Ammonia was detected to have leaked into the curling brine system during the 2016/2017 operating season at the Fernie Memorial Arena. Examination of the curling brine chiller after the incident identified the source of the leak as a carbon-steel tube failure within the curling system brine chiller. The failed tube showed evidence of corrosion pitting along the inner tube walls with accelerated pitting on an electric resistance weld line due to weld line fusion defects. A corrosion penetration occurred at a weld location resulting in a hole measuring approximately 2.2 mm x 0.2 mm with potential adjacent smaller holes along the same weld line.

The potential for corrosion in this type of system results from the chemical reactions between the calcium chloride brine solution and the carbon steel welded tubes. Brine systems of this type are also subject to periodic air ingress that can promote corrosion. Removal of this trapped air from the system is part of regular operation and maintenance. Evidence indicates that a corrosion inhibitor (brinehib) was being added periodically to the brine solution to slow the corrosion process within the system.

Corrosion penetration is one type of wear-out failure risk that can increase with the length of service or age of equipment and become accelerated at some defect areas. Vessels in similar service conditions are generally considered to have a useful life of 20-25 years, although there are many factors that influence how long a vessel might remain serviceable. The curling chiller was manufactured 31 years prior to its failure in 2017. The investigation did not discover documentation indicating the exact date the chiller was put into active service at the facility.

Detection of a curling chiller ammonia leak during the 2016/17 operating season first occurred during seasonal shutdown in April/May of 2017. The curling system remained shut down through the summer months and was re-started on October 16, 2017. Hours after starting the curling system, ammonia that leaked into the brine began to accumulate into the mechanical room through the brine expansion tank. At 3:53 a.m. on October 17, 2017, an ammonia alarm was triggered within the mechanical room when a concentration of 100 ppm was detected. Brine had also leaked into the ammonia system and was detected in the compressor oil.

In response to the ammonia leak, the brine expansion tank and curling chiller were isolated. This isolation impeded brine expansion while isolating liquid ammonia within the leaking chiller. The brine system was shut down and valves were closed at the pump, inhibiting absorption of the leaking ammonia throughout the entire brine system volume. In response to the brine leaking into the ammonia system, a service call was arranged for a mechanic to perform an oil change that morning.

As ammonia continued to leak into the brine, the brine nearest the leak likely reached ammonia saturation concentrations. The likely effects within the brine system near and within the chiller were:
- an ammonia saturated volume of brine;
- a temperature increase;
- a pressure rise within the brine system and chiller; and
- a displaced volume of brine from ammonia being added to the saturated solution.

A brine system pipe segment near the curling chiller was joined at two locations by pipe couplings. These joints were not supported to resist movement from pipe loading due to pressure or mechanical forces. The rising pressure within the brine system eventually exceeded the strength of the joint and one of the coupling joints separated.

Once the coupling separated, the brine system piping suddenly depressurized and the ammonia within the solution and piping rapidly expanded. The contents of the pipe were propelled out by the rapidly expanding ammonia. The released ammonia quickly expanded within the room, reaching estimated concentrations above 20,000 ppm within the mechanical room.

The Fernie Memorial Arena mechanical room scene is documented in photos in Appendix C for reference. An itemized system schematic is provided in Figure 3.
Figure 3: Schematic of the Fernie Memorial Arena curling refrigeration system. Numbers identified correspond to the items and descriptions in the Table 1 below.

<table>
<thead>
<tr>
<th>#</th>
<th>ITEM DESCRIPTION &amp; FINDING</th>
<th>#</th>
<th>ITEM DESCRIPTION &amp; FINDING</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>Curling Brine Chiller</strong> – One 2.2 mm x 0.2 mm hole found in an upper tube along a weld seam.</td>
<td>7a</td>
<td>Valve found in OPEN position</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7b</td>
<td>Valve found failed in OPEN position</td>
</tr>
<tr>
<td>2</td>
<td><strong>Brine analysis results – prior to incident:</strong> (sample locations indicated as item 2)</td>
<td>8</td>
<td>Valve concluded to be effectively CLOSED. A very small opening may have facilitated some leakage, while pressure relief was impeded.</td>
</tr>
<tr>
<td></td>
<td>0 ppm ammonia – Jan 2016</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3,320 ppm ammonia – May 2017</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1,830 ppm ammonia – Aug 2017</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td><strong>Brine analysis results – post-incident:</strong> (sample locations indicated as item 3)</td>
<td>9</td>
<td>Ammonia system valves found CLOSED, isolating an estimated 90 lb. ammonia in chiller</td>
</tr>
<tr>
<td></td>
<td>113,400 ppm ammonia measured on Oct 20 2017</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td><strong>Brine analysis results – post-incident:</strong> (sample locations indicated as item 4)</td>
<td>10</td>
<td>Compressors contaminated – salt deposits found indicate brine leaking from chiller</td>
</tr>
<tr>
<td></td>
<td>5,395 ppm ammonia measured on Oct 23 2017</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td><strong>Brine filter changed April 13, 2017</strong> – log book notes strong smell of ammonia. Filter valve found plugged and filter element clean</td>
<td>11</td>
<td>Separated brine system coupling. Pipe segment not supported for pressure loading</td>
</tr>
<tr>
<td>6</td>
<td><strong>Brine system valves found CLOSED</strong></td>
<td>12</td>
<td>Brine spray in mechanical room</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13</td>
<td>Emergency discharge valve (firebox) - OPEN</td>
</tr>
</tbody>
</table>

Table 1: Items and descriptions as referenced from Figure 3 – Curling Refrigeration System Schematic. Item numbers (#) correspond to the components and system locations in the schematic, Figure 3.
FINDINGS RELATED TO THE CURLING BRINE CHILLER

Multiple potential sources of an ammonia leak were examined and tested. The curling brine chiller was determined to be the only source of ammonia that could have leaked into the room. This conclusion was determined based on several factors:

- Leak tests and visual inspections of all ammonia system piping and equipment did not reveal any leaks other than within the curling system chiller.
- Brine analysis reports indicated the curling system chiller was leaking prior to the incident.
- Following ventilation of the room, the only source of ammonia detected to be entering the room was measured at the separated curling brine system coupling.
- Higher ammonia readings were detected at the separated brine system pipe connected to the chiller.
- The arena system brine analysis did not indicate an ammonia leak from the arena chiller.

When the chiller heads were removed in the mechanical room in January 2018, they revealed the following:

- Tubes and tube sheets appeared corroded and contaminated.
- Lower tube contamination was dark and oily in appearance.
- Contamination was soluble in water.
- Ultrasonic measurement detected one leaking tube (row 2, tube 3).
- The identified leaking tube was noticeably less contaminated than other tubes.

Photo 1: Curling chiller opened showing contamination. The leaking upper tube is identified by the white arrow – second row, third tube from the right side of the photo.
Destructive testing and laboratory analysis of the chiller was completed and included in Appendix E. A leak check of each tube confirmed only the one identified tube was leaking. The failed tube showed evidence of corrosion pitting along the inner tube walls with selective pitting on an electric resistance weld (ERW) line. The tube ERW weld lines were found to contain fusion defects resulting from the welding process that increased the potential for corrosion in unfused areas (Appendix E). A corrosion penetration occurred on the ERW weld seam resulting with a hole measuring approximately 2.2 mm x 0.2 mm. Adjacent smaller pits along the same ERW weld line were identified that may have penetrated the tube wall.

**FINDINGS RELATED TO THE DETECTION OF AMMONIA IN THE CURLING SYSTEM BRINE**

High ammonia levels were detected within the curling system brine solution. It is likely that at the time of the incident, the ammonia concentration within the brine closer to the leak within the chiller was much higher. Following the incident, a sample within the mechanical room close to the chiller detected 113,400 ppm ammonia, while a sample further from the chiller, outside of the mechanical room measured 5,395 ppm ammonia.

As part of the annual shut-down of the facility’s refrigeration system, the maintenance contractor took samples and coordinated brine analysis to monitor for a number of items, including the presence of ammonia. Ammonia concentrations measured during this time were as follows:

- January 2016 – No ammonia was detected in the sample.
- April 13, 2017 – during interviews, city employees stated that there was an ammonia smell from the brine. The maintenance log also recorded “a strong smell of ammonia in the curling rink filter” following a filter cleaning task.
- May 2017 –3,320 ppm ammonia detected in a sample and a recommendation was made by the maintenance contractor to monitor and take another sample.
- August 2017 - 1,830 ppm ammonia detected in a sample. The reduced concentration is likely due to off-gassing throughout the summer months while the brine sat idle in the system. During shutdown periods the liquid ammonia is pumped out of the chiller shell side with minimum vapour remaining.

Results from the May 2017 brine sample analysis with a recommendation by the maintenance contractor to monitor was found within the mechanical room (Appendix C). The brine analyses conducted indicate the curling chiller had begun to leak ammonia into the curling system brine during the 2016/2017 operating season.
**FINDINGS RELATED TO THE VALVE POSITIONS**

The valve positions of the ammonia and brine systems were recorded prior to any manipulation for hazardous materials removal. These valve positions, documented in Appendix B and Figure 4, record those positions immediately following the incident. An analysis of the timing for isolation and system shutdown (Investigation Findings II) concludes that these valve positions, with the exception of the closed valves at compressor #1, likely represent how the system was configured after the shutdown at 4:30 a.m. on October 17, 2017.

This configuration isolated an estimated 90 lb. of ammonia within the chiller (Appendix A) and inhibited brine system venting and pressure relief through the expansion tank.

An inlet valve to the curling system brine expansion tank was found slightly cocked, as shown in the upper inset of Photo 5. The valve handle had been re-installed in a flipped condition allowing for a different orientation and range of motion. Lab analysis (Appendix E) estimated the handle angle at 10 degrees from perpendicular. Radiography and leak testing to determine if the valve was fully closed or permitting free flow (unplugged) was inconclusive. An exemplar valve was configured per the as-found valve and suggests this valve may not have been completely closed. In such an ‘almost closed’ and unplugged configuration, this valve may have facilitated some leakage while impeding pressure relief from brine expansion or displacement. This valve is concluded to be effectively closed but may have contributed to a small leakage of ammonia or brine as the brine system pressurized.

The log of ammonia alarms recorded by the alarm monitoring company for the Fernie Memorial Arena (Appendix G) indicates a number of ammonia alarms in the morning leading up to the incident. It is reportedly common for ammonia alarms to be triggered while work on a refrigeration system is being conducted and refrigeration mechanics reported it is common for those alarms to be disregarded. These alarms could have been triggered from ammonia escaping at the brine expansion tank, brine system coupling locations or as compressor #1 was being prepared for ammonia purging in anticipation of the upcoming oil change.
FINDINGS RELATED TO BRINE CONTAMINATION WITHIN THE COMPRESSORS

In addition to the ammonia leaking into the brine system, brine was also leaking into the ammonia system through the leaking chiller tube. The compressor oil was identified in the maintenance log on October 16, 2017 as being milky. Following the 3:53 a.m. alarm and subsequent system shutdown on October 17, 2017, the maintenance contractor was requested to dispatch a mechanic to get the refrigeration system running for the arena system and to perform oil changes on the compressors due to the visual appearance and level of the oil.

Oil with a cloudy or milky appearance is identified as an indication of a water/brine contamination. The compressor and cylinder heads were removed post incident and inspected which revealed the presence of salt deposits most likely from brine contamination of the ammonia.

Photo 6: Compressor #2 (#1 similar) showing salt crystal build-up on lower compressor cylinder heads, upper heads were clean.

Photo 7: Build-up of salt crystals from brine around lower compressor cylinder heads of compressors #1 and #2.
FINDINGS RELATED TO THE SEPARATED BRINE SYSTEM COUPLING

Rising pressure from the ammonia leak into the isolated brine system exceeded the strength of a coupling joint in the brine system piping located near the curling chiller. The separated joint relieved the pressure, which resulted in rapid release and expansion of the ammonia within the brine system and solution.

As shown in Figure 5, a segment of the brine system piping was connected by two in-line water system couplings. One coupling was oriented vertically while the other horizontally. The pipe segment weight was supported on a wooden block at one location. There was no support for either longitudinal or torsional loading.

The horizontal coupling was found separated as shown in Figure 5 and Photo 8.

As part of the investigation, a test was conducted to evaluate the pressure required to separate a similar pipe coupling. A new exemplar coupling was installed per the manufacturer’s specifications onto 4-inch diameter piping similar to that used at the Fernie Memorial Arena. The pipe-coupling joint was pressurized and at 30 pounds per square inch (psi) the coupling began to slip toward separation.

The curling chiller is protected on the shell side (ammonia) by an over-pressure relief device set to relieve at 150 psi. This valve was tested and demonstrated to relieve at the designed pressure. An inspection revealed no evidence of brine deposits within the valve. It is concluded that the overpressure relief device likely did not activate.

It is therefore estimated that the pressure within the brine system reached between 30 psi and 150 psi. The friction from the weight of the pipe and the torsional friction of the vertical coupling would have added to the force needed to separate the coupling beyond that associated with the 30 psi coupling separation pressure.
FINDINGS RELATED TO AMMONIA-BRINE SPRAY INTO MECHANICAL ROOM

Once the brine system coupling separated and relieved the internal pressure, the ammonia in solution and any ammonia in the brine pipe quickly expanded, projecting the contents of the brine pipe outward from the pipe opening. The ammonia quickly vaporized and expanded to fill the mechanical room reaching estimated concentrations exceeding 20,000 ppm.

Evidence of brine chiller and pipe contents projecting from the separated brine system coupling was observed immediately following the incident as shown in Photo 10 and Photo 11 below.

Exposed copper pipe and locks within the mechanical room were observed to be corroded (blue) indicating exposure to ammonia.

Residue patterns were observed on the mechanical room walls and around the maintenance log books that are consistent with having originated from the separated coupling as shown in Figure 5.

Samples from the residue on the walls were taken and analyzed. The results are contained in Appendix I and identified the likely presence of calcium chloride, consistent with brine having originated from the chiller/brine system piping.

Photo 10: Separated coupling and projected brine system contents. Photo taken on October 18, 2017.

Photo 11: Projected contents of the brine piping from the separated coupling.

Photo 12: Lock-out board showing corroded (blue) copper consistent with ammonia exposure.
Figure 6: Photos of residue locations on the mechanical room wall. Pattern location is consistent with originating from the separated brine coupling. Samples of the residue tested identified a likely presence of calcium chloride consistent with brine.