

Appendix A

Engineering Analysis
Fernie Memorial Arena Investigation
Cold Dynamics Ltd.



Fernie Memorial Arena Investigation

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REPORT FOR TECHNICAL SAFETY BC
FERNIE MEMORIAL ARENA

Executive Summary

On October 17, 2017, ammonia from the refrigeration system at the Fernie Memorial Arena in Fernie, BC was unintentionally released into the machine room from the secondary coolant piping. The refrigeration system at the arena used two chillers to provide heat transfer from a Calcium Chloride (CaCl_2) brine secondary coolant to the ammonia in the refrigeration system. One chiller provided the cooling for the arena ice surface and another provided the cooling for the curling ice surface.

The curling chiller developed a leak due to pitting corrosion along the weld line of one tube, which provided the opportunity for ammonia to enter the brine system and brine to enter the ammonia system depending on the operating conditions of the refrigeration system. On October 17, 2017, approximately 5 hours after an initial emergency response to address ammonia leaking from the brine expansion tank into the machine room, a coupling on the brine system separated and the contents of a portion of the chiller and brine piping was released into the machine room.

The purpose of this report is to provide engineering analysis of the refrigeration system and the modes and consequences of failure. It is outside the scope of this report to comment extensively on the chiller failure and the corrosion of the chiller tubes. Technical Safety BC requested the following analysis:

- 1) An estimate of the quantity of ammonia in the refrigeration system and in the curling chiller during normal operation.
- 2) An estimate of the quantity of brine in the secondary coolant circuit.
- 3) A description and analysis of the system failure, including an estimate of the amount of ammonia that was released.
- 4) An estimate of the ammonia concentration in air in the machine room after the failure with consideration of the ventilation system.
- 5) Analysis showing the possible impact to the community following the accidental ammonia release and the subsequent intentional ammonia release through the emergency discharge valve.

The ammonia inventory documented on site was 1200 lb [545 kg]. However, measurement records from both May 2017 and August 2017 in combination with ammonia quantity calculations indicate that the ammonia charge was lower at approximately 885 lb [402 kg]. The CaCl_2 brine quantity was estimated to be 5000 L.

From the time the chiller tube began leaking until the incident, there was an opportunity for ammonia to leak into the brine during some operating regimes. Lab results from brine samples taken by the maintenance contractor in May 2017 and August 2017 both indicate that ammonia was leaking.

On October 16, 2017, the curling chiller and brine system were started-up; in the early morning on October 17, 2017, the ammonia alarm activated in the machine room indicating that the ammonia concentration at the ammonia detector was 100 ppm. During the response to this alarm, it appears that valves were closed to stop ammonia from escaping from the brine expansion tank; the brine system was found effectively isolated from the atmosphere. The ammonia system was also found isolated with closed valves on both the inlet and outlet ammonia piping.

The reaction between ammonia and brine is exothermic and as ammonia continued to leak into the brine, heat transfer occurred to increase the temperature, and consequently the pressure, of the remaining ammonia in the chiller. The ambient air in the machine room was warmer than the chiller and would have also contributed to



REPORT FOR TECHNICAL SAFETY BC
FERNIE MEMORIAL ARENA

this increase of temperature and pressure. Once the brine in the vicinity of the leak location was no longer able to absorb and diffuse ammonia as quickly as it was leaking, the pressure in the brine system would have increased and become close to the same pressure as the ammonia system. Under pressure, brine can absorb an increasing amount of ammonia. When the coupling separated, there was most likely a portion of the brine-side of the chiller that had ammonia concentrations at or near saturation. A very rapid depressurization would have occurred and caused a large amount of this ammonia to vaporize and propel the brine solution out of the separated coupling.

The type of coupling that was used can separate at relatively low pressures depending on how well it is supported and braced. While it is not known at what pressure the coupling in Fernie separated, it was most likely between 30 psig [207 kPag] and 150 psi [1034 kPa]. An analysis of the potential temperature increase based on 5 lb [2.3 kg] of ammonia leaking into the brine while the system was isolated and using the outdoor ambient temperature as the machine room temperature, resulted in an estimated pressure of 50 psig [345 kPag] in the chiller after 5 hours.

The initial conditions of the ammonia concentration in the brine prior to the incident are not known and it is not possible to know the exact details of how the dynamic situation of ammonia mixing into the brine during the start-up on October 16, 2017 and subsequent coupling failure on October 17, 2017 unfolded. However, a possible scenario was constructed using the available evidence to estimate the amount of ammonia released.

An estimated 22 lb [10 kg] of ammonia was released in 83 L [22 US Gal] of brine solution when the coupling separated. Most of this ammonia would have evaporated and aerated quickly as the brine spray had a lot of surface area contact with the air and the surfaces in the room. However, some of the ammonia likely stayed absorbed in liquid brine on the floor for a period of time. The ammonia remaining in the chiller would have evaporated slowly and leaked out through the separated coupling at a low rate for several days.

An estimated 9 lb [4 kg] of the ammonia was in a highly concentrated solution and would have been released very quickly when the coupling separated. The exhaust fans in the machine room provided ventilation to reduce the ammonia concentration but it is likely that the concentration in the room reached an average of at least 20,000 ppm when the coupling separated and was above 5000 ppm for more than 5 minutes. A basic dispersion analysis was performed; a concentration of ammonia of 5 ppm (the approximate smell threshold of ammonia) would have reached the vicinity where witnesses reported smelling ammonia with a release of 18 lb [8 kg].

During the response to the incident on the afternoon of October 17, 2017, the emergency discharge valve was opened. This valve allows the refrigerant in a system to be released to atmosphere. In this incident, as much as 687 lb [312 kg] of ammonia could have been released through the emergency discharge valve. The peak flow rate occurs quickly as the ammonia in the refrigeration system evaporates and the temperature of the system is reduced to correspond to the saturation temperature at atmospheric pressure. In this case, an estimated 55 lb [25 kg] would have been released from the high pressure receiver in 15 minutes with 80% of that in the first 6 minutes. An additional 45 lb [20 kg] would have been released relatively quickly from the arena chiller, but over a longer period than the high pressure receiver. Most of the ammonia remained in the system and evaporated slowly.



REPORT FOR TECHNICAL SAFETY BC
FERNIE MEMORIAL ARENA

Table of Contents

Executive Summary	2
Scope of Work	7
General Information	7
Methodology	9
Ammonia Inventory	12
CaCl ₂ Brine Inventory	15
Ammonia Concentrations in CaCl ₂ Brine	16
CaCl ₂ in the Ammonia System	17
Chiller and System Failure Scenario	18
Ammonia Release and Ventilation	27
Emergency Relief and Ammonia Dispersion	31
Completion Notes	35
References	36
Disclaimer of Liability	36
Revision Log	37



REPORT FOR TECHNICAL SAFETY BC
FERNIE MEMORIAL ARENA

List of Figures

Figure 1: Chiller cross section schematic.....	7
Figure 2: Leak on chiller tube with pitting corrosion along ERW line.	8
Figure 3: Return head of chiller showing clear tubes on upper half of the tube sheet and arrow indicating tube with leak	9
Figure 4: Indication of August 2017 receiver ammonia level.....	13
Figure 5: CaCl ₂ Evidence in Compressor Cylinder Heads.....	17
Figure 6: Cut out from Technical Safety BC Report Appendix B showing the valves that isolated the ammonia in the curling chiller.....	19
Figure 7: Cut out from Technical Safety BC Appendix B Diagram. The red cross-outs indicate the valves that isolated the brine system from the atmosphere and the blue arrows indicate the location of the brine sample measurements. Valve Z was found with the handle 10° open but was assumed to be effectively closed because of debris in the valve and piping.	20
Figure 8: The pressure temperature relationship of saturated ammonia	21
Figure 9: Separated brine coupling on 4" brine piping	22
Figure 10 The green highlighted areas represent the approximate volume of ammonia-CaCl ₂ brine solution that was released into the mechanical room	23
Figure 11: Representation of the areas that were considered near saturation for the release scenario (the drawing is not to scale). The arrow indicates the approximate location of the tube leak.....	24
Figure 12: Temperature rise of the chiller over time based on the heat of solution from 2.3 kg of ammonia and a 12.2°C mechanical room.	25
Figure 13: Flow diagram summarizing ammonia and brine mass quantities from the time the system was isolated. Based on the scenario assumptions described in this report. The brine quantities in this figure represent the approximate brine piping and chiller volume between the separated coupling and isolation valves on the inlet side of the chiller.....	28
Figure 14: The dilution rate of the ammonia in the machine room for a 4 kg instantaneous release of ammonia, assuming a volume averaged concentration.....	29
Figure 15: Dispersion modeled at the odour threshold of 5 ppm for a 4 kg (purple) and 8 kg (green) release, using Aloha (EPA;NOAA)	30
Figure 16: A simplified piping diagram showing the configuration of the emergency discharge valve. The purple components contained refrigerant that would have been released relatively quickly. The orange components would have released more slowly because they did not have a direct path to the discharge point. The red arrow is pointing at the emergency relief valve.	31
Figure 17: Mass of ammonia in high pressure receiver as a result of the opening of the emergency discharge valve.....	33
Figure 18: Approximate 25 ppm and 35 ppm dispersion when the emergency relief valve was opened.....	34

List of Tables

Table 1: Summary of Vessel and Piping Ammonia Inventory by Component.....	12
Table 2: Summary of Chiller Ammonia Inventory	13
Table 3: Summary of Condenser Ammonia Inventory	14
Table 4: Table of emergency exhaust fan capacities.....	29
Table 5: A summary of the estimated ammonia quantity in various components at the time the system was isolated. The bold numbers represent the estimated quantity of refrigerant that was released when the emergency discharge valve was opened.....	32



REPORT FOR TECHNICAL SAFETY BC
FERNIE MEMORIAL ARENA

Scope of Work

The purpose of this report is to provide engineering analysis and expertise regarding the refrigeration system, the modes of failure, and the consequences of failure to the Technical Safety BC team investigating the ammonia release that occurred at the Fernie Memorial Arena on October 17, 2017. Discussion and analysis of varying degrees was requested on the following broad topics:

- Ammonia inventory
- Calcium chloride (CaCl_2) brine inventory
- Ammonia mixing with a CaCl_2 brine solution
- Failure scenario and ammonia leak estimates
- Machine room ventilation
- Ammonia dispersion to the atmosphere

General Information

It is beyond the scope of this report to provide a detailed description of the entire refrigeration system; however, it is necessary to provide some key information as certain information and terminology is used throughout the report without additional explanation.

The Fernie Memorial Arena had one refrigeration system that was used to provide cooling to both an ice rink and a curling rink. This refrigeration system used two shell and tube heat exchangers to transfer heat from the ice surface to the refrigerant using CaCl_2 as a secondary coolant; these heat exchangers are commonly referred to as chillers. At the Fernie Memorial Arena, the chillers are referred to specifically as the “Arena Chiller” for the ice rink and “Curling Chiller” for the curling rink. In these heat exchangers, the refrigerant is designed to be contained in the shell and the secondary coolant is pumped through the tubes. Therefore, references to the “ammonia-side” of the chiller refer to the shell of the heat exchanger and references to the “brine-side” of the chiller refer to the tubes. Figure 1 shows a schematic of the key elements for this type of heat exchanger.

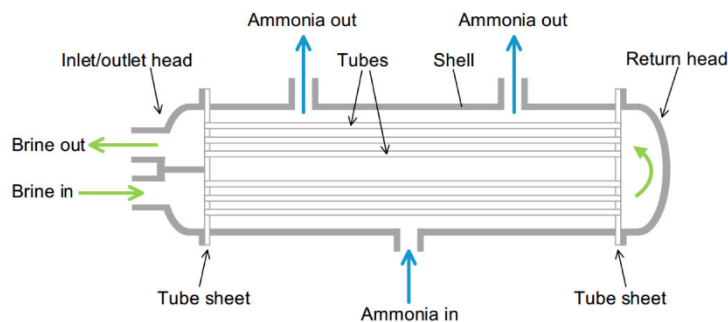


Figure 1: Chiller cross section schematic

Calcium chloride is one of the most common substances used to depress the freezing point of water for use as a secondary coolant in ice rinks. It is often referred to as brine because of the salt solution formed when mixing

the CaCl_2 with water. Throughout this report, the secondary coolant is generally referred as CaCl_2 brine or “brine”.

The incident at the Fernie Memorial Arena involved a leak in a chiller tube that allowed both ammonia to leak into the CaCl_2 solution, and CaCl_2 solution to leak into the ammonia refrigeration system. Examination of the chiller was performed by Acuren, refer to the Technical Safety BC Investigation report for additional details. The following summarizes some relevant details.

One tube was found leaking in the chiller. There was one elliptical opening approximately 2.2 mm x 0.2 mm in size and several smaller openings in the same vicinity on the same tube, see Figure 2. The leak occurred due to pitting corrosion along the electrical resistance welding (ERW) weld line. This tube was located in the second row from the top of the chiller and is indicated on Figure 3.

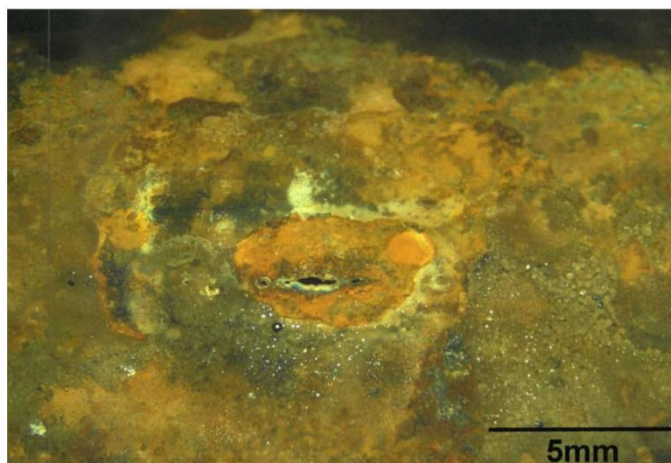


Figure 2: Leak on chiller tube with pitting corrosion along ERW line.



Figure 3: Return head of chiller showing clear tubes on upper half of the tube sheet and arrow indicating tube with leak

Methodology

The methodology used for the analysis in this report varied depending on the particular topic and level of detail required. The following subsections provide an overview of the methodology for the different analyses completed.

Ammonia & Solution Properties:

The thermophysical properties of ammonia were used extensively in calculations throughout the analysis. In general, these properties were calculated using REFPROP Version 9.1 (Lemmon, Huber, & McLinden, 2013). Properties of aqueous ammonia and of a CaCl_2 solution were obtained from the CoolProp Thermophysical Property Library (Bell, Wronski, Quoilin, & Lemort, 2014) and the properties of saturated ammonia and water were used from the ASHRAE 2017 Fundamentals handbook (ASHRAE, 2017).

Thermophysical properties of a solution of CaCl_2 brine and ammonia were not readily available. In some cases, such as density, these properties are straightforward to estimate or calculate. In the case of the heat of solution, an experiment was performed, and the results used to show that the reaction is similar enough to water that the data available for water was appropriate for the level of analysis completed for this report.

Ammonia Concentration:

Ammonia concentration measurements can be given in two forms. The first, and most common in brine analysis reports associated with ice rinks, is parts per million (ppm); this result represents the total mass of the ammonia compared to the total mass of the solution. The second form is in milligrams per liter (mg/L); this result

represents the total mass of ammonia in one liter of solution. The difference between these two forms is the density of the solution.

The density of ammonia is lower than both calcium chloride and water. As a result, the density of a solution that includes ammonia decreases as the ammonia concentration increases. This makes converting between the two types of results an iterative process. Throughout the analysis, in order to perform these calculations, a density - concentration curve was constructed for a 20% calcium chloride solution based on the available data for water and increasing the density for the mass added by the calcium chloride.

Ammonia Inventory:

Calculating the quantity of ammonia normally contained within most components is a straightforward computation based on the volume of the component and the average density of the refrigerant in the component. In some cases, the information is available from the manufacturer. In order to estimate the amount of refrigerant in the curling chiller, three methods were used and compared. These methods include a correlation to refrigeration capacity (Industrial Refrigeration Consortium, 2004), a published empirical constant using the average density that is applicable to a different type of heat exchanger (Industrial Refrigeration Consortium, 2004), and a volume calculation based on the level float control and sight glass location.

Heat Transfer:

Heat transfer analysis was based on established heat transfer calculations and constants for both conduction and convection. Most material properties and convection coefficients used were available in the ASHRAE Fundamentals Handbook (ASHRAE, 2017). There were no cases where it was necessary to include heat transfer from radiation.

Any heat transfer analysis that involved the warming of a vessel with saturated ammonia necessarily included the energy required to vaporize a portion of the liquid refrigerant. The methodology for performing these calculations was to use the rate of heat gain from both ambient and the ammonia mixing, in an energy balance that included ammonia's heat of vaporization and a sensible temperature increase of the ammonia and brine in the entire heat exchanger. This vaporization causes a pressure and temperature increase and as the temperature increases, the heat transfer from ambient decreases.

The heat of solution used to determine the amount of heat generated when ammonia mixed with the brine was available from a commercial source (Air Liquide, 2018).

Ventilation:

The methodology used to determine the room concentrations following the ammonia leak was the analysis typical of a dilution ventilation situation. This method introduces a mixing factor to account for less than perfect mixing in the room. While the mixing factor is subjective, guidance to help choose the value for particular fan and intake louver arrangements is available and was used to estimate the mixing factor at 4 for the purpose of this analysis (ACGIH, 2016).

Ammonia Dispersion:

Ammonia dispersion calculations and threat zone estimates were completed using the ALOHA software package. This software uses a gaussian dispersion analysis to predict the air-borne contaminant concentrations (EPA;NOAA). Inputs for the software included ambient weather and atmospheric conditions and the estimated ammonia release quantities on the day of the incident.

REPORT FOR TECHNICAL SAFETY BC
FERNIE MEMORIAL ARENA

The rate of ammonia release from the emergency discharge valve required analysis of pressure drop and flow in a compressible flow situation; this means that the ammonia vapour was treated as an ideal gas. This assumption is reasonable given the accuracy required of the calculations. A numerical method was used to calculate the declining mass flow because of the pressure decrease. The equations were developed from fundamental compressible flow analysis and assumptions typical of ammonia relief scenarios (White, 2008) (Reindl & Jekel, 2006). The latent heat of vaporization as the liquid ammonia evaporated was included in the analysis.

A Note About Units:

When referring to measurements regarding the refrigeration system and ice rink mechanical system, this report will use the primary units most commonly encountered in the refrigeration industry. For the most part, this means that inch-pound units will be used when discussing the technical information contained in this report. In most cases, an equivalent SI unit will be presented in parentheses. When referring to weather and other ambient conditions, the SI or metric units will be used, and few equivalent inch-pound units will be provided.

When calculating ammonia concentrations in liquid, they will be in parts per million (ppm) on a mass basis and the unit milligram per liter (mg/L) will be shown in parentheses. The density of the CaCl_2 brine was used to convert between these units. Ammonia concentrations in the air are in parts per million (ppm) on a volume/molar basis.

Ammonia Inventory

Ammonia was used as the refrigerant in a single stage vapour compression refrigeration system that provided the cooling capacity to both the arena and curling ice sheets at the Fernie Memorial Arena.

The on-site documentation in Fernie indicated that the system refrigerant inventory was 1200 lb [544 kg]. In order to better understand how much ammonia was released, an ammonia charge calculation was completed using details and measurements obtained during the investigation. The general methodology used to perform the ammonia charge calculation is summarized below by component type; the following conditions were used to determine the properties of the refrigerant.

- 1) Discharge Pressure: 160 psig [1100 kPag]
- 2) Saturated Condensing Temperature: 82.5°F [28.1°C]
- 3) Saturated Suction Pressure: 25 psig [170 kPag]
- 4) Saturated Suction Temperature: 10°F [-12.2°C]

Vessels & Piping:

Calculating the amount of ammonia in a vessel depends on whether the vessel contains liquid, vapour or a mixture of liquid and vapour. In all cases, the density of the refrigerant was used to calculate the mass in the vessel; these results are summarized below in Table 1. The high pressure receiver level was measured based on a recording of the ammonia level during start-up in August 2017, see Figure 4. The Condenser Drain piping was assumed to be completely full of liquid, but because it was piped in a sewer flow arrangement, the results likely overestimate the ammonia quantity in that piping.

Table 1: Summary of Vessel and Piping Ammonia Inventory by Component

Vessel or Pipe	Size/Details	Liquid Level (%)	Refrigerant Mass (lb [kg])
High Pressure Receiver	24 in [610 mm] x 161 in [4089 mm]	20	374 [170]
Oil Separator #1	12 in [305 mm] x 43 in [1092mm]	0	1.2 [0.54]
Oil Separator #2	12 in [305 mm] x 43 in [1092 mm]	0	1.2 [0.54]
Arena Surge Drum	16 in [406 mm] x 108 in [2743 mm]	0	3.3 [1.5]
Curling Surge Drum	10.75 in [273 mm] x 84 in [2134 mm]	0	0.6 [0.3]
Arena Oil Pot	6 in [152 mm] x 24 in [610 mm]	100	15.4 [7.00]
Curling Oil Pot	6 in [152 mm] x 24 in [610 mm]	100	15.4 [7.00]
High Pressure Liquid	1 in [25 mm] x 10 ft [3048 mm]	100	1.9 [0.86]
Condenser Drain	2 in [51 mm] x 40 ft [12,192 mm]	100	30.7 [13.9]
Discharge Piping	4 in [102 mm] x 40 ft [12,192 mm]	0	1.4 [0.64]
Suction Piping	3 in [76 mm] x 30 ft [9144 mm]	0	0.2 [0.1]



Figure 4: Indication of August 2017 receiver ammonia level.

Chillers:

Manufacturer's information regarding ammonia inventory was not available for the curling chiller. Because it is challenging to calculate the ammonia charge in a shell and tube evaporator without this information, the ammonia inventory was estimated using three methods. The first method used an average refrigerant density that was determined based on the operating conditions and an empirical constant. This method is appropriate for flooded air-unit evaporator coils and is not normally used for flooded shell and tube chillers, however, it was applied in this case using the net internal volume of each chiller. The second method used a correlation that is based on chiller capacity and approach temperatures (Industrial Refrigeration Consortium, 2004). The third method calculated the quantity of ammonia based on the approximate level control float location. Exact measurements were not available, but the approximate level was based on photos and the chiller sight glass location. These calculations yielded results between 83.7 lb [38.0 kg] using the first method and 97.5 lb [46.2 kg] using the third method. An average of the three methods was used in the results that are summarized in Table 2.

The chiller refrigerant charge for the arena chiller was available from the manufacturer.

Table 2: Summary of Chiller Ammonia Inventory

Chiller	Capacity (TR [kW])	Size/Details	Refrigerant Mass (lb [kg])
Arena	90 [317]	18 in [457 mm] x 168 in [4267 mm]	312 [142]
Curling	35 [123]	12.75 in [324 mm] x 118 in [2997 mm]	89.5 [40.7]

Evaporative Condenser:

The refrigerant inventory for the evaporative condenser was available from the manufacturer and is summarized in Table 3 below.

Table 3: Summary of Condenser Ammonia Inventory

Condenser Model	Refrigerant Mass (lb[kg])
Baltimore Air Coil VC-125	145 [65.8]

Inventory:

The total refrigerant inventory estimated using the conditions at the arena during the August 2017 start-up, is 885 lb [402 kg].¹

The receiver level was also recorded following the spring shut-down that was performed by CIMCO in May 2017. This information provides an alternative method to determine the ammonia inventory because most of the refrigerant would have been contained in the receiver or condenser at this time. Using this recorded liquid level results in an ammonia inventory of approximately 785 lb [356 kg]; this result is consistent with the August 2017 measurement and estimate. Neither the maintenance log books or the contractor's documentation show that any ammonia was added to the system during this time.

Note that the receiver volume at 80% full corresponds to an ammonia inventory of 1200 lb [544 kg] which may be why the on-site documentation indicated that ammonia quantity.

Summary of Results:

- 1) The ammonia charge in the system at start-up in August 2017 was approximately 885 lb [402 kg].

¹ This measurement was recorded prior to the start up of the curling chiller. As such, the operating charge of the curling chiller and oil pot was not included in the total.

CaCl₂ Brine Inventory

In an ice rink cooling system, the refrigerant does not typically flow directly under the ice surface to provide cooling. Instead, a liquid secondary coolant is used to transfer heat from the ice surface to the refrigeration system. The Fernie Memorial Area used a Calcium Chloride (CaCl₂) solution, commonly referred to as brine, to depress the freezing point of water so that a below-freezing fluid could be circulated under the ice surface. While there was both an ice rink and curling rink connected to the refrigeration system at the Fernie Memorial Arena, the secondary coolants were separated because the system used an individual chiller for each ice surface.

There was no onsite documentation found for the CaCl₂ brine quantity in the curling arena. However, estimating the quantity was important in order to understand the consequences of ammonia being released to the solution. The following information was used to estimate the brine inventory:

The curling sheet dimensions are approximately 46 m x 18.9 m. The underfloor tubing is 1 in [25 mm] internal diameter (ID) and is installed such that there is a tube every 4 in [100 mm] under the floor. This results in approximately 28,075 ft [8557 m] of underfloor brine tubing. There is also approximately 240 ft [73 m] of 4 in [100 mm] header distribution piping and the internal volume of the tube side of the condenser is 3.3 ft³ [93 L].

The above information was used to estimate the volume of secondary coolant at 177 ft³ [5012 L].

Summary of Results:

- 1) The total volume in the curling arena brine system was approximately 5000 L.

Ammonia Concentrations in CaCl_2 Brine

Prior to the incident, two brine samples were taken that indicated ammonia was present in the brine. These samples follow a January 2016 result showing no ammonia in the brine. The concentrations recorded in these results help establish a baseline for the amount of ammonia that had leaked into the brine prior to the 2017/2018 season start-up on August 4, 2017. In addition to these samples, the maintenance log book indicates that operators could smell ammonia in the brine during a brine filter change in April 2017.

The first brine sample that indicated ammonia was present in the brine was taken on May 11, 2017. The test result for this sample indicated 3320 PPM [3964 mg/L] ammonia. This result means that approximately 44 lb [20 kg] of ammonia had become absorbed into the brine prior to the test.

A subsequent test was completed on a brine sample that was taken on August 4, 2017. This test result indicated an ammonia concentration of 1830 PPM [2186 mg/L]. This lower result could have occurred because the brine system was not well mixed as only the arena chiller was started on August 4, 2017 and the curling brine pump was likely not operated for a significant length of time. The brine system is also open to atmosphere and a small amount of ammonia would have evaporated throughout the off-season, lowering the concentration. Additionally, a sight glass was added to the brine expansion tank and the tank was cleaned and flushed prior to the start-up which may have had an impact on the brine analysis depending on exactly when and where the sample was taken. There is an additional complication because ammonia will react with disassociated hydrogen ions in water to form ammonium ions (NH_4^+). The amount of ammonia that becomes ammonium is small and predictable in pure water in a closed system. However, as the ammonia reacts with other chemicals in the brine solution and with the air, the amount of NH_3 is further reduced. Chemicals are occasionally added on purpose to promote this reaction to remove ammonia from the solution and it is important to consider that not all test methods detect the ammonium ions. Regarding this incident, there was no documentation or evidence available to suggest any chemicals were added to purposely reduce the ammonia concentration, nor do the test results suggest this was the case.

It is also of interest to consider that if the entire ammonia charge leaked into the brine the concentration would have reached approximately 78,405 mg/L (6.7% mass) based on the assumed 885 lb [402 kg] ammonia inventory. If the ammonia charge was as high as the documented quantity of 1,200 lb [546 kg], then the concentration would have reached 105,400 mg/L (9.1% mass). At atmospheric pressure and a temperature of 30°F [-1.1°C], the solubility of ammonia in water is approximately 50%. It is important to realize that if the entire ammonia charge were to leak in to the brine, there would be a resulting volume increase due to the additional mass of the ammonia.

Summary of Results:

- 1) It is likely that the chiller was properly pumped down with little ammonia remaining in the refrigeration system and that no significant amount of ammonia leaked from the refrigeration system into the brine during the period between the May 2017 shut down and the August 2017 start up.
- 2) The curling rink brine could have absorbed the entire ammonia charge and not become saturated.



REPORT FOR TECHNICAL SAFETY BC
FERNIE MEMORIAL ARENA

CaCl₂ in the Ammonia System

During operation, the pressure of the CaCl₂ brine would have routinely been higher than the pressure in the ammonia system. The brine pump outlet pressure was recorded at 33 psig [228 kPag] and the ammonia system operated at approximately 20 psig [138 kPag]; this would have resulted in a pressure difference of approximately 8-13 psig (assuming a 5 psig pressure drop in the chiller) allowing brine to leak into the ammonia. When the brine system was off, the pressure was reduced to atmospheric pressure and the ammonia system would operate at a pressure between 20 psig and 40 psig allowing ammonia to leak into the brine.

CaCl₂ brine had the opportunity to leak into the ammonia refrigeration system up from the time the leak developed until the system was pumped down in May 2017 and again after the curling brine system was started in October 2017. Evidence of CaCl₂ was found in the refrigeration system in both the arena chiller and the compressor oil and cylinders; an example is shown in Figure 5 below. CaCl₂ present in the refrigeration system can cause increased corrosion and damage.



Figure 5: CaCl₂ Evidence in Compressor Cylinder Heads

Following the incident, a sample of the liquid remaining in the curling chiller oil pot was taken. Because the oil pot was drained during the May 2017 shut down, there was likely very little oil present in the oil pot and the sample likely contained primarily ammonia and brine. The results from testing this sample indicated an ammonia concentration of 410,000 mg/L [382,000 ppm]. It is not possible to tell from this sample how much brine was in the oil pot because the sample was close to saturation, and a large amount of ammonia could have evaporated.

Summary of Results:

- 1) CaCl₂ brine leaked from the secondary coolant system into the refrigeration system prior to shut down in May 2017 and after the curling chiller was started in October 2017.

Chiller and System Failure Scenario

On October 16, 2017, the curling chiller was put into service. This procedure includes filling the chiller with liquid ammonia and starting the brine pump. Initially, the ammonia pressure in the chiller would have been higher than its normal operating pressure because the brine was warm. The initial brine temperature was recorded as 52°F [11°C] which could have resulted in initial ammonia pressures as high as 78 psig [538 kPag]. This pressure would have been reduced quickly as the brine cooled and the refrigeration compressors maintained a lower pressure. The arena chiller was turned off for the starting procedure to allow the curling sheet to cool as fast as possible. After approximately 8 hours of curling chiller operation, the arena chiller was turned back on and the refrigeration system was operating automatically. At this point the ammonia pressure in the chiller was recorded at 26 psig [179 kPag]. Once the curling slab reached 23°F [-5.0°C], an operator adjusted the curling slab set-point warmer which allowed the curling chiller and brine system to cycle off so that the arena slab temperature could recover from being off all day. During the curling chiller start-up, the compressor oil was reported as being murky and foamy which is an indication of water in the oil.

At approximately 4:00AM on October 17, 2017 the ammonia alarm was engaged indicating that the ammonia sensor detected an ammonia concentration of 100 ppm. During the response to this alarm, the curling brine tank was reported as vibrating and shaking; this is a symptom that has been observed with some chiller failures and is caused by ammonia leaking into the secondary coolant. During the emergency response, an operator isolated the curling chiller and the brine system by closing several valves (see Appendix B of the Technical Safety BC Investigation Report for the complete as-found positions of all valves). This response was sufficient to stop or reduce the amount of ammonia leaking into the mechanical room as the recorded ammonia concentrations decreased from an initial 300 ppm when the responders first arrived to 50 ppm approximately one-half hour later.

The as-found valve positions indicate that the refrigerant side of the curling chiller was isolated. Both the liquid (inlet) and the suction (outlet) isolation valve were closed by the operators responding to the ammonia alarm, see Figure 6 below. The firefighters and refrigeration plant operators that responded to the alarm were not in the room long enough to perform a pump down procedure to remove the ammonia from the chiller and no such procedure was described by any of the firefighters during their interviews. Since it was not pumped down, the curling chiller would have had approximately 90 lb [41 kg] of ammonia remaining when it was isolated. For additional details regarding the ammonia quantity, refer to the Ammonia Inventory section of this report.



REPORT FOR TECHNICAL SAFETY BC
FERNIE MEMORIAL ARENA

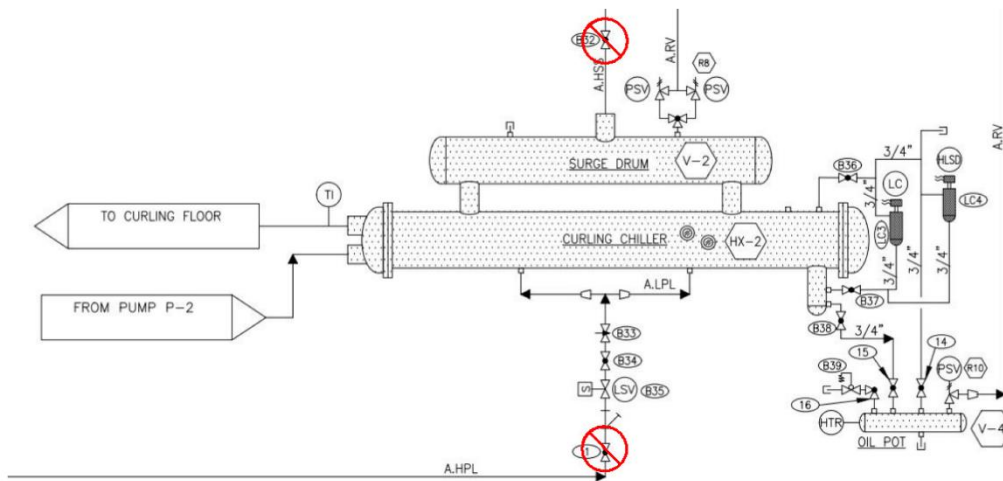


Figure 6: Cut out from Technical Safety BC Report Appendix B showing the valves that isolated the ammonia in the curling chiller.

The brine system was also isolated and the brine pump electrical was turned to off during the response. Following the incident, a brine sample was taken that indicated an ammonia concentration in the brine filter of 130,000 mg/L [113,400 ppm]. An additional brine sample was taken from the curling header that indicated there was an ammonia concentration of 5395 ppm [6435 mg/L] throughout the system. Figure 7 below shows the location of the two brine samples and the normally open valves that were effectively closed, isolating the brine system from atmosphere.

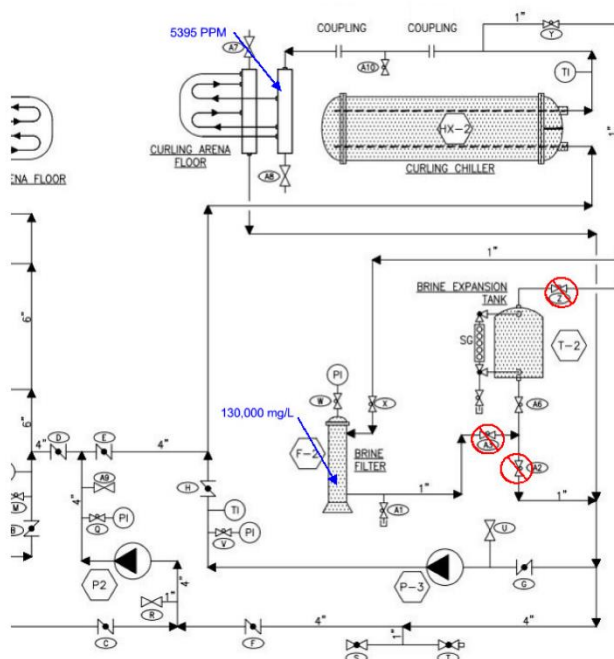


Figure 7: Cut out from Technical Safety BC Appendix B Diagram. The red cross-outs indicate the valves that isolated the brine system from the atmosphere and the blue arrows indicate the location of the brine sample measurements. Valve Z was found with the handle 10° open but was assumed to be effectively closed because of debris in the valve and piping.

Since the brine filter was most likely isolated during the initial response, the gradient of ammonia concentration between the filter and the measurement location in the curling brine header suggests that the brine pump was not operating at the time the system was isolated.

The properties and exact details of the dynamic reaction from the mixing of ammonia and CaCl_2 that occurred in the chiller are difficult to know because no concentration, temperature or pressure measurements are available from between the initial emergency response and the final failure.

The ammonia remaining in the chiller was in a saturated state and the pressure corresponded to its temperature (Figure 8 illustrates this relationship). When the chiller was isolated, the pressure would have been approximately 36 psig [248 kPag] as this corresponds to a 22°F (-5.6°C) brine temperature. The pressure of the the shell side of the vessel would have continued to increase as the temperature increased. The brine pressure would have been approximately 0 psig [0 kPag] when the system was shut down because the pump was not running.

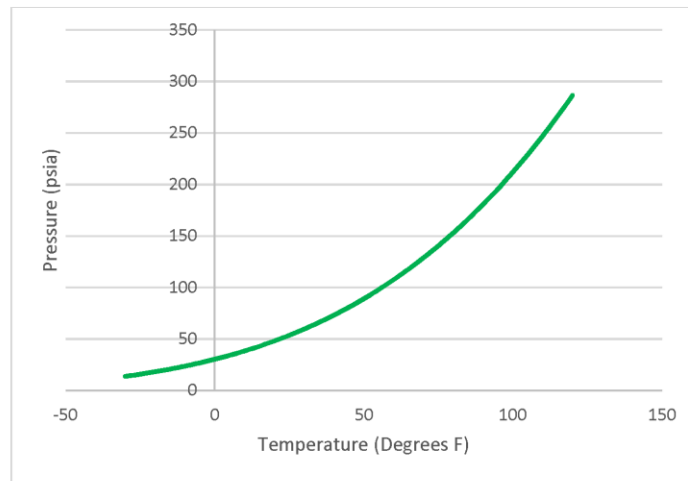


Figure 8: The pressure temperature relationship of saturated ammonia

Two factors would have contributed to an increasing chiller temperature.

1. Heat transfer would have occurred from the ambient air to the chiller because the machine room was warmer than the refrigerant contained in the curling chiller.
2. Heat is generated from the chemical absorption of ammonia into the brine inside the chiller tubes.

The reaction of mixing ammonia and CaCl_2 brine is exothermic, meaning it releases energy in the form of heat. This is due to the reaction of ammonia with water in the brine solution and the reaction between the ammonia and the CaCl_2 . While the relationship between water and ammonia is relatively well understood, there is not a lot of information available regarding the mixing of ammonia and a CaCl_2 solution. Simple experimental tests were conducted to compare the heat of solution rates for ammonia into a CaCl_2 solution to those for ammonia into water. For a 5% ammonia concentration, the measured heat of solution for ammonia into a CaCl_2 solution was significantly higher (10% - 70%) than measured or published values for those of ammonia into water. Because the published values for ammonia in to water are conservative and they are readily available for most concentration levels, they have been used in the analysis.

Heat would have been generated both from ammonia that remained unabsorbed when the leak was isolated during the initial response to the incident and from any ammonia that continued to leak after the system was isolated. Heat from this reaction and heat transfer from the surroundings acted to raise the temperature and the pressure of the ammonia in the heat exchanger.

Once a portion of the brine around the leak became saturated and the ammonia could not no longer move or diffuse quickly enough through the brine, ammonia vapour would have collected in the chiller tubes and the brine system would have begun to build pressure. If there was no volume available in the brine system to accommodate additional mass (i.e. no initial ammonia vapour or air pockets), there would have been very little delay in the pressurization and the pressure in the brine system would have increased to match the pressure in the ammonia system. If the chiller had volume available, the pressure would not have increased immediately but would have increased more slowly which would have allowed additional ammonia to leak into the brine.

This leak would continue until the ammonia could no longer mix and diffuse quickly enough to prevent the buildup of additional vapour. The curling brine tank was described as shaking and vibrating at the time of the initial response, which indicates that some ammonia vapour was present in the brine system when it was isolated; it is likely that ammonia continued to leak into the brine following the isolation.

The ammonia vapour would have most likely collected in the top of the chiller tube bundle which means that any solution in this area would likely be close to saturated. As the pressure was increased on the solution of ammonia and brine, its ability to absorb ammonia is increased. For example, the maximum ammonia concentration in 32°F [0°C] water increases from approximately 48% at atmospheric pressure to 85% at 30 psig [207 kPag] (ASHRAE, 2017).



Figure 9: Separated brine coupling on 4" brine piping

Approximately 5 hours after the initial emergency response that isolated the curling chiller and brine system, a 4-inch coupling installed on the brine supply line suddenly separated spraying a mixture of ammonia and CaCl_2 brine into the room; the coupling can be seen in Figure 9 above. When the coupling separated there would have been a rapid depressurization of the brine system. When this occurred, a portion of the ammonia in the ammonia saturated brine, located near the tube leak and in the upper tubes and heads of the chiller, would have expanded from liquid to vapour rapidly; the brine and ammonia contents from the top half of the chiller and the section of the brine piping between the chiller and the separated coupling would have been pushed rapidly by the expanding ammonia into the mechanical room. Figure 10 shows a graphical representation of the approximate volume of the release. The visual evidence of the spray from the coupling indicated that all of the flow was in the direction from the chiller into the room and not from the curling header and underfloor brine piping which corroborates that a high ammonia concentration was in the chiller and not in all of the brine piping.

An exemplar coupling was tested, which revealed that, installed with no support, this coupling could have failed at a pressure as low as 30 psig [207 kPag]. For details regarding this testing, see the Technical Safety BC Investigation Report. The installed coupling was better supported than the test rig, so it would have likely failed

at a higher pressure. In normal operation, the installed coupling would have been subject to pressures of approximately 30 psig [207 kPag].

If the pressure in the chiller had reached 150 psig [1034 kPag], a pressure relief valve would have opened on the ammonia side of the chiller. Lab results were inconclusive and could not determine if the relief valve opened. However, there was no evidence of calcium chloride present in the relief valve outlet or in the outlet piping, which suggests it did not open and that the pressure did not reach 150 psig [1034 kPag].

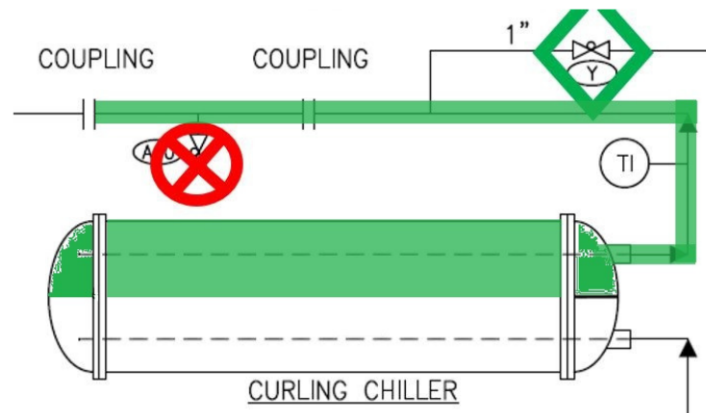


Figure 10 The green highlighted areas represent the approximate volume of ammonia- CaCl_2 brine solution that was released into the mechanical room

There is not enough information and evidence available to perform detailed calculation on the dynamic situation that occurred in the chiller during the leak event. However, in an effort to determine the approximate amount of ammonia that was released, the following scenario was considered:

- 1) The pressure in the brine system reached at least 30 psig [414 kPag]. This assumption is based on the minimum failure pressure of the coupling.
- 2) The brine pump was off prior to the initial response to the ammonia alarm. This assumption is based on the concentration gradient observed between the curling filter and the brine header.
- 3) The ammonia concentration of the solution in most of the chiller and inlet brine piping at the time of isolation was 130,000 mg/L. This assumption is based on the 130,000 mg/L [113,400 ppm] brine sample taken from the brine filter that was isolated during the initial ammonia leak response. Since the inlet piping and lower half of the chiller were not released during the coupling separation, the ammonia concentration in these components does not affect the results.
- 4) The ammonia concentration of the solution in the return head and top tubes of the chiller was approximately 30% at the time the chiller was isolated. This assumption was made because the ammonia concentration near the leak would have been higher than the concentration at the curling filter. The higher concentration was chosen so that the heat of absorption estimates were conservative.

- 5) The ammonia concentration of the solution from the outlet header to the separated coupling was 6435 mg/L [5395 ppm]. This assumption was made based on the ammonia concentration measurement made downstream on the curling header.
- 6) When the ammonia leak flow path was removed by isolating the brine system, unabsorbed ammonia vapour and the brine solution with the highest ammonia concentration migrated to the upper portion of the chiller. This assumption is made because the chiller was the highest point in the isolated system and the higher concentration solution and vapour have the lowest density.
- 7) The ammonia continued to leak into the chiller following the initial response where it was isolated, causing the following components to become close to saturation at a concentration of 75%. This assumption is made because a pressure difference between the ammonia and brine side of the chiller would have persisted until the ammonia could no longer be absorbed and diffuse into the solution. Additionally, the small size of the leak would have likely resulted in a slow pressurization and an increase in ammonia absorption. This volume is represented in Figure 11.
 - a. The top row of tubes (3 tubes)
 - b. The tube with the leak in the second row (1 tube)
 - c. The entire head on the return side of the chiller
- 8) The concentration of the remainder of the chiller tubes and the piping to the brine filter did not increase significantly after the system was isolated. This assumption was made because without the benefit of buoyancy (i.e. the ammonia vapour moving upward through the solution), the only driving force available to move ammonia through the brine is mass diffusion which is a very slow process.
- 9) Concentration values and saturation limits can be estimated using the relationship between ammonia and water. This assumption was made because data of this nature for a CaCl_2 brine/ammonia solution was not available.



Figure 11: Representation of the areas that were considered near saturation for the release scenario (the drawing is not to scale). The arrow indicates the approximate location of the tube leak.

Based these assumptions, the following approximate ammonia and brine quantities were determined:

- 1) 44 lb [20 kg] of ammonia was absorbed in the 186 L [50 US Gal] brine located in and surrounding the chiller at the time of isolation.

- 2) 5 lb [2.3 kg] of additional ammonia leaked into the brine after the system was shut down.
- 3) 83 L [22 US Gal] of solution was released when the coupling separated.
- 4) 22 lb [10 kg] of ammonia was absorbed in the 83 L [22 US Gal] of solution that was released.

The heat generated from the ammonia released into the brine following the isolation in combination with the temperature rise from the ambient air would have likely increased the temperature in the chiller to at least 34°F [1°C], the approximate rate of rise can be seen in Figure 12. At this temperature, the pressure in the chiller would have been 50 psig [345 kPa]. It is likely that additional heat was also generated from ammonia vapour that had not been absorbed prior to the system being isolated during the initial emergency response. The effect of having this additional energy would have been a larger temperature and pressure rise in the chiller. However, since there is no evidence available to help determine the scale of this heat addition and there would not be a significant change in the ammonia concentration results, it has been purposely ignored in the analysis.

The temperature of the machine room is unknown so the outdoor ambient temperature at the time of the incident was used as the machine room temperature.

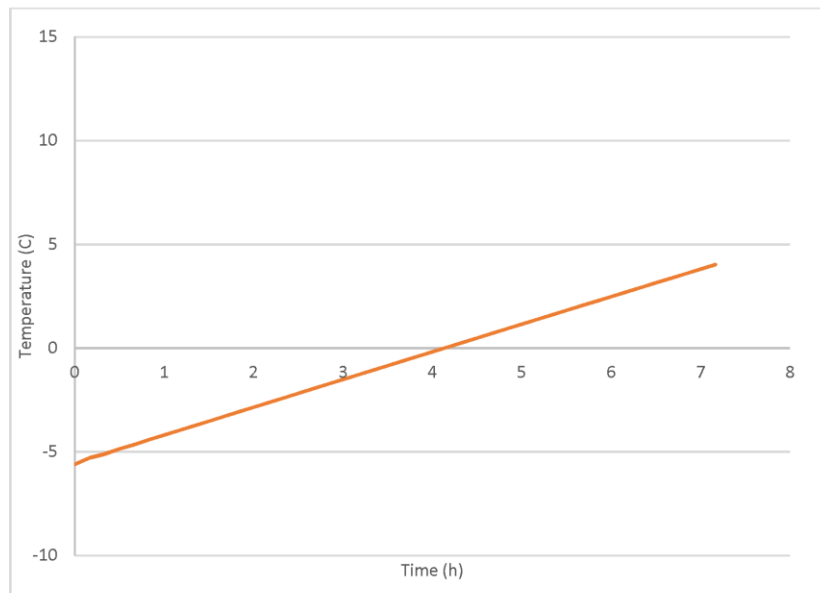


Figure 12: Temperature rise of the chiller over time based on the heat of solution from 2.3 kg of ammonia and a 12.2°C mechanical room.

Summary of Results:

- 1) The brine pump was not likely in operation, having cycled off because the curling floor reached temperature, leading up to the initial ammonia alarm.
- 2) The refrigeration system was isolated with approximately 90 lb [41 kg] of ammonia in the chiller.
- 3) The curling brine system was isolated and not open to atmosphere.

- 4) The brine system was likely pressurized to at least 50 psig [345 kPag].
- 5) 22 lb [10 kg] of ammonia was absorbed in the 83 L [22 US Gal] of solution that was released when the coupling separated.

Ammonia Release and Ventilation

A solution of ammonia and CaCl_2 brine was released into the mechanical room suddenly from the separated coupling. The spray pattern was dramatic and evidence of high velocity. The direction of flow was almost exclusively out of the side of the coupling closest to the chiller. This is consistent with the release of a solution that is being propelled by a fluid that is expanding from liquid to vapour. For additional details regarding the spray pattern, see the Technical Safety BC Investigation Report.

During the rapid depressurization a portion of the ammonia that was mixed with the brine would have evaporated almost immediately and more would have been released as the solution was sprayed in the air.

In addition to the ammonia that was released quickly from the brine coupling, approximately 14% of the liquid ammonia mass remaining in the chiller would have vaporized as quickly as the leak size would allow it until the chiller reached its saturation temperature at atmospheric pressure, at which point the pressure of the ammonia would have been 0 psig [0 kPag]. This would have caused approximately 13 lb [6 kg] of ammonia to be released into the room. The water and brine present in the ammonia-side of the chiller would have acted to increase this saturation temperature from that of pure ammonia which is approximately -28°F (-33°C) (Nelson, 2010). However, because the amount of brine that leaked into the ammonia is unknown and accounting for this effect would not likely have a large effect on the final amount of ammonia released, it was purposefully neglected. Once the ammonia reached the saturation temperature at atmospheric pressure, the evaporation rate would have balanced with the heat transfer from the surroundings and it would have likely taken days for the remaining ammonia to evaporate.

The portion of brine in the section of piping from the separated coupling to the chiller would have been released first. The amount of ammonia released from this brine would depend on many factors including the size of the spray droplet, the velocity, and the pH of the solution. It is possible that a portion of this ammonia remained in solution on the floor and evaporated more slowly. Next, the solution that was released from the chiller would have been a combination of the brine-ammonia solution and ammonia vapour from the expanding ammonia propelling it. A significant portion of the ammonia contained in this solution would have been released relatively quickly as the fluid contacted the air and walls of the mechanical room. Most of the ammonia contained in the solution that was near saturation around the chiller leak would have been released in the room as ammonia vapour immediately following the brine solution.

In the described scenario, it is reasonable to expect that most of the estimated 22 lb [10 kg] of ammonia contained in the brine solution was released into the room and vaporized/evaporated. When the release happened suddenly, it is likely that the majority of the 9 lb [4 kg] of ammonia contained in the most highly concentrated solution would have been released almost immediately along with a portion of the remaining ammonia in the less concentrated solution. As some of the ammonia may have stayed in solution and evaporated more slowly in the room, an 18 lb [8 kg] release was used as the upper bound in the dispersion analysis that follows below.

Figure 13 shows a flow diagram of the different brine and ammonia concentrations that were calculated based on the combinations of assumptions given in the scenario in the previous section of this report and the above discussion.

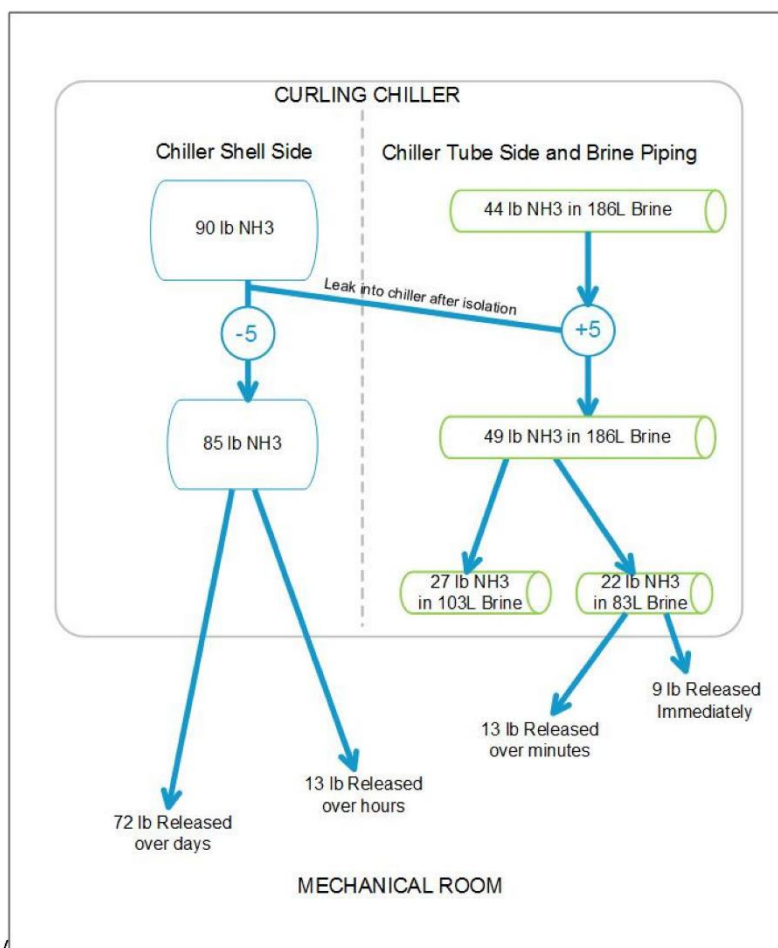


Figure 13: Flow diagram summarizing ammonia and brine mass quantities from the time the system was isolated. Based on the scenario assumptions described in this report. The brine quantities in this figure represent the approximate brine piping and chiller volume between the separated coupling and isolation valves on the inlet side of the chiller.

The mechanical room at the Fernie Memorial Arena had two exhaust fans installed. One fan was used to meet the minimum ventilation requirements and the other was used for emergency exhaust. The fans were tested as a part of the investigation and the results are available in the Technical Safety BC Investigation Report; a summary of the relevant information is shown in Table 4.

Table 4: Table of emergency exhaust fan capacities

Ventilation Scenario	B52 Code Requirement	Installed Fan Capacity	Actual Measured
Minimum flow rate	375 cfm	800 cfm	1062 cfm
Leak / Rupture Scenario flow rate	3500 cfm	4000 cfm	2619 cfm

Following the release, these exhaust fans would have functioned to reduce the ammonia concentration in the room by exhausting contaminated room air. Outside air could enter the room through permanently installed louvres and the open machine room door. Figure 14 illustrates the results of a general contamination removal calculation with 9 lb [4 kg] of ammonia being released instantaneously. The grey curve represents the results with the capacity of the fans in the condition they were found and includes a mixing factor of 4. A mixing factor is used to account for the fact that some air drawn in from outside bypasses the contaminant and is exhausted outside. The blue curve shows the results if the mixing was perfect and the orange curve shows the results of perfect mixing with the air flow as designed.

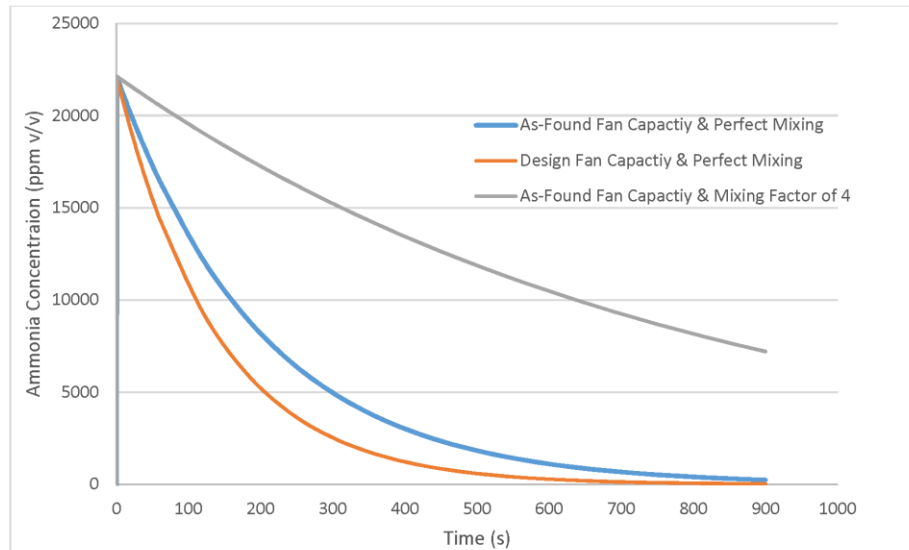


Figure 14: The dilution rate of the ammonia in the machine room for a 4 kg instantaneous release of ammonia, assuming a volume averaged concentration.

It is important to note that the calculations used to obtain the curves in Figure 14 assume a single volume concentration in the room. It is possible that some highly concentrated air and ammonia vapour was initially captured by the exhaust in the time immediately after the leak occurred. Based on the airflow patterns observed in the room during the smoke test, it is not likely this condition would have existed for a long period of time.

The ammonia and air mixture was dispersed to the atmosphere by the exhaust fans. A simple Gaussian simulation of the dispersion of the ammonia was created using Aloha Software and is shown in Figure 15 below (EPA;NOAA). This was created using the atmospheric conditions from the neighboring community of Sparwood,

BC at the approximate time of the incident. The wind direction was changed to match the typical wind pattern through the valley where Fernie is located. The green shading indicates areas that may have reached concentrations of 5 ppm for a release of 18 lb [8 kg] in the mechanical room. This value was chosen to represent an approximate upper release amount because it was previously assumed that not all of the 22 lb [10 kg] of ammonia that was contained in the brine solution was released immediately. The purple shaded area represents the area that concentrations of 5 ppm or above in a 9 lb [4 kg] release. The concentration of 5 ppm for this diagram was chosen to represent the approximate odour threshold of ammonia.

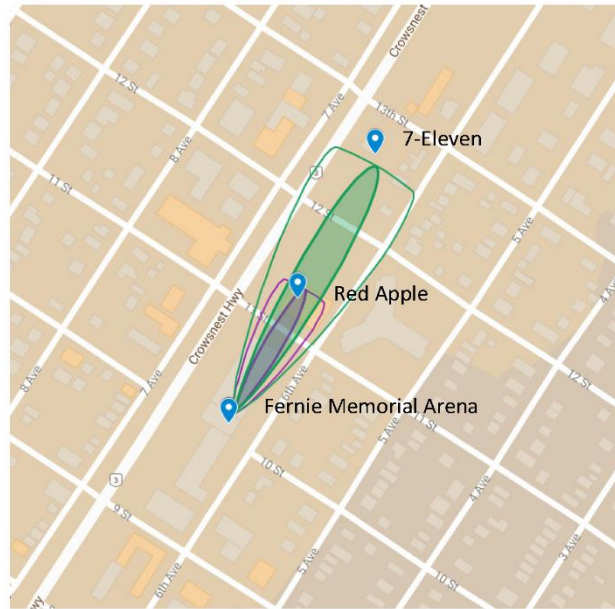


Figure 15: Dispersion modeled at the odour threshold of 5 ppm for a 4 kg (purple) and 8 kg (green) release, using Aloha (EPA/NOAA)

Witnesses at two locations, 7-Eleven and Red Apple (noted in Figure 15) reported the smell of ammonia. Because this is a relatively simple model, it is certainly possible that a pocket of ammonia traveled far enough to be detected at the 7-Eleven in either release scenario. Additionally, as previously discussed, it is also possible that the initial concentration of the ammonia in the exhaust air was higher than predicted.

Summary of Results:

- 1) It is likely that at least 9 lb [4kg] of ammonia was released immediately into the machine room when the brine line coupling separated.
- 2) The remaining 13 lb [6 kg] of ammonia that was in the brine that was released ultimately evaporated and aerated from the brine during and shortly after the release.
- 3) Approximately 13 lb [6 kg] of the ammonia remaining in the shell side of the chiller evaporated and leaked into the room before the chiller reached a temperature of -28°F [-33.3°C].
- 4) The remaining ammonia evaporated over a period of days.
- 5) The ammonia concentration in the room reached over 20,000 ppm and likely remained above 5,000 ppm for at least 5 minutes.

Emergency Relief and Ammonia Dispersion

At approximately 1:50 PM on October 17, 2017, during the emergency response, the emergency discharge valve was opened. This valve is provided on some refrigeration systems to allow the refrigerant to be released to the atmosphere. In this case it was connected to the receiver as shown in Figure 16.

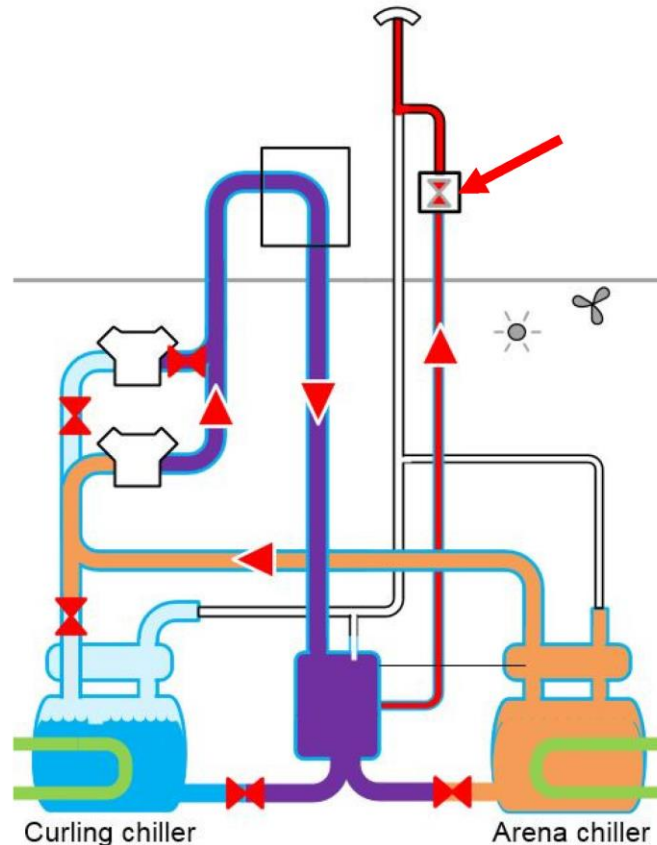


Figure 16: A simplified piping diagram showing the configuration of the emergency discharge valve. The purple components contained refrigerant that would have been released relatively quickly. The orange components would have released more slowly because they did not have a direct path to the discharge point. The red arrow is pointing at the emergency relief valve.

As can be seen in Figure 16, the high side of the system that included the condenser, high pressure receiver, and the associated piping would have been depressurized quickly. The arena chiller would have depressurized more slowly because the refrigerant had to move through the compressor. Based on the ammonia charge calculations summarized earlier in this report and the amount of ammonia that was assumed to leak into the brine, the high side of the system would have contained approximately 360 lb [163 kg] of ammonia and the arena chiller and oil

pot would have contained approximately 327 lb [149 kg] of ammonia; this information is summarized in Table 5 below.

Table 5: A summary of the estimated ammonia quantity in various components at the time the system was isolated. The bold numbers represent the estimated quantity of refrigerant that was released when the emergency discharge valve was opened.

Description	Refrigerant Quantity (lb [kg])
Initial Ammonia Inventory	885 [402]
Ammonia that leaked into brine between start up and system isolation based on the 5395 ppm and the 1830 ppm concentration measurements.	49 [22]
Ammonia that leaked in the brine in the chiller and surrounding brine piping prior to isolation	44 [20]
Ammonia in the Curling Chiller at the time of isolation	90 [41]
Ammonia in the Curling Chiller oil pot at the time of isolation	15 [6.8]
Ammonia in the Arena Chiller	312 [142]
Ammonia Arena Chiller Oil Pot	15 [6.8]
Ammonia located in the receiver and other high side components	360 [164]

Based solely on the high side components, the initial release rate through the emergency discharge valve would have been approximately 11.7 lb/min [5.3 kg/min]. As the liquid ammonia in the high-pressure receiver boiled, it removed heat from the surrounding liquid and reduced its temperature. This reduction in temperature would have caused a corresponding reduction in pressure and less mass flow out the emergency discharge line. This is often described as a self-arresting leak situation. After 8 minutes, the release rate would have likely decreased to below 2.2 lb/min [1 kg/min]. Figure 17 illustrates the approximate mass change in the receiver as the refrigerant was released. Approximately 55 lb [25 kg] would have been released over 15 minutes until the vessel reached the saturation temperature corresponding with ambient pressure, the remaining 305 lb [139 kg] would have evaporated slowly over several hours and days as heat transferred to the refrigerant in the vessel.

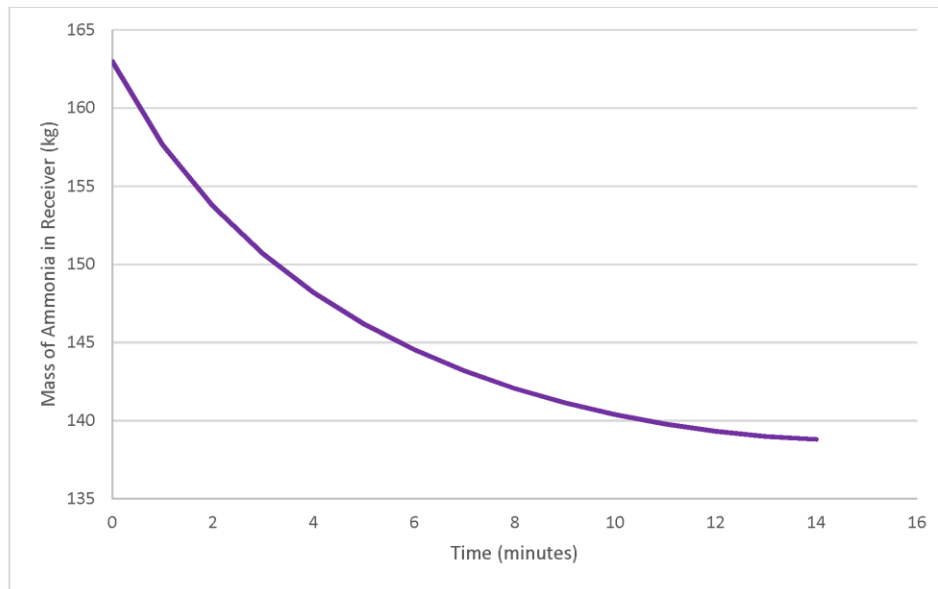


Figure 17: Mass of ammonia in high pressure receiver as a result of the opening of the emergency discharge valve.

As was previously mentioned, the arena chiller would have released refrigerant more slowly because of the additional restriction of the compressor. The start of the release would also have been delayed until the pressure on the high side of the system had reduced to below the pressure in the chiller. Because of this, it was assumed that it would not have affected the peak dispersion concentration of the refrigerant.

Approximately 46 lb [21 kg] of the ammonia in the arena chiller would have been released in order to reduce the refrigerant to a saturation temperature corresponding to atmospheric pressure. The remaining 281 lb [128 kg] would have evaporated slowly due to the heat transfer into the vessel. Because this vessel is insulated, and the room was kept at the outdoor ambient conditions, this would have likely taken days.

Aloha software was also used to model the vessel release and to verify the previously mentioned calculations(EPA;NOAA). Figure 18 represents the areas that could have reached 25 ppm (yellow) and 35 ppm (orange) based on this release rate. Note that of the 55 lb [25kg] of ammonia that would have been released in the first 15 minutes after opening the emergency discharge valve, more than 80% would have been released in the first 6 minutes.

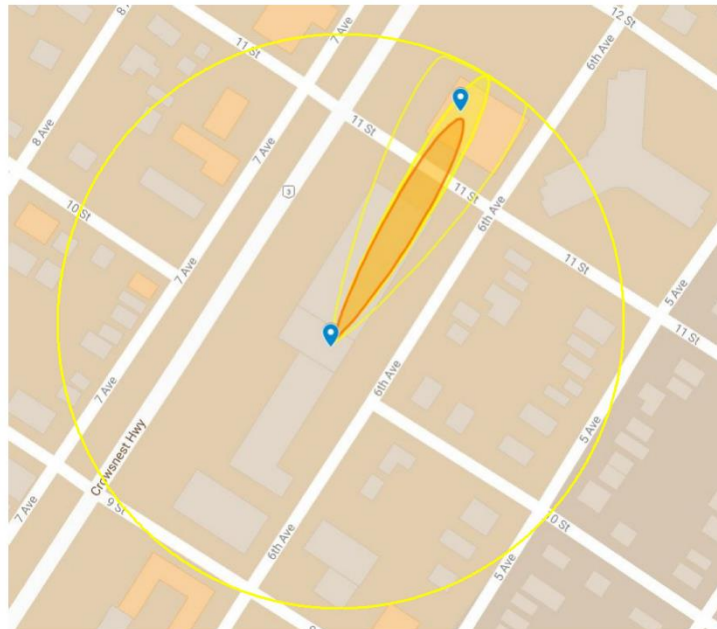


Figure 18: Approximate 25 ppm and 35 ppm dispersion when the emergency relief valve was opened.

In an effort to be conservative and show a worse case, the ammonia that leaked into the brine was not removed from the quantities used in this section of the analysis.

Summary of Results:

- 1) As much as 687 lb [312 kg] of ammonia was released through the emergency discharge valve.
- 2) Approximately 55 lb [25 kg] of ammonia was released from the high pressure receiver and high side in 15 minutes after first opening the valve and the remaining 305 lb [139 kg] was released more slowly.
- 3) Approximately 46 lb [21 kg] of ammonia was released as the arena chiller and oil pot depressurized. The timing is unknown because flow was through a compressor. The remaining 281 lb [128 kg] was released more slowly.

Completion Notes

This report and analysis was completed by:


17 July 2018
Greg Schriener, P.Eng.

REPORT FOR TECHNICAL SAFETY BC
FERNIE MEMORIAL ARENA

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Disclaimer of Liability

This report was completed at the request of Technical Safety BC as part of a larger involvement in investigation of the October 2017 ammonia refrigerant release incident in Fernie, BC.

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REPORT FOR TECHNICAL SAFETY BC
FERNIE MEMORIAL ARENA

Revision Log

Revision Number	Date	Description of Changes

REPORT FOR TECHNICAL SAFETY BC
FERNIE MEMORIAL ARENA