasing the height at which the ammonia is released. Increasing the height to just thirty feet from ten feet dramatically changes the impact on the human population in the area because the ammonia disperses to lower concentrations by the time it reaches near ground level where people live. This is a drawback to both the scrubber system and the water dispersion tank. If they fail, leading to an ammonia release, the ammonia is released much closer to the ground than if the flare fails to burn off the ammonia or if the ammonia is discharged through a thirty foot tall stack.

When the expected cost of an ammonia release was factored in with the probability of a mitigation system failure, the flare is the best option, with a relative cost of 65% of the water diffusion tank. It has a relative failure rate that is higher than that of the scrubber or the water diffusion tank, but because of the higher release height, the downwind ammonia concentrations are reduced significantly compared to the scrubber or diffusion tank. The water diffusion tank was the next best option, followed by the scrubber. Direct discharge to atmosphere causes the highest consequent human costs despite its relatively low cost of an individual release, because it allows a release every time ammonia leaves the refrigeration system through the relief valves.

When the scrubber and diffusion tank are modified to include a 20 foot stack, similar to that of the flare, they each perform better than any of the original systems. The water diffusion tank with a 20 foot stack becomes the most effective system of the ones modeled, with a relative cost of only 16% of the original water diffusion tank.

The water diffusion tank was shown to have the lowest failure rate of the mitigation systems, followed by the scrubber and then the flare. Those in the industry have voiced concerns that the water diffusion tanks are not generally well maintained, so it could be that they are not quite as reliable as this study indicates. On the other hand, the flare and scrubber systems are more complicated and will likely require more diligent maintenance than the water diffusion tank to operate as intended.

When any of these systems are used in conjunction with an Emergency Pressure Control System (EPCS), there will very rarely be a failure leading to an ammonia release. The EPCS has a fairly low failure rate, so it would be highly unlikely that the EPCS would fail, followed by the secondary mitigation system failing. With a properly working EPCS installed, any of the other mitigation systems could be used, depending on designer preference. The water diffusion tank would probably be cheaper to install and maintain than the flare or scrubber, but any of the three could be used. Depending on the local population density surrounding the plant, discharging the ammonia directly to the atmosphere through a tall stack could be a very good option, when used with the EPCS to prevent most releases.

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