TECHNICAL SAFETY BC

Appendix I – Engineering analysis by Laporte Engineering Ltd

TECHNICAL SAFETY BC

LOCATION: Kamloops, British Columbia, Canada

ARCTIC GLACIER - KAMLOOPS

CASTB001

ENGINEERING ANALYSIS

Rev.: 01

2022-Oct-26

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ACKNOWLEDGEMENT AND SIGNATURE

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This report is the opinion of the authors.

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EXECUTIVE SUMMARY

On May 26, 2022, an ammonia release occurred at an Artic Glacier facility in Kamloops, BC. The ammonia was released through a hand valve on a high-pressure receiver vessel that was part of an ice production system (P34). The hand valve was connected to a liquid dip-tube which extended to the bottom of the vessel; during the release, liquid ammonia in the pipe flashed and was released into the facility as a liquid-vapour mist.

The P34 system was located inside the facility, near another ice production system (P24). The P24 system was not directly involved in the incident that occurred on May 26, 2022. However, there was an ammonia leak the previous day during demolition and ammonia was purged from the system following this release.

The purpose of this report is to document the engineering analysis completed by Laporte Experts Conseils (Laporte). Technical Safety BC requested the following work:

1. Investigation and analysis to estimate the total mass of ammonia that was released from the P34 system and the mass flow rate of the ammonia during the release.
2. Discuss the potential effects that adding heat to the P34 receiver vessel could have had prior to the release.
3. Analysis of the P24 system and associated pre-incident and post-incident purging to estimate the mass of ammonia vented from the system.
4. Analysis of the effectiveness of a ventilation system in decreasing the risk of deflagration.

P34 SYSTEM

The P34 system was designed to operate with 1,600 lbs of ammonia (Vogt Tube Ice, L.L.C, 2000). The minimum ammonia inventory of the P34 machine and the associated piping was estimated to be 1,300 lbs. These calculations accounted for modifications to the machine that had been completed after the machine was manufactured. The maximum safe total inventory in the vessel was estimated to be 1,645 lbs.

The mass flow rate of the ammonia release was estimated using the Fauske HEM model for flashing flow corrected for outlet pressure drop (Fauske & Epstein, 1988). This model estimated between 2,042 lbs and 2,403 lbs of ammonia was released during the incident at a rate between 227 lbs/min and 267 lbs/min. Video surveillance footage shows the duration of the release was between 9-10 minutes. Comparing these results with the vessel inventory calculation determined that it would not be possible for this mass to be released since the vessel could not possibly hold this much ammonia. Several factors were identified that may have caused the model to overestimate the release. It is likely that the vessel was a minimum of 70% full prior to the release which aligns with an assumption that the vessel contained the charge of the entire machine since it is common practice to move the ammonia charge from each component of the machine into the receiver for an extended shut down.

While not believed to have an impact on this incident, the P34 vessel did not have a pressure relief valve, creating the risk of a failure caused by overpressure. The temperature at which the vessel would have exceeded the Maximum Allowable Working Pressure is 114.6°F. It is possible that the ammonia would have reached this temperature if exposed to large external heat inputs, such as a fire, for a short period of time or small external heat inputs for an extended period of time.

P24 System

The P24 receiver was purged by workers during demolition by allowing water from a garden hose and ammonia from the high-pressure receiver to flow into a bucket where it mixed and then overflowed into the yard of the facility. Based on video footage of the puddle and calculated possible flow rates in garden hoses it was determined that the water flow rate was likely between 3.2 USGPM and 17.4 USGPM. Reports from bystanders and workers stated that the puddle had significant odour which means the concentration was likely at least 6%, since this is the concentration of commercially available ammonia cleaners. The maximum concentration would have been approximately 25%, depending on the specific flow rates and temperature. With these flow rates and concentrations, the amount of ammonia that could have been purged is between 150 lbs and 1,044 lbs.

After the incident the remaining ammonia in the P24 high-pressure receiver was purged by releasing the ammonia into a 250 USG tank of water. It was reported that the tank was initially 3/4 full of water, and the purging stopped when the tank indicated the water was saturated. A new water tank was used to finish purging the vessel of ammonia until the pressure in the tank was measured to be 0 psig. The contractor estimated 100 lbs of liquid ammonia was removed. Based on the ambient temperature and the temperature of the water and ammonia, it would have been possible to purge 256 lbs into a single tote.

The minimum total amount of ammonia that was vented from the P24 system, both pre-incident and post-incident, is estimated to be 250 lbs and the maximum total ammonia of ammonia vented from P24 is estimated to be 1,044 lbs. The amount of ammonia vented was quite likely near the upper bound of this range and therefore the vessel was likely close to 90% full prior to any purging. This result aligns with an assumption that the system was pumped down and contained the entire refrigerant inventory in the receiver.

Ventilation

The objective of an emergency ventilation system for ammonia refrigerant is to decrease the risk of deflagration. Ammonia is flammable when the concentration is between approximately 148,000 ppm and 335,000 ppm. Not enough information was available to make specific conclusions; however, in general, emergency ventilation effectively decreases the amount of time the system is above the lower flammability limit, even when the leak exceeds the design case used to determine the emergency ventilation rate, as is the case in an event with a large liquid release.

1. SCOPE OF WORK

The objective of this report is to provide the results of the engineering analysis performed for Technical Safety BC regarding the ammonia release at Arctic Glacier in Kamloops, BC on May 26, 2022. Analysis and discussion were requested by Technical Safety BC to establish the following:

1. Ammonia inventory in the P34 receiver vessel prior to the release, including the total ammonia quantity released.
2. The approximate duration and rate of the ammonia release.
3. The temperature at which the high-pressure receiver for P34 would have been above the Maximum Allowable Working Pressure (MAWP) and the possible effect of external heat sources on a potential overpressure situation.
4. Remaining ammonia inventory in the P24 receiver and the quantity of ammonia that may have been removed prior to the incident.
5. Concentration of ammonia in the building and the possible impact of ventilation systems on the deflagration event.

2. GENERAL INFORMATION

There were two separate refrigeration systems at the Arctic Glacier facility in Kamloops that are identified as the P24 and P34 systems in this report. Both systems were part of the demolition work that was in progress when the ammonia release occurred. The P34 system was the source of the primary release while the P24 system was the source of a smaller release that occurred earlier during the demolition. The P24 system also had refrigerant vented by the workers performing the demolition.

It is beyond the scope of this report to describe the refrigeration systems in detail. However, certain information is necessary to explain the analysis that was completed.

2.1. P34 SYSTEM

The P34 system was originally a packaged refrigeration system with a water-cooled condenser. In this configuration, the refrigerant was contained on the ice machine skid inside the building. At some point during its operational life, this system was modified to use an evaporative condenser located outdoors. This modification involved piping three refrigerant lines from the skid inside to the condenser outside. The condenser had been removed prior to this demolition work. As part of this demolition work, the ice machine skid was separated into two pieces with the evaporator on one skid and the compressor and high-pressure receiver (HPR) on the other. The evaporator had been removed from the building and the compressor/HPR skid was in the process of being moved when the release occurred.

The source of the ammonia release was a 1" valve located on the HPR, shown below in Figure 1. This nozzle connection to the vessel was for the high-pressure liquid supply piping. Prior to being cut, this piping would have been connected, through control valves and a surge drum, to the evaporator.

Figure 1: The 1" valve on the P34 HPR that was the source of the release

At the time of the incident the HPR had been isolated from all other components and much of the piping had been cut away. Figure 2 shows the receiver and how it was isolated from the system. The HPR also contained internal refrigerant piping as the compressor discharge piping ran through the vessel and the high-pressure liquid piping had a dip tube extending to the bottom of the vessel.

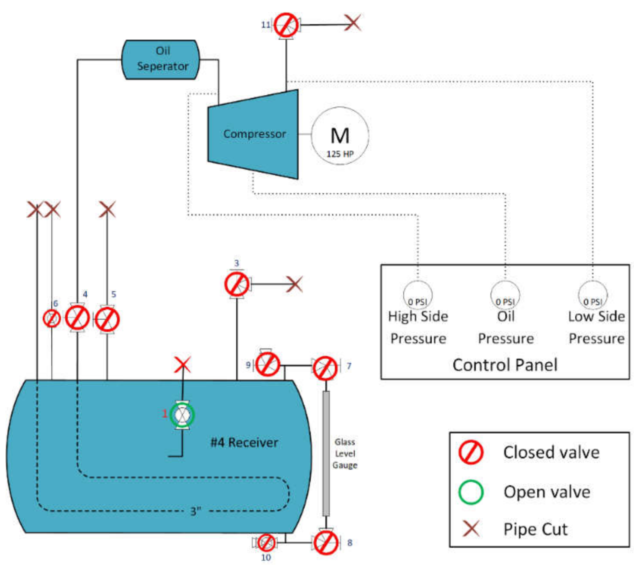

Figure 2: High Pressure Receiver configuration at the time of the incident.

2.2. P24 System

The P24 system consisted of two P24 Vogt Tube-Ice machines connected to a common refrigerant receiver and an outdoor evaporative condenser. The receiver was located in a lean-to style building addition. Ammonia was discovered and vented from this receiver during the demolition prior to the incident.

3. METHODOLOGY

3.1. Ammonia Properties

The analysis required reference to the thermophysical properties of ammonia and aqueous ammonia. These properties were generally calculated using REFPROP Version 10 (Lemmon, Bell, Huber, & McLinden, 2017). Certain properties of aqueous ammonia were taken from 2021 ASHRAE Handbook - Fundamentals (ASHRAE, 2021).

3.2. Ammonia Concentration

The concentration of ammonia in water is represented as a mass percentage of the solution. For example, 20% concentration means that 20% of the mass of the solution is ammonia as NH_3 and 80% of the mass of the solution is water. See Section 7.1 for additional details related to the mixing of ammonia and water.

The concentration of ammonia in air is the ratio of ammonia to the total volume of gas represented in parts-per-million. The unit of measurement for the concentration of ammonia in air is ppm v/v and will be abbreviated ppm in this report. If analysis or discussion requires the use of parts-per-million on a mass basis it will be identified as ppm w/w.

3.3. Ammonia Inventory

The quantity of ammonia in each component of a system is typically calculated using the volume of the component and the average density of ammonia in that component. In some cases, this calculation is straightforward and in other cases it is difficult to determine the average density of the refrigerant. When possible, information from the manufacturer is used to increase the accuracy.

4. ESTIMATE OF P34 REFRIGERANT INVENTORY

The quantity of ammonia recommended by the equipment manufacturer to properly operate the P34 tube ice machine in the original system configuration was 1,600 lb (Vogt Tube Ice, L.L.C, 2000). To evaluate the amount of ammonia that was released during the incident, an ammonia inventory calculation was completed comparing the original system configuration, the modified system configuration, and the lowest possible ammonia inventory for system function.

During the demolition the piping was cut to isolate the HPR from the evaporator. This means that at some point prior to the demolition work, the high-pressure liquid line and condenser drain line valves were closed as shown in Figure 2, isolating whatever refrigerant was remaining in the HPR. The procedure to move the refrigerant to the HPR is a common procedure, often called a “pump down”, and is typically done on a system in preparation for any extended shutdown

4.1. Minimum Refrigerant Inventory of Original System

The methodology for calculating refrigerant inventory depends on the component being evaluated. The methodology used for each component of the P34 system is outlined in the subsections that follow. The conditions used to determine the refrigerant properties are as follows:

- Saturated Condensing Temperature: 90°F
- Saturated Suction Temperature: -1°F

The system would have operated at a range of different temperatures. The suction temperature would have varied from approximately 30°F at the beginning of the ice making cycle to -1°F at the end of the cycle (Vogt Tube Ice, L.L.C, 2000). The original condenser was water-cooled, and water flow was likely regulated to maintain a condensing temperature of approximately 100°F (Vogt Tube Ice, L.L.C, 2000). When the condenser was replaced with an outdoor evaporative system condenser, the condensing temperature would have been more variable and likely reduced in colder weather.

4.1.1. Vessels and Piping

It is straightforward to determine the amount of ammonia contained in piping and most vessels by using the refrigerant density and the internal volume of the piping or vessel. Vessel sizes were available from the original construction U-1 forms. However, the HPR has internal piping, and these details were not available on drawings or design registration forms. The 3” discharge piping from the compressor is routed through the receiver and the 1” liquid outlet piping uses a dip-tube that is likely quite close to the bottom of the vessel. The lengths of these piping were estimated based on the vessel size. In general, pipe sizes were available from the manufacturer’s literature. Pipe lengths were estimated through a comparison of site pictures and drawings contained in a more recent version of the P34 installation manual (Vogt Tube Ice, L.L.C, 2000).

The tube ice maker uses refrigerant vapour from the receiver to melt the ice in the tubes when the ice is ready for harvest. Due to this, the manufacturer published an approximate minimum receiver level required for proper operation. The minimum receiver ammonia inventory for the P34 is approximately 625 lb (Vogt Tube Ice, L.L.C, 2000).

The minimum operating charge in each piping and vessel component was estimated as shown in Table 1.

Table 1: Ammonia quantity in piping and vessel components of P34 Tube-Ice system.

Component	Size (ft^3)	Inventory (lb)
Piping	Various	15.3
Receiver	49.5	625
Oil Separator	2.5	1.5
Surge Drum (Accumulator)	20.9	2.2
Total		**653**

Note: The 3" discharge piping that routes through the vessel was considered to decrease the total vessel volume by approximately 0.8 ft^3.

4.1.2. CONDENSER

The original condenser was a water-cooled shell and tube heat exchanger which was factory installed on the skid with the complete P34 system. In these types of condensers, the cooling water flows through the tubes of the heat exchanger and the refrigerant condensers in the shell of the heat exchanger and drains through the condenser drain line into the receiver. A density of 10 lb/ft^3 was assumed for the refrigerant in the condenser (Industrial Refrigeration Consortium, 2004). The internal volume of the condenser was calculated by removing the volume associated with the cooling water tubes from the total volume of the shell.

The approximate minimum ammonia inventory of the initial configuration of the water-cooled condenser is approximately 214 lb.

4.1.3. FREEZER/EVAPORATOR

The freezer/evaporator was flooded which means that it was filled with liquid ammonia. To make ice in these types of machines, water is frozen in vertical tubes that are enclosed in a shell that is flooded with liquid ammonia. A float is used to control the ammonia liquid level in the shell; on the P34 machine the float is located near the top of the vessel. The internal volume of the freezer was estimated by subtracting the volume of the ice making tubes from the volume of the shell and an empirical correlation for flooded evaporators was used to estimate the ammonia charge (Industrial Refrigeration Consortium, 2004). It is likely that this correlation underestimates the ammonia that would be required in the evaporator under low load near the end of the ice making process.

The approximate minimum inventory in the freezer/evaporator is 439 lb.

4.2. Refrigerant Inventory Changes Due to Condenser Modifications

During the life of the equipment the original water-cooled condenser was replaced with an evaporative condenser located outdoors. To understand the implications that this may have had on the ammonia inventory, the inventory was calculated for the new condenser and the piping modifications.

4.2.1. Piping Modifications

Installing a condenser outdoors required extending the compressor discharge line, vent line and the condenser drain line approximately 25 ft. This resulted in an increase of the ammonia inventory in the piping to 36 lb.

4.2.2. Condenser Modifications

The most accurate way to estimate the ammonia inventory of an evaporative condenser is to get the information from the manufacturer. Unfortunately, the condenser that was connected to the P34 system was no longer on site and the exact model information was unavailable. A second method of estimating the ammonia inventory of the condenser is to use an empirical correlation with the heat rejection capabilities of the condenser (Industrial Refrigeration Consortium, 2004). This information was not directly available and instead, the heat rejection specification of the P34 system was used with the correlation to estimate the ammonia quantity.

The modified condenser had an approximate ammonia inventory of 166.3 lb. It is worth noting that condensers operating on systems with low and varying loads can have an increased inventory in cold weather operation that is not accounted for in this estimate.

4.3. Charge calculation Summary

Documentation from the manufacturer shows that the equipment was charged to 1,500 lbs during testing (Passanisi, 2022) and the more recent service manual for the P34 systems estimate that approximately 1,600 lbs is required (Vogt Tube Ice, L.L.C, 2000).

A summary of the minimum inventory calculation is shown in Table 2. These results represent a possible minimum amount of ammonia that may have been in the system if it was shut down while operating normally. Of interest is that the addition of the evaporative condenser did not appear to necessitate an increase in the ammonia inventory. The discrepancy between the calculated results and the manufacturers recommendations is likely accounted for by the evaporator ammonia quantity needed at the end of the ice making cycle when the system would be operating with a small load on the evaporator causing the average density in the evaporator to increase as less ammonia was evaporating.

Table 2: Estimated minimum ammonia inventory for both the original configuration and after condenser modifications

	Original Configuration Inventory (lb)	Inventory with Condenser Modification (lb)
Piping & Vessels	644.0	664.6
Evaporator	438.6	438.6
Condenser	213.9	166.3
Surge Drum (Accumulator)	2.2	2.2
Total	**1298.7**	**1271.7**

It is also possible that the equipment had been charged above the recommended operating level. The maximum allowable charge in any vessel according to CSA B52 (Canadian Standards Association, 2018) is 90% liquid volume at a 90°F saturation temperature. For this receiver, the maximum allowable charge corresponds to a maximum inventory of 1,645 lbs. The absolute maximum ammonia quantity that could have been stored in the receiver if it was overfilled is 1,828 lbs.

Summary of Findings:

1) The minimum ammonia inventory for normal operation was approximately 1,300 lbs.
2) The manufacturer recommended ammonia charge for this specific P34 system was 1,600 lbs.
3) The maximum allowable and safe quantity of ammonia in the receiver was 1,645 lbs.

5. HEAT ADDITION TO P34 RECEIVER

Note: Heat addition to the P34 receiver was not identified as a factor in this ammonia release. The following analysis was completed to provide information on the condition of the vessel prior to the release.

At some point during its life, the pressure relief valve was removed from the P34 receiver. It is of interest to understand the temperatures at which the vessel would have exceeded its Maximum Allowable Working Pressure (MAWP), including how external heat sources could have contributed a potential overpressure situation with no relief valve in service.

To remain compliant with CSA B52, a high-pressure receiver can be filled to a maximum of 90% volume at 90°F. This temperature parameter is an essential part of this requirement because it affects the density of the refrigerant. Filling with lower temperature refrigerant will result in more mass of refrigerant in the vessel. Figure 3 shows how the pressure in a vessel increases due to a temperature change for different initial temperatures. The vessel reaches the MAWP of 250 psig at 114.6°F for all cases. However, the temperature required to cause extremely high pressures decreases significantly when it is filled to 90% volume at lower temperatures.

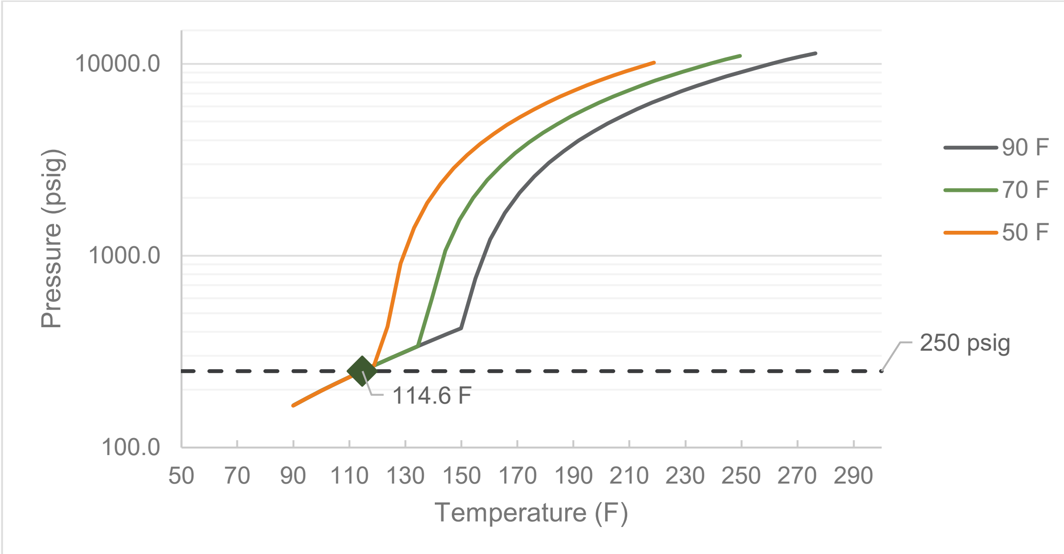

Figure 3: Pressure increase caused by increasing temperature for a vessel filled to 90% volume at different initial temperatures.

The primary mechanism of temperature increase in an isolated vessel is typically ambient air conditions; in this case the room would have to have been 114.6°F or above for the vessel to reach a pressure above the MAWP. However, there are external heat inputs such as a space heating element, welding/grinding on the vessel, or a fire that could cause a temperature increase above a normal anticipated ambient temperature.

In the case of the P34 HPR being filled to 90% volume at 90°F, Figure 4 shows how the pressure would increase for two different heat inputs of 150 Btu/min/ft^2 and 375 Btu/min/ft^2. These inputs correspond to estimates for the heat input from a fire depending on whether combustible materials are located within 20 feet of the vessel (ASHRAE, 2020). The over-pressure situation would happen quicker if less refrigerant was in the vessel. Figure 4 also shows a comparison for the P34 HPR at 50% full.

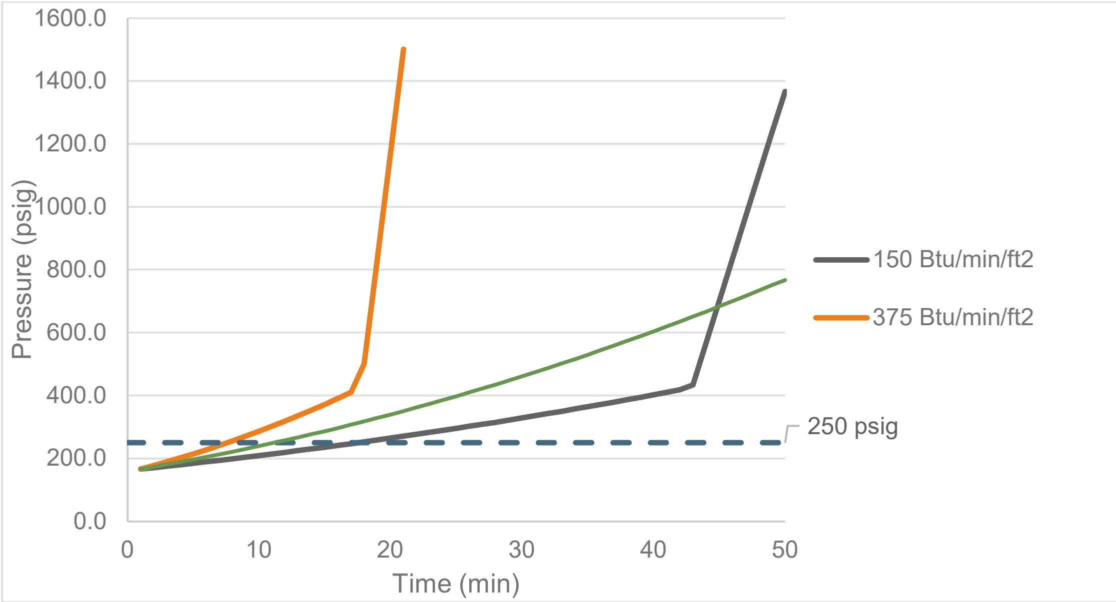

Figure 4: The pressure increase caused by external heat addition to the P34 receiver at 90% and 50% full for two heat input values, beginning at 90°F.

While the heat inputs in a fire are likely higher than those from other external heat sources, a lower heat source with a longer exposure time would have a similar effect. For example, if 1kW of heat was added to a 90% full vessel, initially at 90°F, from a space heater, then it would reach the MAWP in approximately 12 hours.

Summary of Findings:

1) The P34 receiver was isolated without a pressure relief valve. The vessel would have exceeded the MAWP at a temperature of 114.6°F.
2) Large external heat inputs with short exposure times or smaller external heat inputs with longer exposure times could have caused the temperature of the vessel to increase significantly above the MAWP even when the ambient temperature was not high enough to raise the temperature of the vessel.

6. AMMONIA RELEASE

Video surveillance of the ammonia release shows a large volume of ammonia exiting the overhead door in a mist or dense vapour cloud as shown in Figure 5. This type of cloud is indicative of a flashing liquid release where pressurized saturated liquid ammonia is released and the sudden drop in pressure causes a portion of the refrigerant to boil (flash). The boiling refrigerant cools the remaining liquid refrigerant in the air and the cloud persists until the ammonia is warmed and the remaining liquid molecules evaporate.

Figure 5: Ammonia cloud indicating a flashing liquid release.

While the video footage does not show the leak directly, it is possible to estimate the amount of time liquid was released by observing the change in the ammonia cloud that is visible moving through an overhead door in the video footage. Approximately 9-10 minutes after the workers evacuated the area, the ammonia stops "pouring" out of the door; while the ammonia continues to visibly move through the door, the density and quantity appear lower.

Ammonia vapour would have continued to be released from the vessel at a much lower rate than the initial flashing release as the residual liquid at the bottom of the receiver boiled. It is likely that majority of the ammonia in the vessel was released over a duration of 9-10 minutes and a smaller amount of vapour ammonia was released for several minutes following the liquid.

6.1. Rate of Leak

As previously discussed, the ammonia release occurred through an open 1" ball valve connected to a short piece of piping exiting the receiver at approximately the mid-height elevation of the receiver. While not possible to verify with any available drawings or specifications, the piping must have extended internally in the vessel as a "dip-tube" for the system to have functioned properly; this type of piping is typical on horizontal receivers.

The Equilibrium Rate Model (ERM) (Fauske H. , 1985) is an effective method for estimating flow rates for choked flashing releases through upstream piping that is shorter than approximately 3 ft (Reindl & Jekel, 2016). In the case of the Kamloops release, with the receiver saturated, the liquid would begin flashing near the entrance of the piping and most of the entire dip tube length would be upstream of the choking point. Not accounting for any elevation change in the fluid, the equivalent length of the dip tube was estimated to be 7.5 ft, this dip tube is shown in Figure 6. In order to account for the upstream piping, a version of the Homogeneous Equilibrium Model (HEM) that accounts for frictional dissipation must be used (Leung & Grolmes, 1987) (Fauske & Epstein, 1988) instead of the simplified ERM.

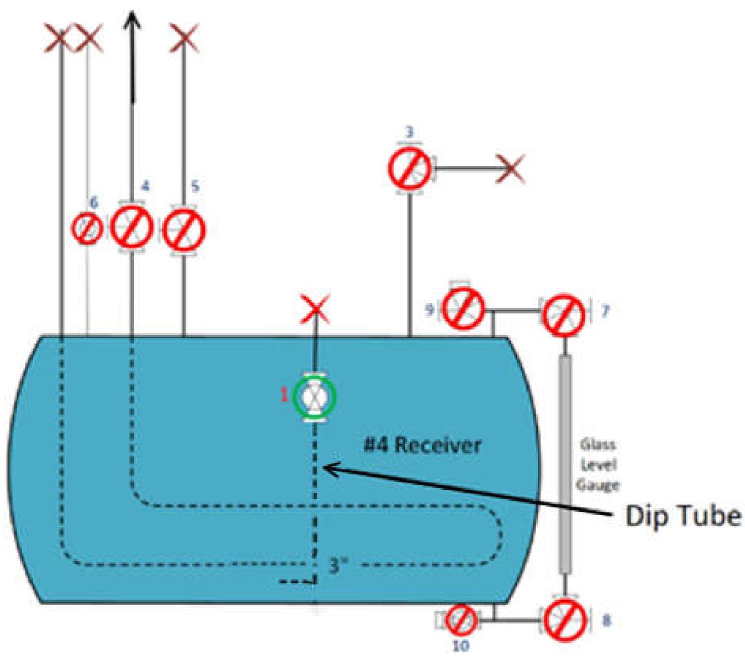

Figure 6: High pressure receiver dip tube

The overnight low ambient temperature in Kamloops on the day of the incident was approximately 9°C and the temperature at the time of the incident was approximately 16˚C. Since the room was likely close to ambient temperature, the pressure in the HPR would have likely been between 71 psig and 95 psig when the release occurred. The estimated initial mass flow rate was calculated under these conditions and is shown graphically in Figure 7 below for both the ERM method and the HEM method accounting for frictional dissipation. The pressure in the vessel would decrease as the release occurred by a factor that corresponds to a balance between the change in mass, the change in internal energy of the refrigerant in the vessel, and the enthalpy of the leaving refrigerant. This calculation was performed assuming that there was no heat transfer between the vessel and the ambient air, the results in Table 3 take into account the resulting pressure decrease averaged over the leak event.

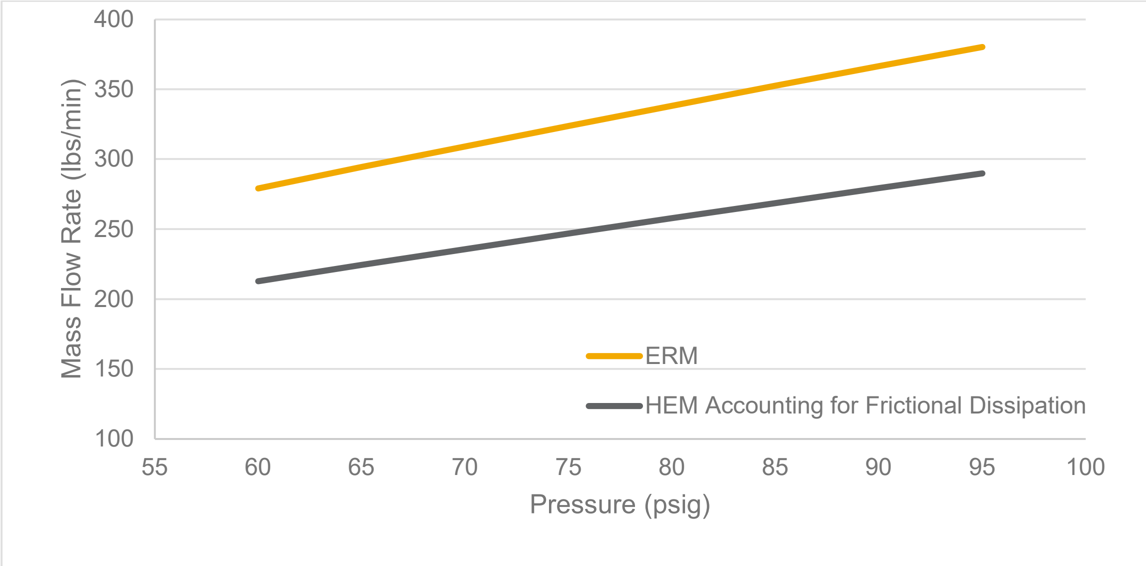

Figure 7: The results of the ammonia leak rate through the open valve using the ERM method with a correction for outlet piping pressure drop.

Using the maximum safe refrigerant inventory in the vessel of 1,645 lbs and the minimum duration of the release of 9 minutes, the maximum estimated release rate is 182 lbs/min. Considering the minimum refrigerant inventory and maximum release duration of 10 minutes, the minimum estimated release rate is 130 lbs/min. A comparison of the mass flow rate ranges modeled using the video footage and ammonia inventory compared to the release rate based on the Fauske model is shown in Table 3 below.

Table 3: The quantity of ammonia released using modelling calculations compared to the release rate estimated from video footage and the ammonia inventory.

Modeled Leak Rate (lbs_{avg}/min)		Ammonia Inventory and Duration - Leak Rate (lbs_{avg}/min)		
Minimum	Maximum	Minimum	Maximum Safe	Maximum Possible
227	267	130	182	203

There are several factors that could cause an overestimation of the leak rate calculated in the model.

The ball valve from which the ammonia was released may have been partially closed during all or a portion of the release. The equivalent diameter of pipe when the ball valve is closed 15 degrees is approximately ¾ inch; the ball valve being partially closed could have restricted the flow enough to decrease the mass flow rate to a range in line with the visual observations.

It is also possible that the internal piping in the vessel is a smaller diameter than the 1'' schedule 80 piping that was assumed or that the length of the piping was longer than estimated.

The room would have cooled off significantly during the release from the flashing ammonia. It is not possible to know how much ammonia evaporated in the space and how much evaporated outdoors, so it's not possible to estimate the temperature of the room. If the air did cool significantly during the release, it is not likely that the vessel cooled quickly during the initial stages of the release when the majority of the ammonia was released, however once the volume of ammonia in the vessel was reduced, a temperature change could have had the effect of decreasing the pressure enough to slow down and extend the release.

Summary of Findings:

1) Based on the HEM modeling between 2,042 lbs and 2,403 lbs of ammonia could have been released during this incident. Several parameters were identified that possibly caused an overestimation in this model.
2) Based on the physical size of the receiver, the amount of ammonia necessary for system operation, and visual observations of the release from the security camera footage between 1,300 and 1,645 lbs of ammonia was released during the incident.
3) The minimum estimated ammonia release results in a receiver that was greater than 70% full and the maximum estimated ammonia release results in a receiver that was filled more than 90%. This result corresponds to a receiver that likely contained the entire ammonia charge of the system.

7. ESTIMATE OF AMMONIA REMOVED FROM P24

The P24 system was not involved directly in the ammonia release. However, it is of interest to estimate how much refrigerant remained in that system prior to the demolition work and how much refrigerant was vented from the system during the demolition work. To perform this estimate, it is necessary to consider two distinct venting/purging events:

- Venting/Purging that was done prior to the incident by the workers completing the demolition work
- Venting/Purging that was done post-incident by Technical Safety BC.

Note that in the context of this report, bleeding, venting, and purging all have the same meaning of purposefully removing ammonia from the system.

7.1. AMMONIA WATER MIXTURE

While it is not within the scope of this report to fully explain the reaction that occurs when ammonia is mixed with water, it is necessary to outline several simplified details about the reaction. When ammonia is mixed with water, two different chemical processes occur. One of the processes creates ammonium (NH_4+) ions and hydroxide (OH-) ions which increases the PH of the solution. Although there is some variability in how much ammonia is used in this reaction, unless other chemicals are present to decrease the PH, it is a small amount compared to the hydrogen bonding. Therefore, this reaction was excluded from the analysis and discussion.

Ammonia vapour is soluble in water and when ammonia vapour is released into water, the ammonia molecules bond with the water molecules using a hydrogen bond. The amount of ammonia that can be absorbed into the water is strongly dependent on the temperature of the water. Figure 9 shows the mass fraction of ammonia that can dissolve in an aqueous ammonia solution at different temperatures.

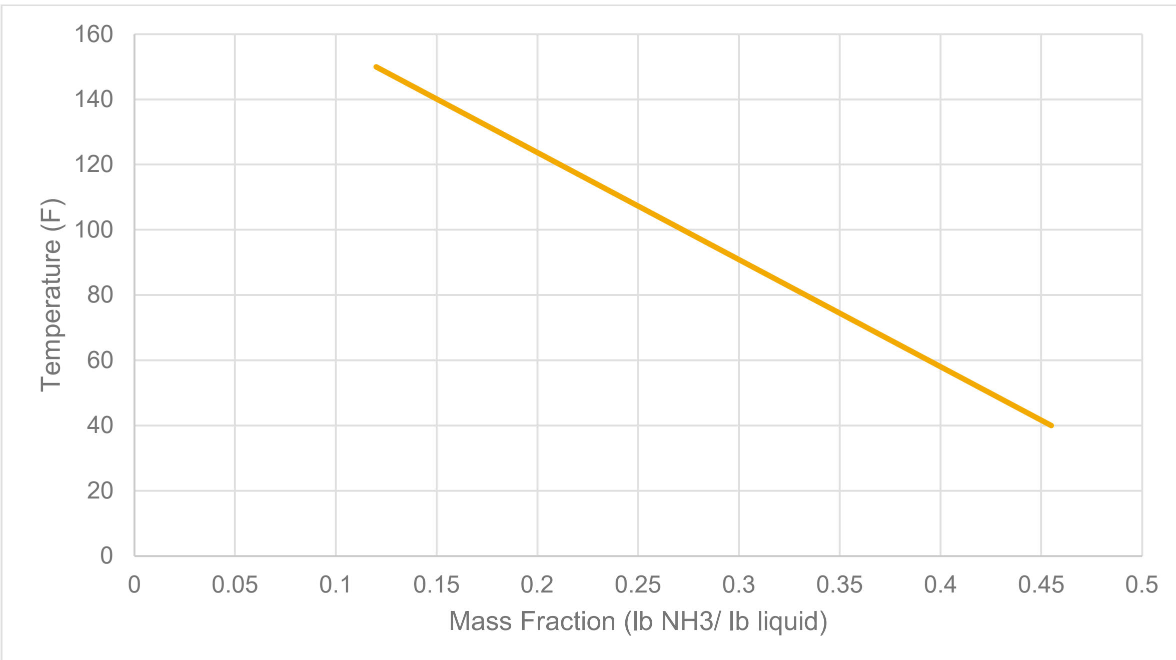

Figure 8: The mass fraction of ammonia in fully saturated water solution at different temperatures and atmospheric pressure (Kim & Herold, 2001)).

Hydrogen bonding is an exothermic reaction which means that energy is released during the reaction causing the solution temperature to increase. The amount of heat generated also depends on the solution temperature and can be estimated if the concentration and temperature are known (Fenton, Noeth, & Gorton, 1991).

7.2. Ammonia Venting During Demolition

During the demolition on May 25th, 2022, ammonia was discovered in the P24 receiver. Over a period of approximately 16 hours, an attempt was made to vent this ammonia from the system using a hose connected to the high-pressure liquid outlet on the HPR. This hose was placed into a bucket along with a garden hose, that was assumed to be 3/4" diameter, that was connected to a domestic cold-water spigot; the ammonia and water were both allowed to flow into the bucket. This technique is a common way of purging small amounts of ammonia from refrigeration systems as it can eliminate the nuisance odour typically associated with venting ammonia directly to atmosphere. Figure 9 below shows a representation of the venting arrangement.

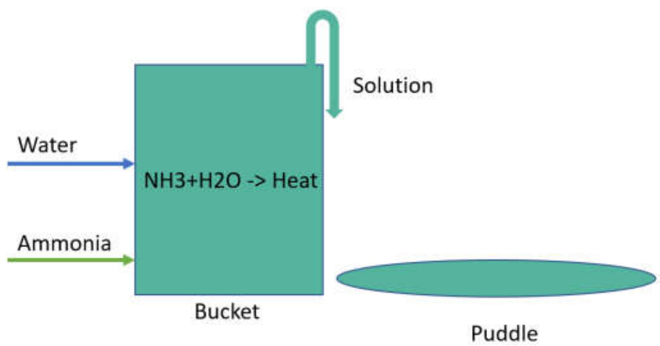

Figure 9: Venting ammonia through a bucket with running water.

To estimate the amount of ammonia that was purged during this time several factors were considered and these factors are outlined in the subsequent sections.

7.2.1. WATER FLOW RATES

The maximum amount of water flow into the bucket was estimated by calculating the theoretical water flow from a 3/4 inch garden hose with an equivalent length of 100 ft connected to a 35 psig water source. Since there is variability in the maximum flow rates through spigots, the water pressure is not known, and the specific details of the hose length and diameter are not known exactly, this calculation serves only as a reasonable estimate of a possible maximum flow rate.

The minimum amount of water flow into the bucket was estimated by observing the growth of the puddle using the security camera footage. Since the puddle is not entirely visible in the footage, the detailed elevation and contours of the ground are not known, and there was no consideration to water soaking into the ground, this observation provides only a conservative rough estimate of the minimum flow rate.

The results of these calculations are as follows:

- Maximum water flow was approximately 17.4 USGPM
- Minimum water flow was approximately 3.2 USGPM

7.2.2. AMMONIA CONCENTRATION

While venting ammonia using this water bucket method, it is desirable to vent the ammonia in a way that removes the ammonia as quickly as possible but minimizes the nuisance odour impact to the surrounding residents and workers. The maximum concentration of ammonia depends on the temperature of the solution; since the temperature of the bucket is not known, it is conservative to assume a maximum of 25% concentration which would be the maximum concentration at 105°F.

Minimizing odours usually means that the resulting concentration of ammonia in solution leaving the bucket is significantly below the maximum possible concentration. Generally, it is possible to perform venting using this bucket water mixing technique with very little ammonia odours in the area. However, reports from people onsite during the venting indicate that the ammonia smell was strong both on May 25th while venting was underway in the afternoon and on the morning of the May 26th after purging was had continued overnight. People's olfactory sensitivity to ammonia varies greatly but given the reports, it is reasonable to assume that the ammonia concentration in the solution leaving the bucket was at least equivalent to commercially available ammonia cleaning solutions of 6%.

- Maximum solution concentration was approximately 25%
- Minimum solution concentration was approximately 6%

7.2.3. Quantity of Vented Ammonia

The quantity of ammonia released from the P24 receiver during the pre-incident venting was estimated by performing a mass and energy balance on the system shown in Figure 9 above. In addition to those described in previous sections, the following assumptions were used to perform the calculation.

- Ammonia was vented for 16 hours
- Water temperature was 12°C
- Perfect mixing occurred in the bucket - This assumption is reasonable unless the ammonia approached saturation.
- The rate of ammonia released over the course of the venting was constant
- The water flow was constant
- Ammonia was released from the vessel as a flashing liquid - This assumption is reasonable given the vent hose was connected to the HPL outlet
- Ammonia was introduced to the bucket as -28°C vapour as would be the case if the valve was only "cracked" open

It would be possible to refine the model to account for the slowly depressurizing vessel due to the venting, and the pressure changed caused by the cooling overnight temperatures, or for more complex ammonia released details, however given the broad nature of the assumptions made in this analysis, this refinement was not considered useful.

Based on the range of possible water flow rate, ammonia concentration, and the assumptions above, the quantity of ammonia that was vented may have ranged from 150 lbs to 3,492 lbs. However, at 90% full, the receiver could have only contained 1,044 lbs which limits the maximum quantity of ammonia that was vented. Figure 10 shows a graphical representation of these results.

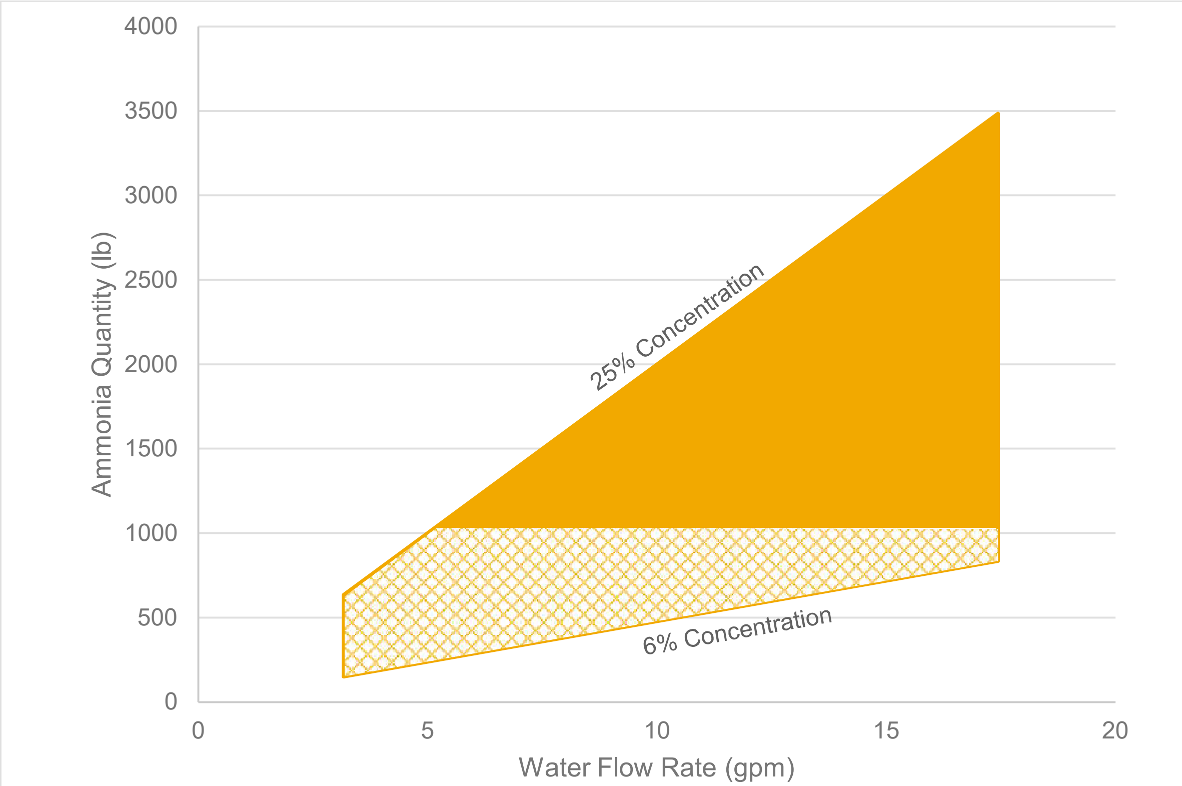

Figure 10: The possible amount of ammonia vented from P24 during the demolition. The hatched area indicates the range of possibilities, and the solid area indicated those possible based on the model but not possible based on the physical size of the receiver.

7.3. AMMONIA VENTED POST INCIDENT

Following the incident, Technical Safety BC contracted Complete Climate Control Inc. to remove any remaining ammonia from the system; liquid ammonia was found remaining in the P24 receiver. The amount of ammonia that was removed from the P24 receiver was not measured directly but was estimated by the contractor to be 100 lbs (Nicol, 2022).

The ammonia was removed into 250 USG totes that were approximately 75% filled with water. Ammonia was purged into one tote for approximately one hour until it was saturated, and the second tote was used for the remainder but did not become saturated (Nicol, 2022).

Since the amount of ammonia that can be dissolved into water decreases with an increase in the temperature of the solution, to determine how much ammonia could have been absorbed in the totes, it is necessary to calculate the temperature increase caused by the chemical reaction that would have taken place as the ammonia dissolved.

The analysis results show that approximately 256 lbs could have been vented into one tote over a one-hour period before the solution truly reached 100% saturated aqueous ammonia. In this scenario, the solution would have had a concentration of 14% ammonia, reached a temperature of approximately 60°C, and filled the tote to 94% full. If 100 lb was released over one hour, as reported, the solution would have had a final concentration of 6%, reached a temperature of approximately 44°C, and filled the tote to 82% full. The solution may have started off-gassing and behaving as if it was saturated before it was truly saturated if the solution was not perfectly mixed. The estimate of 100 lb is approximately 40% of the theoretical maximum, assuming all the liquid ammonia was bled into the first tote and none was purged into the second.

Figure 11 shows the temperature increase for both the theoretical maximum ammonia quantity and the contractor estimated quantity as a function of time assuming that the venting lasted for one hour. This analysis assumes an initial water temperature of 12°C. This initial water temperature assumption is consequential as a change to 25°C initial water temperature decreases the quantity of ammonia the water can absorb by approximately 20%. Analysis was completed to calculate the cooling effect to the ambient air but the results were negligible, so the effect was ignored.

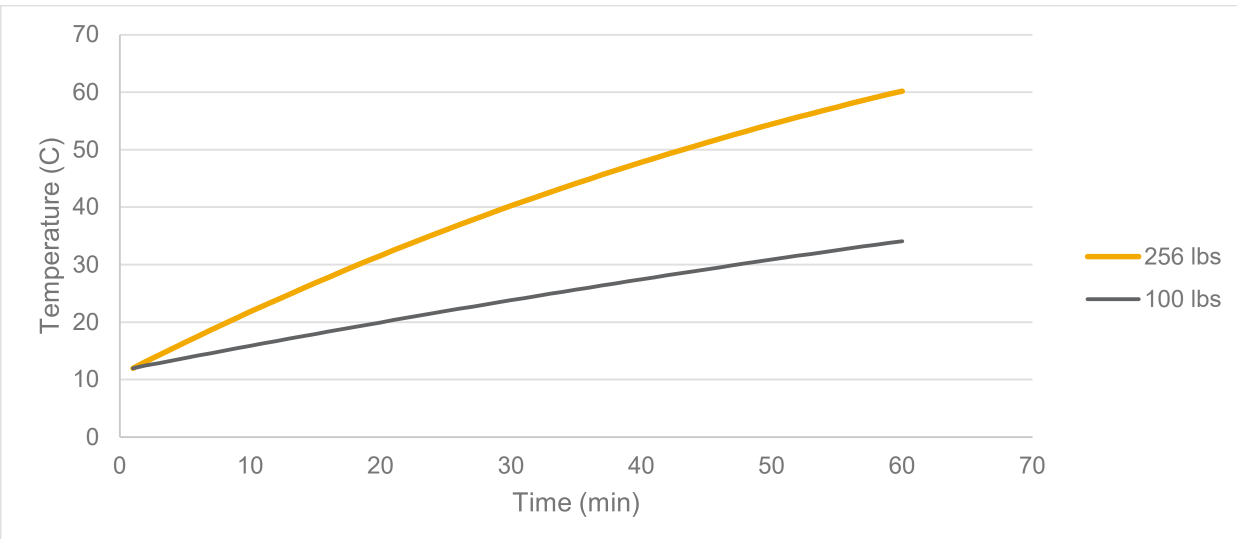

Figure 11: The temperature increase in the tote as a result of the ammonia absorption.

Following the liquid ammonia venting into the tote, the residual vapour ammonia was vented. When vapour is vented, the remaining refrigerant in the system is cooled and it is typical for frost to form where any remaining liquid is present in the system. In this case, a frost line formed on the bottom of the receiver, as shown in Figure 13, indicating that there was still a small amount of ammonia remaining. Based on rough measurements from the photos, there was approximately 25 lb of ammonia remaining in the bottom of the P24 receiver after the liquid was vented.

Figure 12: P24 receiver frost line after purging

A pressure gauge connected to the receiver prior to removing ammonia post-incident indicated that the pressure was 50 psig (Nicol, 2022). Because of the ambient air temperature, this pressure is not possible if the contents of the vessel were entirely anhydrous ammonia; the presence of water or oil in the ammonia tank would cause the overall pressure to be lower. Assuming the temperature of the ammonia was between 50°F to 60°F, this pressure corresponds to an ammonia mass fraction of 60-65% remaining in the vessel post-incident.

7.4. Total Ammonia Vented

The minimum ammonia quantity necessary to operate a single P24 machine is 800 lbs (Vogt Tube Ice, L.L.C, 2000). Based on the previous P34 ammonia inventory calculations, the two P24 machines connected to a common receiver would require an additional ammonia quantity approximately equal to 1/3 of the total charge of a single machine. This means the minimum ammonia quantity of this P24 system was approximately equal to the maximum inventory of the receiver of 1044 lb.

It is very difficult to determine the total amount of ammonia that was vented from the P24 receiver with a high level of accuracy. Figure 13 shows a visualization of the summary of the amount of ammonia that was vented from the P24 system receiver. The yellow bars indicate the minimum ammonia quantity that was vented in both pre-incident and post-incident purge activities. The pink bar shows the amount that could have been purged pre-incident based on the less conservative assumptions. The blue bars indicate how the combination of pre-incident and post-incident purging could have resulted in a release of an amount equal to the maximum storage capacity of the receiver.

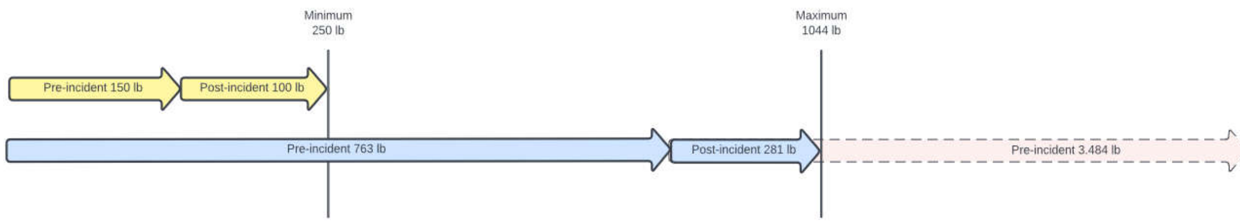

Figure 13: The estimate of the amount of ammonia released from the P24 system in both pre-incident and post-incident venting. Not to scale.

It is not typical to remove refrigerant from a system and leave only a portion remaining. Since there was no service or leak history available for the system that would provide a rationale for it being left with 250 lbs of ammonia, it is more likely that the entire system charge was pumped down and stored in the receiver.

Summary of Findings:

1) The minimum amount of ammonia purged in pre-incident and post-incident purging was 250 lbs.
2) The maximum amount of ammonia purged in pre-incident and post-incident purging was 1,044 lbs.
3) It is reasonable to assume that the entire system charge was pumped down into the receiver leaving it approximately 90% full.

8. VENTILATION

Emergency ventilation for ammonia refrigeration systems is a code required safety system that is intended to decrease the risk of a deflagration by removing the ammonia-air mixture and introducing non-contaminated ventilation air into the space to reduce the ammonia concentration. Ammonia is flammable between the concentrations of approximately 148,000 ppm and 335,000 ppm in air.

In Canada, there are two different standards for emergency ventilation design that are used in ammonia machine room design, CSA B52 and IIAR-2 (International Institute of Ammonia Refrigeration, 2021). Regulation requires compliance with CSA B52, which bases the ventilation requirements on the quantity of ammonia in the system. Assuming the P34 receiver contained 1,600 lbs of ammonia, CSA B52 would require 4,000 CFM of emergency ventilation. IIAR-2 requirements are based on the volume of the room that contains the refrigeration equipment; based on the size of the room at Arctic Glacier in Kamloops, IIAR would require approximately 11,200 CFM of emergency ventilation.

During this incident, deflagration occurred approximately 15 minutes after the valve release began. Along with the possibility that a small unknown amount of ventilation may have been provided by an operating exhaust fan, an accurate model of the ammonia concentration in the room is complicated significantly by the fact that the overhead door was open, and a large quantity of ammonia released directly to the outdoors. Given the nature of the assumptions, a reliable model is not possible. However, it remains interesting to compare the time the facility would have been at risk of deflagration during the release if the facility had functioning emergency exhaust equipment. Figure 14 shows the approximate ammonia concentration for three scenarios,

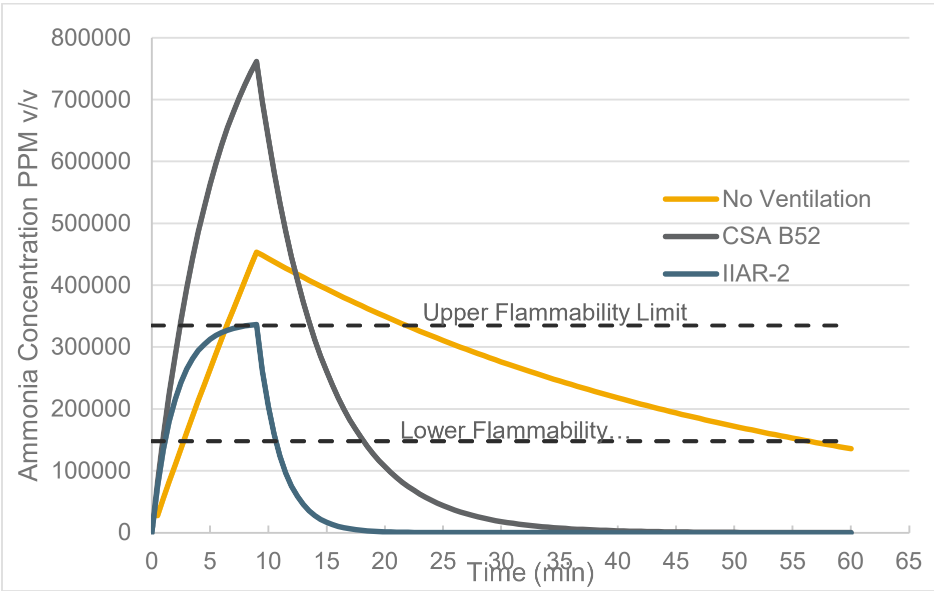

Figure 14: Ammonia concentration in the mechanical room in three different ventilation scenarios. The "No Ventilation" scenario is a simplification of the situation that occurred during this incident with a large amount of ammonia leaving the room through an open door.

There are too many assumptions in the comparison of ventilation rates to draw specific conclusions related to this event. Most importantly, it was not possible to accurately quantify the amount of ammonia that moved outside through the open door. However, it is apparent that increasing the ventilation rate decreases the amount of time the concentration in the room is within the flammability range. It is important to note that concentrations are an average and that during any leak event there will be pockets of ammonia that are within the flammability range.

Summary of Findings:

1) Emergency ventilation systems decrease the amount of time a room is above the lower flammability limit even when the leak is larger than the emergency system is designed to accommodate.

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