Incident Summary #II-762099-2018 (#9286) (FINAL)

SUPPORTING INFORMATION	Incident Date			October 24, 2018
	Location			Langley
	Regulated industry sector			Refrigeration – Boilers and Pressure Vessels
	Impact	Injury	Qty injuries	0
			Injury description	N/A
			Injury rating	N/A
		Damage	Damage description	Ruptured evaporator (also referred to as heat exchanger or cold trap) released estimated 485 to1,500 lbs of ammonia from refrigeration system and resulted in an extensive area evacuation for two days.
			Damage rating	Major
	Incident rating			Major
	Incident overview			After unscheduled maintenance to drain oil from the pumps, the refrigeration system was noted to be slow to return to performance and oil contamination of some system evaporators was suspected. The responding refrigeration mechanic stated he attempted to improve system performance by closing valves to generate pressure within an evaporator to move or dislodge potentially trapped oil. The pressure rose very rapidly once the evaporator was isolated between closed valves, breaking a pressure gauge needle (photo 3) and rupturing the evaporator (photos 1 and 2). An estimated 485 to 1,500 lbs of ammonia was released from the ruptured evaporator into the freeze-drying production chamber. The chamber is not designed to contain ammonia and therefore ammonia escaped the chamber into the atmosphere. There was no provision for ammonia extraction from the chamber. As a result a significant volume of ammonia entered into the chamber and could not be quickly removed. The release resulted in an extensive area being evacuated for two days (Diagram 1) while the leaked ammonia was dispersed into the atmosphere and contained within a water solution.
INVESTIGATION CONCLUSIONS	Site, system and components			The refrigeration system is depicted in Diagram 2, consisting of four operating chambers (A, B, C and D) and three flash freezers. Liquid ammonia was pumped to the chambers and freezers to remove heat and moisture. Ammonia was returned to high pressure and low pressure receivers (LPRs) via compressor suction and liquid pump pressure. The total refrigerant charge of the system was identified as 9,500 lbs of ammonia. The LPR incorporated an oil trap to remove compressor oil prior to circulation of the liquid ammonia to the pumps and heat exchangers. Compressor oil is heavier than liquid ammonia and will settle at the bottom of the receiver vessels where oil traps are located or at low points in system piping. Oil from the oil pot would be removed at regular maintenance intervals to prevent accumulation and circulation throughout the refrigeration system. Oil drainage provisions were incorporated at system piping low points located at each chamber.

	A maintenance program will establish and monitor oil removal and management activities. If oil is allowed to accumulate within the vessel, it will eventually contaminate the liquid ammonia flowing into the system. At very low temperatures consistent with that of liquid ammonia, compressor oil viscosity is high and the oil may not flow or move easily through the system or components. Excessive oil in the ammonia system can reduce ammonia flow and interfere with mechanical motion (pumps). The effects can be reduced performance or the generation of system / component faults from monitoring circuits. Liquid ammonia is metered into the evaporators within each chamber by a hand expansion valve as shown in Diagram 2. The hand expansion valves are set at the desired operating point during system commissioning and not intended to be adjusted during normal operation. The operating point associated with the hand expansion valve will correspond to a ratio of liquid refrigerant to total volume. Typically, a steady state operating evaporator's set point corresponds to approximately 50% of the volume being liquid refrigerant within an evaporator. Ammonia has a relatively high liquid expansion coefficient. It is important to never trap liquid ammonia inside a vessel or between valves without a significant portion of vapour volume present to allow for expansion. With small temperature changes, trapped liquid can cause a rapid and significant pressure increase.
Failure scenario(s)	Oil was not being sufficiently removed from the refrigeration system following a change in compressor output setting. On October 23, 2018, an overload failure of the ammonia pump occurred and was suspected to be a result of oil contamination. Once service was restored to the refrigeration system, performance of the evaporators was suspected to be affected by oil contamination. The evaporator at one of the chambers was being supplied through a hand expansion valve set to the full open position, leading to a condition where liquid ammonia had flooded the evaporator and associated piping. Troubleshooting of the evaporator performance included isolating the component between valves, without pumping down the liquid ammonia. The isolation of liquid ammonia caused an overpressure condition to rapidly develop, rupturing the evaporator at a location of high stress and a manufacturing defect.

Facts and evidence	**Compressor Oil Migration and Maintenance**
	• Owner/Operator stated that compressor output temperature/pressure setting was increased shortly after commissioning in 2015 to improve oil separation. Oil migration into the system was communicated to be problematic and causing upsets such as liquid ammonia pump contamination and overload tripping.
	• Owner/Operator stated that compressor output temperature/pressure setting was reduced a few months prior to the incident to save energy.
	• Maintenance log shows the following:
	    ○ Weekly LPR oil pot drainage task – typically removes 10 litres oil
	    ○ Oct 11 – 12 litres oil removed from LPR oil pot
	    ○ Oct 12 – 38 litres of oil drained from chamber D evaporators and associated piping (located adjacent to failed chamber C)
	    ○ Oct 18 – 20 litres oil removed from LPR oil pot with the following note added: *THIS AMOUNT IS MUCH MORE THAN PREVIOUS WEEKS

- The following volumes of oil were removed from the chambers following the incident:
  - Chamber A: 15 litres
  - Chamber B: 10 litres
  - Chamber C (contains failed evaporator): 20 litres
  - Chamber D: 1-2 litres (in addition to the 38 litres drained on Oct 12)
- Owner/Operator stated that they did not believe the evaporators had been drained of oil since entering service and were not aware that 38 litres was reported drained by an employee from chamber D on October 12.
- Owner/Operator stated that they were not aware of changes to the amount of oil drained by employees from the oil pot on October 11 and 18 or the recorded notes in the maintenance logs.
- Refrigeration mechanic stated that he did not consult maintenance or operator logs and had not been informed of changes to the oil removal volumes or the volume of oil removed from the adjacent chamber D on October 12.
- Refrigeration mechanic stated that he normally only interacted with facility managers and did not interact with the chief engineer or employed power engineers.
- Owner/Operator stated that there was no designated chief engineer during the months leading up to the incident however there are a number of 4th class power engineers assigned to maintenance and operations.
- Owner/Operator stated that the mechanic arrived on site at approximately 9:20pm to drain oil from the ammonia pumps and restore system operation.

Conclusion 1:
Evidence existed that an increase in compressor oil migration was occurring. There was no evidence that changes were made or being planned to the maintenance program, to correct the problem or prevent the effects of increased oil migration.

Valve Settings and Manipulations

Troubleshooting and pre-rupture

- The refrigeration mechanic stated that the hand expansion valves had been set at approximately 3.5 turns in the open position during commissioning as instructed by the design engineer.
- Refrigeration mechanic stated he closed one hand expansion valve to the chamber C cold trap to confirm an upstream pressure increase and liquid flow into the cold trap.
- Refrigeration mechanic stated he recalled that the hand expansion valves were in the 'wide open' position and required an estimated 10 turns to close.
- Refrigeration mechanic stated that he returned the hand expansion valve to the found operating position of 'wide open'.
- Refrigeration mechanic stated that management asked to drain oil from the cold traps but mechanic explained that it was not possible because of the vacuum condition and liquid ammonia present in the cold trap.
- Refrigeration mechanic stated that at the request of management, an attempt was made to temporarily increase the pressure within the evaporator with the use of the suction valve.
- Refrigeration mechanic stated both hand expansion valves were closed followed by closing the suction valve to achieve the pressure increase. It is estimated that approximately five to eight minutes elapsed between the closing of these valves, which occurred at approximately 1:30am on October 24, 2018.

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- Refrigeration mechanic stated that both hand expansion valves feeding the chamber C cold trap were in the 'wide open' position prior to their closing.
- Owner/Operator and refrigeration mechanic stated that two of the three chambers were reported to be slow returning to operating performance following the removal of oil and servicing of the ammonia pumps. The subsequent actions associated with manipulating hand expansion and suction valve of chamber C were in response to suspected oil contamination of the evaporators from this inhibited performance.
- Owner/Operator and refrigeration mechanic reported that chamber C troubleshooting during mid-cycle operation was motivated by an interest in saving the batch of product that had remained in the chamber throughout the pump maintenance procedure.

Post-rupture

- Refrigeration mechanic stated that the suction valve was immediately re-opened following rupture in an attempt to pump out any remaining ammonia from the cold trap.
- Refrigeration mechanic stated the liquid supply valve was closed and the hand expansion valves re-opened. The refrigeration mechanic did not recall the order of these two operations. It is possible that additional liquid ammonia was supplied into the failed cold trap.
- The suction valve was re-closed approximately 20-30 minutes following the rupture upon recognition that the vacuum in the chamber was at a lower pressure, pulling additional ammonia vapour into the chamber from the system.

Conclusion 2:
Suspected oil contamination of the evaporators motivated system performance troubleshooting efforts during operation.

Conclusion 3:
The system was being operated with hand expansion valves fully open, contrary to design specifications which resulted in the evaporator becoming flooded with ammonia and left no room for expansion.

Conclusion 4:
It is likely that additional ammonia trapped between the liquid feed valve and suction valve was released into the chamber during the time the suction valve was re-opened and during the re-opening of the hand expansion valves.

Standard Operating Procedures (SOPs)

- There were no SOPs identified specific to the procedure being attempted to move or dislodge suspected trapped oil within evaporators during operation.
- A SOP existed for removal of oil from the evaporator titled "Cold Trap Oil Drain SOP"
- Managers who were supervising the refrigeration mechanic stated they were unaware of the existence and content of the SOPs prior to the incident.
- The SOP for the removal of oil, while not applicable to the procedure being attempted, contained relevant information about the potential hazards:
    - provides instructions to pump down the system prior to closing the suction valve
    - provides the following statements: *Potential HAZARDS: Improper operation could cause severe damage to cold trap and piping due to excessive pressure built up inside cold trap and associated system components.*

- The refrigeration mechanic stated he was not made aware of or provided any training relative to the SOPs and had never performed the cold trap oil drain task.
- Owner/Operator stated they deferred to the guidance of the refrigeration mechanic given their qualification and familiarity with the system.

Conclusion 5:
There was no designated chief engineer for the facility at the time of the failure and there was no effective chief engineering function at the facility. One important function of the chief engineer is to facilitate the work of onsite contractors and the knowledge of developing maintenance issues. Knowledge of site or system specific hazards, such as those contained in facility SOPs, may be considered during troubleshooting.

System Design and Assessment

- No automatic over-pressure protection was provided for the evaporators. The Mechanical Refrigeration Code CSA B52-13 requires over-pressure protection in certain circumstances. The two most relevant circumstances relate to maintenance, where unspecified controls are required (7.2.4.3) or evaporators where a heat source is in close proximity (7.3.2.1).
- It was reported that designers may consider awareness and training of maintenance personnel as a means of control to prevent hydrostatic over-pressure, in compliance to 7.2.4.3 of CSA B52-13.
- The system designer stated that no pressure relief was provided because the potential heat sources did not meet the requirements in CSA B52-13 7.3.2.1 for pressure relief.
- No lock-outs or other preventative methods were in use to prevent the adjustment of hand expansion valves following commissioning.
- No maintenance signs were posted near the hand expansion valves or the suction valve to provide caution to employees or contractors concerning the trapping of liquid ammonia although warning of potential evaporator failure were included in the oil drainage SOP.
- Assessment of the system included in Appendix A, *AFD Canature Investigation by Cold Dynamics Ltd.* concludes:
  - If operated at design conditions, isolating the evaporators as occurred prior to the incident should not have produced a concerning liquid expansion scenario.
  - Risk factors including operating with the hand expansion valves wide open led to a flooded condition between the two sets of valves.
  - The flooded condition could have resulted in a rapid and substantial pressure rise, reaching pressures in the order of 10,000 psi.
- The amount of liquid that could have been contained between the liquid feed valve and the suction valve was approximately 485 lbs.
- The amount of ammonia added to the system following the event was reported to be 1,000 lbs. The amount of ammonia in the system prior to the event was not known.
- An estimated 2,500 litres of solution (ammonia and water) was observed via frost lines on the chamber following the release.

Conclusion 6:
There was a reliance upon maintenance awareness and contractor qualification for over-pressure protection. Signage or lock-outs, while not typical for the refrigeration industry, were not used to warn of or prevent opening the hand expansion valves or provide pump down caution prior to closing the suction valve.

	Conclusion 7: Closing the hand expansion and suction valves when the system is operating as designed and commissioned would likely have not resulted in the incident. Conclusion 8: The amount of ammonia released during the event was between 485 and 1,500 lbs. See Appendix A for analysis. **Gauge examination and testing** An examination of the failed pressure gauge (Photo 3) and testing of an exemplar gauge is documented in Appendix B, *Cold Trap Failure Analysis by Acuren Group Inc.*, and concludes: • Failure of the pressure gauge was due to a rapid pressure increase. • The failed pressure gauge was subjected to pressure in excess of 700 psi. **Heat exchanger (cold trap) examination and testing** An examination and testing of the failed evaporator (Photos 1 and 2) is documented in Appendix B, *Cold Trap Failure Analysis by Acuren Group Inc.*, and concludes: • Failure is due to overload that led to bulging and ductile tearing of the cold trap header attachment welds. • Failure occurred in an area of the evaporator plate structure that was an area of high stress and also weakened due to drilling defects. • Pressure required to produce the material failure was 10,000 psi. Conclusion 9: The evaporator material failure was due to structural overload, consistent with an over-pressure condition. Conclusion 10: The system pressure rise was rapid and may have reached 10,000 psi.
Causes and contributing factors	Rupture of the evaporator and release of ammonia was caused by an overpressure condition. The overpressure condition developed as a result of trapping an excessive volume of liquid ammonia between valves. The overpressure condition was a result of the following factors: - Failure to effectively mitigate oil migration, respond to changes in oil migration and remove migrated oil from the refrigeration system led to the unusual actions to attempt to bring the system back to normal performance. - Operation of the system with the hand expansion valve fully open caused the system to be fully flooded between the hand expansion valves and suction valves. - Closing the suction valve without pumping down the liquid ammonia level from the evaporator increased the risk hydrostatic expansion. - No effective chief engineer to oversee maintenance trends, system performance, troubleshooting and adherence to procedures by contractors caused oil migration conditions to not be understood by management. - Lack of methods to promote awareness or prevention of a hydrostatic over-pressure condition led to no consideration of the consequences to the system of manipulating the hand expansion valves or the suction valve beyond normal operating conditions.

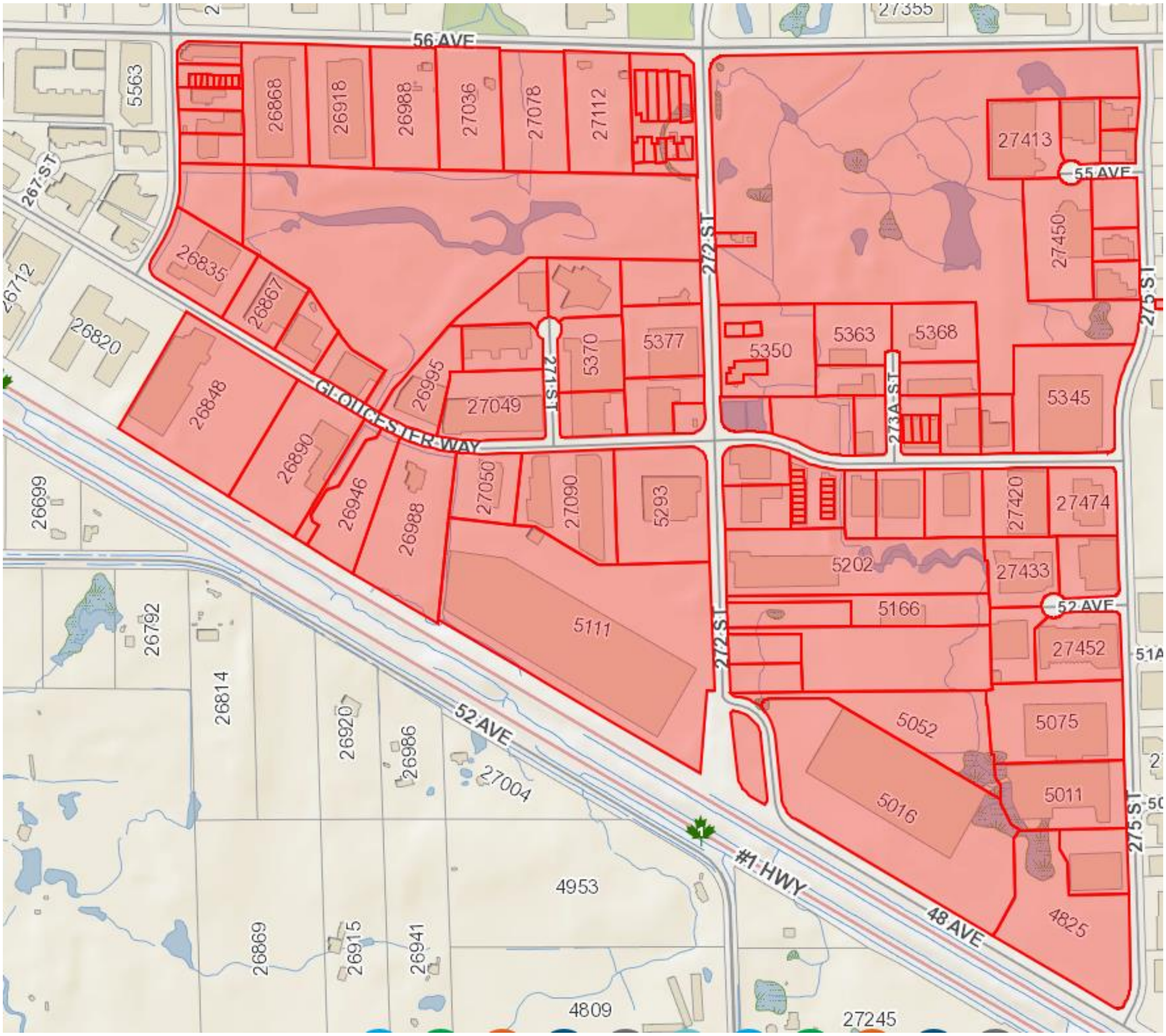

Diagram 1: Evacuation area enforced and [communicated by the Township of Langley](#) while responding to the ammonia release. Affected area is industrial and the evacuation was enforced for approximately 48 hours from October 24th through October 26.

Photo 1: Heat exchanger plate showing bulge deformation on both sides of the plate.

Photo 2: Failed weld on heat exchanger plate at location of bulge deformation. Similar weld failure on opposite side of plate.

Photo 3: Broken ammonia pressure gauge – needle is broken at location of stopper pin and internal calibration mechanism shows deformation or offset.

Photo 4: Freeze drying chambers at processing facility. Labels visible on chambers A and B while access door is opened on chamber C.

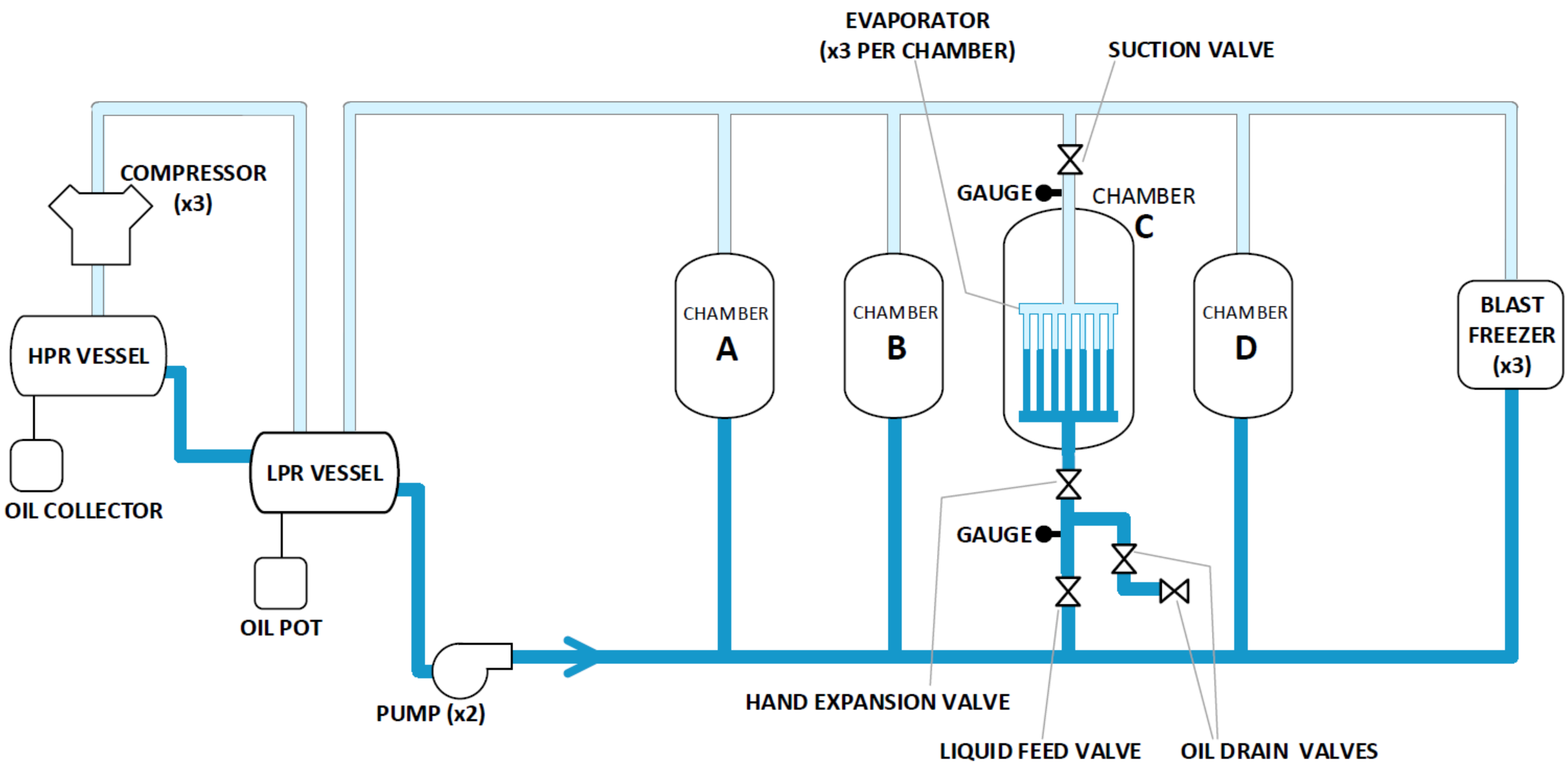

Diagram 2: Simplified refrigeration system schematic

Appendix A:

AFD Canature Investigation

Cold Dynamics

1212-FR01.0

COLD DYNAMICS

TECHNICAL SAFETY BC

AFD Canature Investigation

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February 20, 2019

PROFESSIONAL PROVINCE OF G. SCRIVENER # 42741 BRITISH COLUMBIA ENGINEER

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Executive Summary

On October 24, 2018, an ammonia release occurred at the AFD Canature facility in Langley, BC. The release was the result of a ruptured plate evaporator in a freeze dryer cold trap. The purpose of this report is to provide an estimate of the quantity of ammonia released and identify and analyze potential failure mechanics that allowed for the overpressure condition in the evaporator.

During normal operation at the reported design conditions, the cold trap, which is made up of two evaporator sections, and the associated piping would have contained approximately 92 lb (42 kg) of ammonia.

The refrigeration system was not functioning correctly prior to the failure. A technician was attempting to raise the pressure in the evaporator by manipulating the hand expansion valves and a suction isolation valve. A combination of factors, including very low load conditions; hand expansion valve setting; vertical riser piping; and oil contamination, likely contributed to a situation where the evaporator was completely filled with liquid. Completely full, the isolated section would hold approximately 465 lb (211 kg) of ammonia.

Based on the evidence available, the expansion of trapped liquid is the only failure mode that could have achieved the 10,060 psi (69,361 kPa) pressure that caused the rupture. When the cold trap evaporators were isolated, they were likely full of liquid ammonia.

Considering the evaporators were likely full of liquid, the temperature and pressure would have been higher than the refrigeration system operating pressure causing improper operation and lower than normal heat transfer. Because the evaporators operate in an ambient vacuum, they have essentially no convective heat transfer; their load is dependent mainly on the temperature difference between the refrigerant and the product, which causes the sublimation of ice from the product to collect on the cold traps. By isolating the liquid supply to the evaporators, the temperature and pressure would have decreased to a pressure close to the refrigeration system operating pressures. This change would have increased the load on the evaporators because of the increased temperature difference between the cold trap and the product. If the suction valve was closed during or immediately following this transient pressure and temperature change, the result would be approximately 96% liquid by volume trapped between the valves. This is a sufficient quantity of liquid to cause the pressure rise witnessed in the cold trap.

It is not possible to determine the amount of ammonia that was released with accuracy. A minimum of 485 lb (220 kg) was released. Approximately 1000 lb (454 kg) was added to the system following the release, however, the ammonia inventory prior to the release is unknown. During the event, the ammonia combined with water/ice in the chamber that resulted in approximately 650 USG (2460 L) of solution in the freeze dryer. It is not likely that all of this solution was ammonia as there was reportedly a significant quantity of ice present in the chamber. Based on the information available, the quantity of ammonia that was released was likely between 485 lb (220 kg) and 1500 lb (680 kg).

Scope of Work

The scope of work for this project was to provide advice to Technical Safety BC during the investigation of an ammonia refrigerant leak that occurred at AFD Canature on October 24, 2018. In addition to support throughout the investigation, a report was requested to address the following:

1) Provide an estimate of the quantity of ammonia released.
2) Identify and analyze potential failure mechanics that allowed for the overpressure condition in the refrigeration evaporator.

Description of Refrigeration System and Piping

On October 24, 2018 an ammonia release occurred at the AFD Canature facility in Langley, BC. The release was the result of a ruptured plate evaporator in Freeze Dry Chamber C. The rupture occurred after the evaporator was isolated during service. The ammonia that was released was contained under vacuum in the freeze dryer chamber and was vented to the atmosphere by the freeze dryer vacuum pump.

The refrigeration system at AFD Canature is a liquid overfeed central plant style system that uses ammonia as a refrigerant. This system provides the refrigeration capacity for four freeze dryers and three blast freezers. The freeze dryers each have two cold traps that remove moisture from the chambers during operation. The large cold trap has two evaporator sections and has a capacity of 50 TR (176 kW) at -40°C (-40°F) Saturated Suction Temperature (SST). The smaller cold trap has one evaporator section and has a capacity of 15 TR (53 kW) at -40°C SST. The evaporators were reportedly commissioned to operate at an overfeed rate of 4:1 when operating at design conditions; the evaporators are bottom fed with the liquid connections on the bottom and suction connections on the top.

The documented ammonia charge of the system is 9500 lb (4309 kg). This was not verified by measurement or calculation.

The liquid valve train, except for the hand expansion valve, is at an elevation of approximately 14 ft (4.3 m) above the floor. Separate 1-1/4” hand expansion valves and oil drain valves are installed at the floor level for each evaporator section of the large cold trap. There is a single suction isolation valve for both evaporators on the branch suction piping at an elevation of approximately 19 ft (5.8 m) above the floor. Figure 1 shows the as-built piping arrangement.

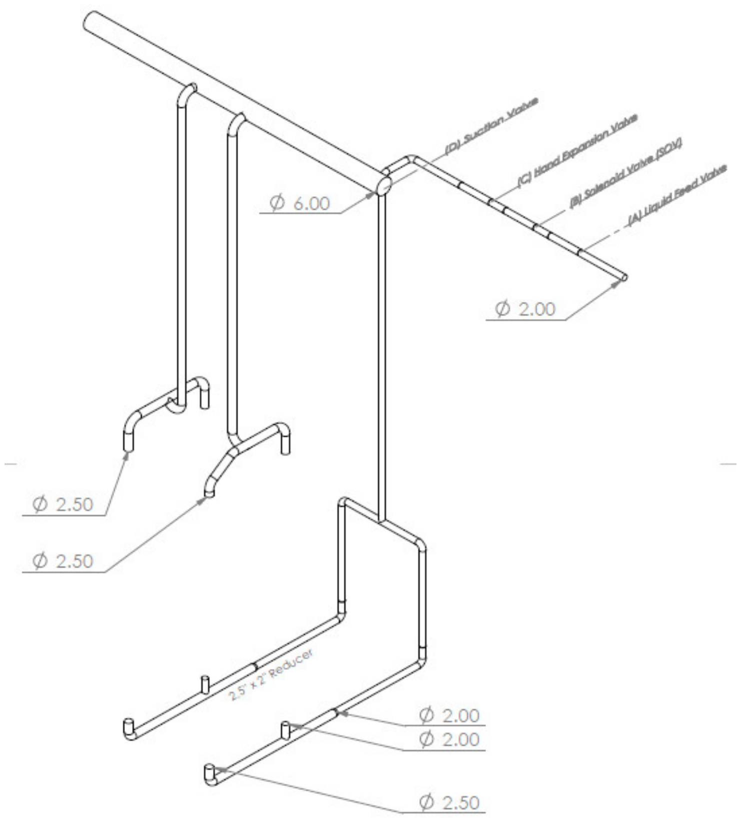

Figure 1: As built wet suction risers prior to being insulated.

Analysis – Refrigerant Quantity in Large Cold Trap

The calculation of the quantity of ammonia present in the evaporator during normal operation and at the time of failure is important in order to analyze the failure and attempt to determine the amount of ammonia that was released following the evaporator failure.

In normal operation, liquid overfed evaporators have a mass flow that is greater than the mass of refrigerant that is evaporated to provide the necessary refrigeration. The effect of having this extra liquid is an increase in heat transfer. These types of liquid overfeed systems are currently one of the most common system types used in industrial refrigeration. The evaporators are designed for a particular overfeed ratio that typically ranges from 1.5:1 to 4:1, although other ratios are used in certain applications. A liquid overfeed ratio is defined as the ratio between the mass of ammonia that is pumped into the evaporator and the mass of ammonia that evaporates.[1]

[1] An alternate definition is occasionally used where the overfeed rate is the ratio of liquid mass flow to vapour mass flow.

To calculate the quantity of ammonia in a liquid overfeed evaporator, it is necessary to determine the average density of the refrigerant in that evaporator. For AFD Canature, this was done using the density of -40°F (-40°C) saturated liquid ammonia at the evaporator entrance and the density of the mixture at the evaporator outlet, based on the quality of the mixture as determined by the overfeed ratio. It is necessary to apply an empirical constant to determine the effective average density in the evaporator (Industrial Refrigeration Consortium, 2004). The maximum refrigerant quantity in the evaporator was determined by assuming the evaporator was completely full of liquid.

The suction line is typically a mixture of liquid and vapour. To determine the approximate ammonia quantity during normal operation, the density of the refrigerant in the suction line was assumed to be the same as the density at the evaporator outlet. The maximum refrigerant quantity was calculated assuming the suction line was full of liquid.

All of the calculations were done assuming an overfeed rate of 4:1. However, these results are not very sensitive to changes in the overfeed ratio within a typical operating range. For example, doubling the overfeed ratio results in an ammonia quantity increase of less than 2%.

Item	Volume [ft^3 (L)]	Normal Refrigerant Quantity [lb (kg)]	Maximum Refrigerant Quantity [lb (kg)]
Cold trap evaporators (including piping from hand expansion valve)	8.5 (240)	92 (42)	366 (166)
Suction line from cold trap to isolation valve	2.3 (66)	0.36 (0.16)	99 (45)
Total Isolated	**10.8/306**	**92/42**	**465/211**

In normal operation, the volume of liquid refrigerant in the isolated section would be approximately 20% of the total volume. Note that the volume ratio does not correspond to the mass ratio. In this case, 20% liquid volume is more than 99.5% liquid mass.

Summary of Findings:

1) **When operating at design conditions, the evaporator and piping that were isolated would have contained approximately 92 lb (42 kg) of ammonia, which results in approximately 20% of the volume.**
2) **Completely full of liquid, the evaporator and piping that were isolated would have contained 465 lb (211 kg) of ammonia.**

Analysis – Mechanisms of Failure

Lab testing directed by Technical Safety BC concluded, based on the material strength, that a pressure of approximately 10,060 psig (69,361 kPag) occurred in the failed evaporator plate. There are three situations that could have caused the ammonia to reach this abnormally high pressure: a large energy input, hydraulic shock, and liquid expansion.

It is possible that with a high enough initial density, the simple addition of large amounts of energy could have caused the pressure to increase to 10,000 psi with the ammonia remaining a vapour or supercritical fluid. However, for this scenario to occur, the vapour/liquid mixture would have had to be in a specific range of initial conditions, be subject to temperatures of at least 300°F (150°C) and have a significant amount of energy transfer. Because there was no evidence or reason to believe that high temperatures were present in this situation, this scenario was not considered further.

Hydraulic shock occurs when transient pressure differences propel a slug of liquid refrigerant at a high velocity through piping. A very large transient pressure spike can occur at the location where this liquid impacts the piping at a header, elbow, valve or other obstruction. These types of failures are typically associated with cracked piping and welds and they most frequently involve a scenario where hot/warm ammonia vapour is present with colder liquid. The subject evaporator did not use hot gas defrost and the failure mode does not appear consistent with hydraulic shock. The location of the failure does not have geometry that is susceptible to travelling ammonia liquid slugs and the lab analysis of the failure indicated a uniform pressure on both sides of the ruptured plate evaporator. No evidence was available to suggest hydraulic shock occurred and no further analysis was completed.

Liquid expansion, sometimes called hydraulic lock-up, occurs when energy is added to trapped liquid. Because liquid is not compressible, a rapid pressure increase can occur with a small amount of energy input. Figure 2 shows how this increase would progress with several different liquid/vapour volume ratios based on the typical operating conditions and volume of the isolated components at AFD Canature. The amount of energy used to create the pressure rise shown in Figure 2 is equivalent to the cold trap operating at design conditions for 3.5 minutes.

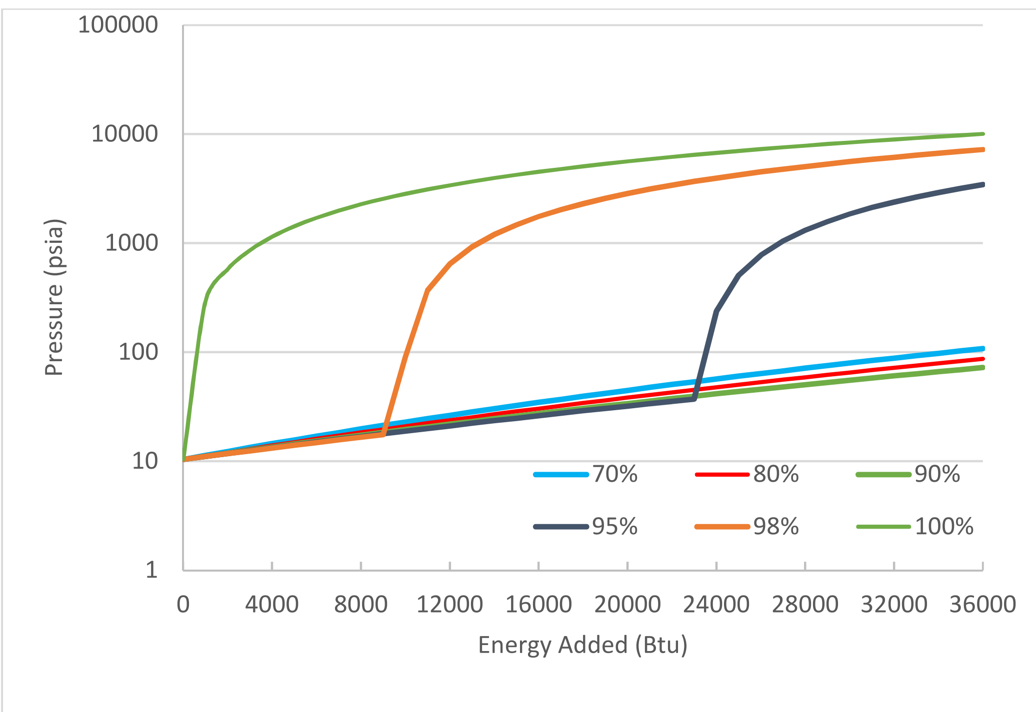

Figure 2: Pressure rise for trapped refrigerant with varying liquid volume quantities (70% to 100% liquid by volume)

At AFD Canature, the cold trap was isolated by closing the hand expansion valves first, followed by the suction isolation valve several minutes later. If the evaporator was operating at design conditions, this isolation procedure should not have resulted in a situation where the expansion of liquid would be a concern because there would not have been sufficient liquid present in the evaporator and piping. Additionally, it would be expected that having the evaporator open to the suction piping for several minutes would have allowed some liquid to evaporate, reducing the liquid quantity further.

There are several risk factors that were present during this incident that likely increased the amount of liquid in the evaporator and associated piping:

- The hand expansion valve was 100% open.
- The vertical suction riser piping is trapped.
- The load on the evaporator was likely significantly below design conditions
- Oil had accumulated in the evaporator.

While the exact effect each of these factors on the liquid level during this incident in unknown, a combination of these interrelated factors and a possible system upset condition allowed the evaporator and piping to be almost completely filled with liquid ammonia.

In a liquid overfeed system, the refrigerant vapour velocity in the suction riser is used to move liquid vertically upwards. Figure 3 shows several different flow regimes that can occur in two-phase vertical flow. A complete discussion of two-phase vertical flow is outside the scope of this analysis; however, it is important to note that as the velocity of the refrigerant vapour increases, there is a point at which flow can be achieved with a minimum pressure drop. It is generally desired to be in an annular flow regime, which is shown on the right side of Figure 3. If liquid is allowed to 'stack', as is shown on the left of the flow regimes in Figure 3, the pressure drop can increase dramatically due to the weight of the liquid refrigerant. Traps in the vertical suction piping add pressure drop and can contribute to the accumulation of unnecessary liquid.

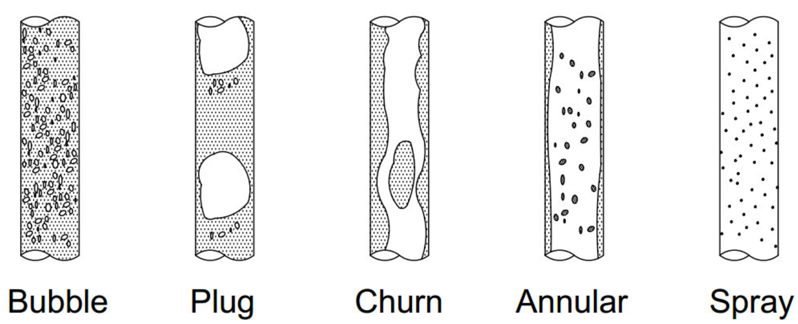

Figure 3: Flow Regimes in vertical suction risers

The increased pressure drop causes two unfavorable conditions. First, the temperature in the evaporator is dependent on the pressure; increasing the pressure in the cold trap evaporator by stacking liquid in the suction riser will cause an increase in the temperature. The second detrimental effect is that because of the increased evaporator pressure, the liquid enters the evaporator subcooled instead of at a saturated condition. This happens because the liquid is cooled in the recirculation vessel to the design condition of -40°F (-40°C) and is pumped at an increased pressure to the evaporator. For example, in the case that the evaporator is operating at -30°F (-34°C), the refrigerant is entering the evaporator with 10°F (5.6°C) of subcooling. The subcooling decreases the effectiveness of the evaporator because no vapour is formed until the refrigerant is warmed to the saturation temperature; the refrigerant vapour is necessary to create the proper flow velocities and turbulence in the evaporator. This effect on the evaporator is often referred to as 'brining'.

In systems that have a widely varying load, it is very difficult to avoid liquid stacking at all times. Figure 4 shows the approximate vapour velocity in the suction riser at different load conditions. At low load conditions, there will not be enough vapour velocity to move the liquid up the riser effectively. Freeze dryer cold traps are uniquely at risk of low load conditions because they operate in an ambient vacuum which eliminates almost all heat transfer by convection. Effectively, the cold trap is limited to radiation and conduction to absorb energy. The energy input from radiation comes from the surrounding chamber. Heat transfer by conduction occurs between the cold trap and the ice. There is an energy input when water vapour deposes (changes from a gas directly to solid ice) on the surface. Collecting the water vapour is the purpose of the cold trap and constitutes the majority of the heat input since the radiation load on the white surface is likely low in comparison. The amount of water that is collected on the cold trap is proportional to the difference in the vapour pressure between the product and the cold trap. This means that in order for water to collect, there needs to be a temperature difference between the product and the cold trap, and the chamber must be in a low enough vacuum to facilitate the sublimation of ice out of the product.

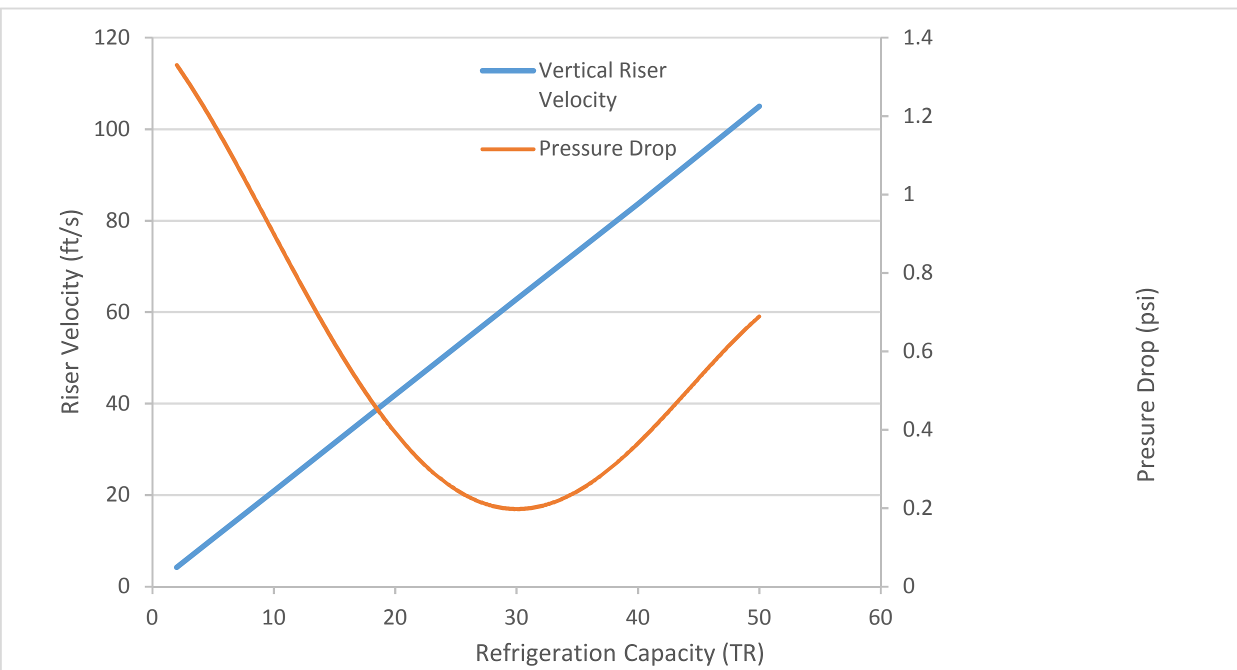

Figure 4: The approximate velocity and corresponding pressure drop in the 2.5" suction riser for several refrigeration capacities. Data was used from the VPS 2010 Software was used to create this chart (IIAR, 2010).

Figure 4 also shows that a high pressure drop would have occurred in periods of high load. Sizing vertical wet suction risers is a challenge and there is always a balance between pressure drop at design conditions and liquid stacking effects at low loads.

Evaporators in ammonia refrigeration systems often suffer from oil contamination because of the high viscosity of oil at low temperatures and the immiscibility of the oil with the refrigerant. Oil contamination causes a decrease in evaporator capacity by reducing heat transfer. The cold trap evaporators at AFD Canature were reportedly suffering from some level of oil contamination. Approximately 5 USG (20 L) of oil was removed from the cold trap with the failed evaporator following the incident. This accounts for approximately 10% of the evaporator volume. As much as 10 USG (39 L) of oil was removed from a neighbouring chamber prior to the incident. There was evidence presented that the refrigeration system at AFD Canature has a higher than normal oil carryover from the compressors and that oil management practices are not adequate.

Hand expansion valves are used to control the flow of refrigerant into an evaporator; they are set up to provide the desired recirculation rate at a pressure difference that is determined by the refrigerant pump and bypass control selection. Hand expansion valves are normally adjusted once during the commissioning period and are not adjusted unless operational problems arise. The valves at AFD Canature should have been open approximately 1.1 turns out of 6 based on the reported pump pressure and evaporator capacity. With the valve completely open, a significant increase in mass flow through the evaporator occurs and may have resulted in an overfeed rate of more than 50:1 when operating at design conditions and significantly higher than that at low loads.

Summary of Findings:

1) **The rupture of the evaporator was caused by an overpressure situation that was most likely the result of trapped liquid (hydraulic lock-up).**
2) **The overpressure of the evaporator would not likely have occurred if the cold trap evaporators were operating at design conditions and the isolation valves were closed**
3) **Several risk factors were present at AFD Canature that likely contributed to an excess of ammonia liquid in the evaporator prior to isolation.**
    a. **Low load conditions**
    b. **Oil contamination of the cold trap evaporators**
    c. **The hand expansion valve position**

Analysis – Failure Scenario Summary

Prior to the evaporator failure, the owner had reported a high evaporator temperature. The rest of the refrigeration system had been brought back into service following an earlier shut-down due to oil logging in the refrigerant circulation pumps, however the chamber in question had not recovered and was operating at an elevated temperature. There is not enough information available to determine the initial cause of the decreased performance but is was likely that a combination of low load, oil contamination, and an improperly set hand expansion valve contributed to a circumstance that allowed the evaporator to become almost completely full of liquid refrigerant. It is also possible that an upset condition in the system, such as a temporary increase in suction pressure, contributed to additional liquid in the evaporator.

If significant liquid stacking was occurring, the temperature in the evaporator could have been as high as -22°F (-30°C), assuming a recirculatory vessel temperature of -40°F (-40°C). This would have caused a very low heat load on the evaporator because of a decrease in the vapour pressure difference between the cold trap and the product. Not enough information is known about the product or the heat input that was occurring at the time of the incident to perform accurate calculations, however it is possible that almost no water was freezing to the cold trap immediately before the incident. This issue would be further exacerbated if the refrigeration system was operating warmer than -40°F (-40°C); it appears that this was regularly the case.

In an effort to get the refrigerant moving, the refrigeration mechanic closed the hand expansion valves and then the suction isolation valve several minutes later. Evidence indicates that there may have been as much as 8 minutes between closing the hand expansion valves and the suction isolation valves, but the timing is not certain. Once the hand expansion valves were closed, the evaporator would have transitioned from having pumped refrigerant flowing to a flooded situation where mainly vapour would be moving up the vertical suction riser. Since the liquid flow through the vertical suction riser stopped or was greatly reduced, the pressure drop would have decreased. This decrease in the pressure drop would have, in turn, caused some of the ammonia in the evaporator to evaporate and cool the remaining liquid to a saturation temperature of -40°F (-40°C). When this occurred, the lower temperature would have increased the load on the evaporator because of both the new vapour pressure difference between the evaporator surface and the product, and the temperature of any ice that had already accumulated. If the suction valve was closed prior to the completion of this transient effect or immediately after, then a significant amount of liquid ammonia could have remained in the evaporator. If the evaporator and piping were full of liquid when the transient move to a lower pressure and temperature began, then approximately 96% liquid by volume would have remained when the refrigerant reached the new lower pressure and temperature.

Summary of Findings:

1) **Closing the hand expansion valves likely caused a decrease in the ammonia temperature and pressure in the cold trap evaporator. This decrease in temperature would have caused an increase in the heat load applied to the evaporator.**
2) **There was not enough time for the liquid ammonia to transition to the lower pressure and evaporate out of the cold trap in any significant way between the closing of the hand expansion valves and the closing of the suction isolation valve. Approximately 96% liquid by volume may have remained in the isolated components.**

Quantity of Ammonia Released

The release occurred when the suction and liquid isolation valves were closed. Assuming that the evaporators and piping were completely full of liquid, this would have limited the resulting release to approximately 465 lb (211 kg) of ammonia.

In response to the incident, the suction isolation valve was opened in an attempt to reduce the pressure and remove refrigerant. Because the freeze dryer was operating in a vacuum lower than the pressure in the ammonia suction line, this action introduced more ammonia into the freeze dryer. Additionally, the liquid isolation valve was closed, and the hand expansion valves were open. There is uncertainty in the order this manipulation occurred, and this action would have introduced at least 20 lb (9.1 kg) of additional ammonia into the freeze dryer.

The freeze dryer contained the ammonia and exhausted it through the vacuum pump exhaust. Evidence of the liquid level can be seen in Figure 5 by the frost line on both sides of the freeze dryer. There is a barrier/dam in the freeze dryer vessel that separates the cold trap area so that it can be sprayed with water in a defrost. The liquid level was scaled using the pictures and matches the height of the dam in the cold trap area. The liquid level on the product side of the freeze dryer appears to be significantly lower, which is consistent with flow over the barrier.

Figure 5: Ammonia frost line in the freeze dryer after the release.

The suction isolation valve was left open for approximately half an hour. The system operating characteristics during this time are not known, however it is likely there was not a large pressure difference between the suction piping and the freeze dryer. The reported pressure of the freeze dryer was 1370 Pa (10,275 microns). However, this is below the triple point of ammonia which would have resulted in the formation of solid ammonia which would not have had the flow characteristics shown in Figure 5.

The approximate volume of the liquid shown in Figure 5 is 650 USG (2460 L); approximately 3860 lb (2412 kg) of ammonia would be required to achieve this liquid level. Since the cold trap would have contained 465 lb (211 kg) when it was isolated and the liquid piping would have only added additional 20 lb (9.1 kg) of refrigerant to the release, it seems likely that a significant portion of the solution in the freeze dryer was water that melted off of the evaporators following the release. Depending on the exact timing of the failure during the freeze dryer cycle, it is possible that approximately 35% of the solution was ammonia which would result in an ammonia release of approximately 1500 lb (680 kg). A system upset or other unreported condition in which liquid was able to leak into the evaporator are a possibility, but no evidence was found to indicate that these events occurred. Without additional information, it is not possible to refine these calculations.

Following the incident, approximately 1000 lb (454 kg) of ammonia was added to the system. Depending on the initial ammonia charge, this amount is consistent with a release of 485 lb (211 kg) to 1500 lb (680 kg).

Summary of Findings:

1) **At least 485 lb (220 kg) of ammonia was released based on the volume that was isolated when the failure occurred and the manipulation of the liquid isolation valve and had expansion valve following the release.**
2) **Based on a 35% ammonia solution, the apparent freeze dryer liquid level contained approximately 1500 lb (680 kg)**
3) **Although unlikely based on the available evidence, it is possible that a condition existed following the initial failure that allowed 3860 lb (2412 kg) of ammonia into the freeze dryer.**

Completion Notes

This report and analysis were completed by:

PROFESSIONAL
PROVINCE OF
G. SCRIVENER
42741
BRITISH COLUMBIA
ENGINEER

Greg Scrivener, P.Eng.
20 February 2019

References

IIAR. (2010). Advanced Riser Design VPS 10.

Industrial Refrigeration Consortium. (2004). *IRC TechNote - Refrigerant Inventory Determination.* Madison: University of Wisconsin.

Disclaimer of Liability

The material in this report reflects our professional opinion based on information made available to us, visual observations of accessible systems and equipment and building owner comments. No physical testing of systems or equipment was conducted, and the ammonia charge was not measured directly. Cold Dynamics Ltd. accepts no responsibility for damages suffered by any third party resulting from decisions made or actions based on this report. Republication of materials in this report requires the permission of Cold Dynamics Ltd. and Technical Safety BC.

Revision Log

Revision Number	Date	Description of Changes
0	02/20/2019	Initial Final Report

Appendix B:

Cold Trap Failure Analysis: Canature Processing Ltd, Langley BC

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Phone: 604.275.3800
Fax: 604.274.7235

A Higher Level of Reliability

COLD TRAP FAILURE ANALYSIS;
CANATURE PROCESSING LTD., LANGLEY B.C.

Prepared for:

Technical Safety B.C.
600-2889 East 12th Avenue
Vancouver, B.C.
V6M 4T5

Attention: Mr. Eric Lalli, P.Eng.

File Number: 60514656 – Revision 1
Date: February 26, 2019

Bob Milne, P.Eng.
[redacted]@acuren.com
[redacted]

1.0 EXECUTIVE SUMMARY

The evidence shows that the end plate header at the 2nd row position on the top side of the cold trap unit suffered an overload condition which led to bulging and ductile tearing of the header attachment welds. It is unknown how a large pressure increase occurred at the failure location. However, the evidence indicates that the pressure increase was rapid enough and high enough to cause the pressure gauge needle to fracture upon impacting the needle stop. It is estimated that a pressure increase up to 10,060 psi would be necessary to cause the observed fractures.

2.0 INTRODUCTION

Technical Safety B.C. is conducting an investigation into an ammonia release that occurred at Canature Processing Ltd. on October 24, 2018. The release occurred in a cold trap assembly manufactured by Dalian Binsh Group. The failure was characterised by bulging and rupture of a header plate in the cold trap unit.

Acuren was asked to evaluate the failed cold trap unit and determine the cause of the rupture. In addition to this work, a broken pressure gauge that was connected to the system was submitted for failure analysis.

3.0 INVESTIGATION

The cold trap unit was shipped to the Acuren laboratory facility on 10 November, 2018. The unit was wrapped in clear plastic and was completely dry. No evidence of ammonia was found with the unit.

Laboratory investigations were initiated on 4 December, 2018. The work was completed in the presence of the following interested parties:

Jeff Coleman, P.Eng. – Technical Safety B.C., Director Risk and Safety
Tom Ng, P.Eng. – Technical Safety B.C., Leader Engineering
Eric Lalli, P.Eng. – Technical Safety B.C., Leader Failure Investigations
[redacted] – Black and McDonald
[redacted]. – JS Refrigeration Engineering Inc.
[redacted] – Envista Project Engineer
[redacted] – AFD Facility Manager
[redacted] – AFD Engineer

4.0 SCOPE OF WORK

The failure investigation involved the following scope of work:

- Photographic documentation of cold trap assembly and pressure gauge,
- Radiography of cold trap in area of rupture and adjacent plate,
- Optical emission spectroscopy to determine material types,
- Fractography using scanning electron microscope (SEM) to classify fracture types,
- Metallography in area of cold trap rupture,
- Hardness testing in area of ruptured plates,
- Dismantle damaged gauge to identified failed components
- Pressure test of exemplar identical pressure gauge to try and duplicate failure mode,
- Dismantle exemplar gauge after pressure test and compare with field damaged unit.

5.0 COLD TRAP FAILURE EVALUATION

5.1 Visual and X-ray Examination

Overall views of the cold trap as received at the Richmond facility are shown in Figures 1 and 2. A single bulged and fractured header plate was found at the location marked with an arrow in Figure 1. A closer view of the bulged end plate (2nd plate over from end) is shown in Figure 3. The bulge appears uniformly distributed on both sides of the plate axis. The plate is torn on both sides of the end plate at the toe of the welds and transitioning to the middle of the welds as shown in Figures 4 and 5.

Each plate was checked with a square and level to determine if any bulging occurred in other cold trap plates. No plate distortion was observed at any location away from the bulged end plate on the second row.

The outer edge header was cut out to expose the bulged header plate on the second row of plates (Figure 6). A rectangular piece approximately 12” x 17” was cut from this location. A rectangular piece approximately 10” x 16” surrounding the bulged plate end was cut from the second row as shown in Figure 7. These two plates were sent for X-Ray inspection before any further cutting was done. The x-rays (Figures 8 and 9) did not reveal any blockages. However, the drilled holes in the header appeared off-centre in both x-rayed plate pieces, with the distance between each hole different depending on the depth of the measurement.

The bulged area was sectioned into 3 pieces as shown in Figure 10. The internal surface consisted of drilled holes, extruded channels, and fractured inter-hole material (Figure 11). Where the holes were drilled off-centre, the distance between adjacent holes varied. This had the effect of weakening the header plate in the "bulging" direction. The inter-hole fractures all appeared as ductile tensile failures (Figure 12).

5.2 Mechanical Testing

Samples of the bulged header plate and the attached extruded plate were machined for tensile testing. The results of testing are shown in Appendix B. The bulged header plate had a yield strength of 30,240 psi and a tensile strength of 34,550 psi. The extruded plate had a yield strength of 24,600 psi and a tensile strength of 31,650 psi. Both of these materials meet the minimum strength requirements of aluminum alloy 6063 in the T6 condition.

5.3 Chemical Analyses

Chemical analysis was performed on the bulged end plate and the attached extruded plate. The results of testing are shown in Appendix B. Both pieces meet the chemical requirements of aluminum alloy 6063.

The weld metal was tested for chemistry using energy dispersive x-ray analysis (EDS) and found to contain only magnesium as an alloy addition. The chemistry of the weld metal meets the requirements of alloy 5050.

5.4 Scanning Electron Microscope (SEM) Examination

Samples of the header – extruded plate weld fractures were examined in the SEM. A typical fractured joint near the center of the bulge is shown in Figure 13. The fracture surface shows two distinct zones with different textures. The features from the zone nearest the fluid passage holes is shown at high magnification in Figure 14. This zone contains nearly vertical ductile dimples which indicate a straight tensile overload. The zone toward the outer edge of the weld transitions to a mostly ductile shear condition, with dimples truncated to form horseshoe shapes (Figure 15). The tears on both sides of the bulge contained identical features.

5.5 Metallographic Examination

The fractures occurred along the heat affected zone of the header to extruded plate weld. This is the weakest part of the joint where a pressure overload failure would be expected. Metallographic samples through the heat affected zone of the weld show evidence of grain boundary segregation and secondary cracking on the weld metal side of the joint (Figures 16 and 17). This type of cracking is typical of high strain rate cracking in welded aluminum alloys.

5.6 Discussion of Findings

The evidence shows that the header end plate bulged and suffered ductile tearing in the weld metal and heat affected zone of the weld. The heat affected zone is the weakest area in the 6063 T6 aluminum material due to a loss of strength caused by the heat of welding. The actual strength in the HAZ of the weld is closer to the T0 or T4 condition. The weld metal is always weaker than the 6063 T6 plate material as it does not respond to heat treatment. The header plate was less able to resist bulging due to a loss of material cross section at the inter-hole tendon location caused by mis-drilling of the internal passage holes.

The ductile tearing observed between the drilled passage hole tendons occurred as pressure built in the bulge area, but before the plate weld fractures occurred. The tendon fractures had to have occurred before the plate welds fractured, since the tendon loading would be stopped as soon as the weld fractures occurred and pressure was relieved.

FEA analysis and full-size burst tests completed by the cold trap designers have indicated that the plate headers at the top of the unit are the location where failures would be expected in the case of a pressure overload. These analyses may provide information with respect to the stress condition in the cold trap during an overpressure condition. The evidence indicates that a high pressure was rapidly developed in the cold trap to create the overload condition.

6.0 PRESSURE GUAGE FAILURE EVALUATION

An overall view of the damaged pressure gauge that was attached to the vessel is shown in Figure 18. The pressure gauge contained a fractured needle that indicated it had been impacted on the needle stop (Figure 19). The gauge had received a burst of high pressure that exceeded the capacity of the gauge. The internal components of the gauge were no longer in calibration at the end of the high-pressure event.

6.1 Needle Fracture

The broken needle was removed from the gauge and was found to be fractured in bending as it contacted the stop post. The needle was analysed for chemistry and found to be made from a wrought aluminum alloy. The thickness of the needle was 0.5 mm.

6.2 Internal Components

The internal components of the damaged gauge are shown in Figures 20 and 21. All of the components, including the pressure tube, appear undeformed and intact. The screw adjustments on the operating levers may have moved slightly to destroy the calibration of the gauge.

6.3 Exemplar Gauge Testing

A new identical gauge was loaded with rapidly released compressed air above the 150-psi rated load of the gauge. Gauge loading was performed in 100 psi increments up to 700 psi. Loading was applied by rapidly opening the control valve to a pre-set value. At the 700-psi load point, the exemplar needle did not fracture.

Loss of calibration occurred at approximately 200 psi. The needle would not return to “0” after this pressure was reached and became progressively worse with each incremental rise in pressure. The unit was then loaded to 1000 psi hydraulically. At this pressure, the needle yielded (bent permanently), but could not be made to fracture. The needle was analysed and found to be made from the same aluminum alloy as the fractured needle.

The exemplar unit was dismantled and examined for evidence of deformation or fractures on the internal components. All of the internal components appeared intact.

7.0 CONCLUSIONS

The evidence shows that the end plate header at the 2nd row position on the top side of the unit suffered an overload condition which led to bulging and ductile tearing of the header attachment welds. It is unknown how such a large pressure increase occurred at the failure location. However, the evidence indicates that the pressure increase was rapid enough and high enough to cause the needle on a pressure gauge attached to the unit to fracture upon impacting the needle stop.

Calculations show that the tendon fractures occurred at a relatively low pressure (lower than that required to fracture the plate welds) during the pressure build-up before the plate welds fractured.

The cold trap was constructed from AA6063 T6 aluminum alloy extrusions and plate, and welded using a compatible filler metal such as AA5050. The weld quality was very good and assembly of the cold trap appeared to be accurate. The only quality issue that was observed with the cold trap was off-centre drilling of the passage holes in the plate headers. This would not affect the operation of the cold trap in normal service, but may have weakened the header (less available cross section) in the bulging direction when a pressure overload occurred.

Bob Milne P.Eng.

Note: Unless otherwise instructed, we shall dispose of all parts and test samples sixty days from the date of this report.

APPENDIX A

FIGURES 1 - 21

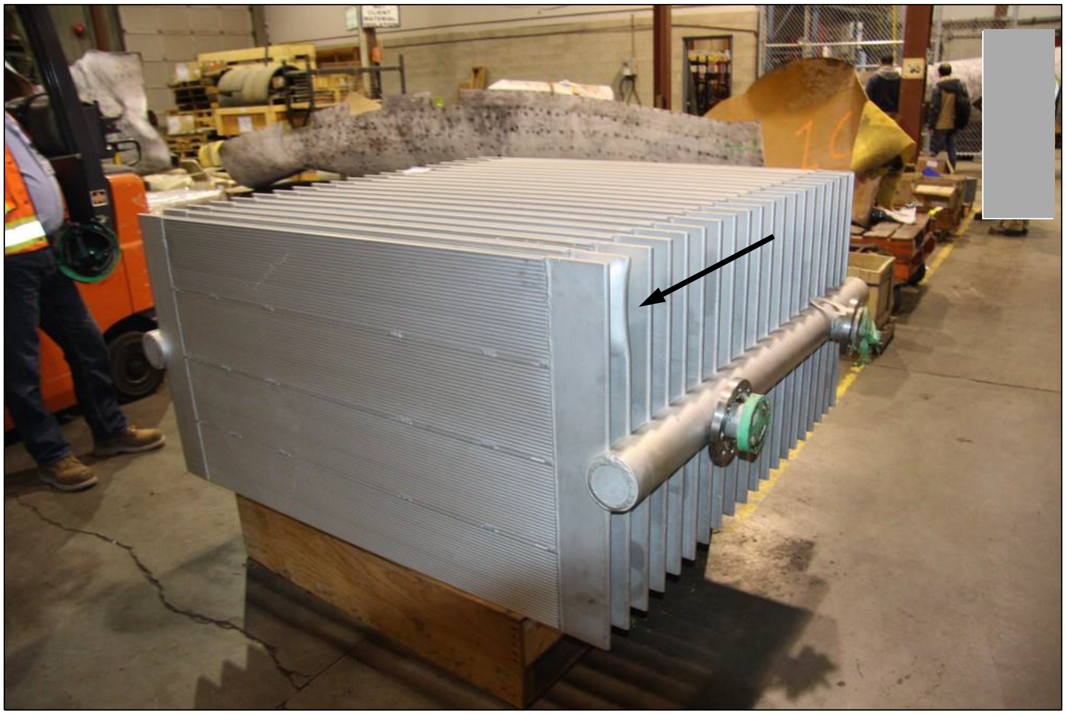

Figure 1 Overall view of cold trap as received at the Acuren facility. Bulged header is shown at the arrow.

Figure 2 Side plates showing no evidence of deformation.

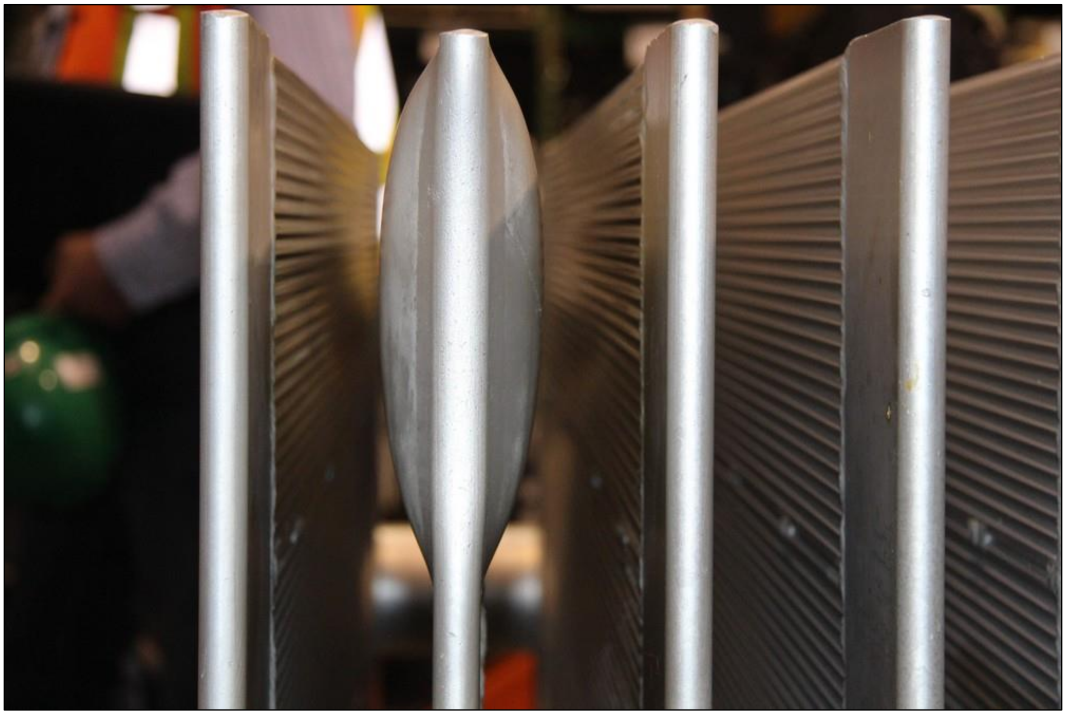

Figure 3 End view of bulge on top of 2nd plate over from side of unit.

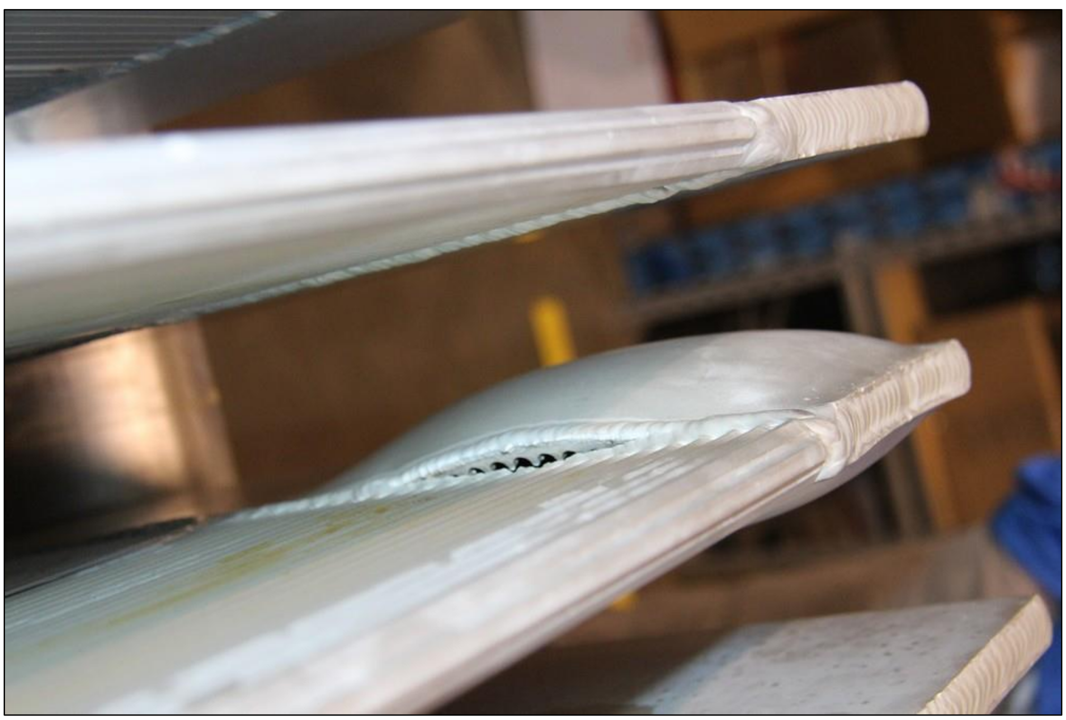

Figure 4 Weld tearing at bottom of bulge. Identical tearing was found on both sides of bulge (see Figure 5).

Figure 5 Weld tearing at bottom of bulge opposite (see Figure 4).

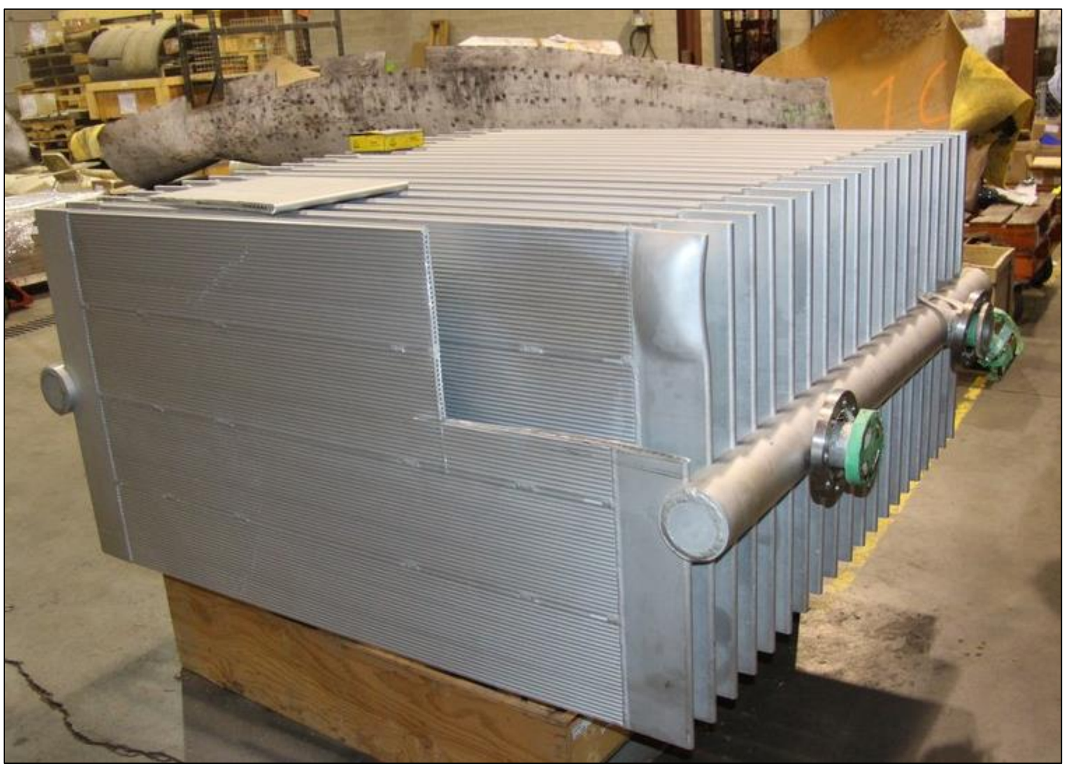

Figure 6 Cut out on edge plate to reveal bulged plate on 2nd row.

Figure 7 Bulged plate removed from 2nd row.

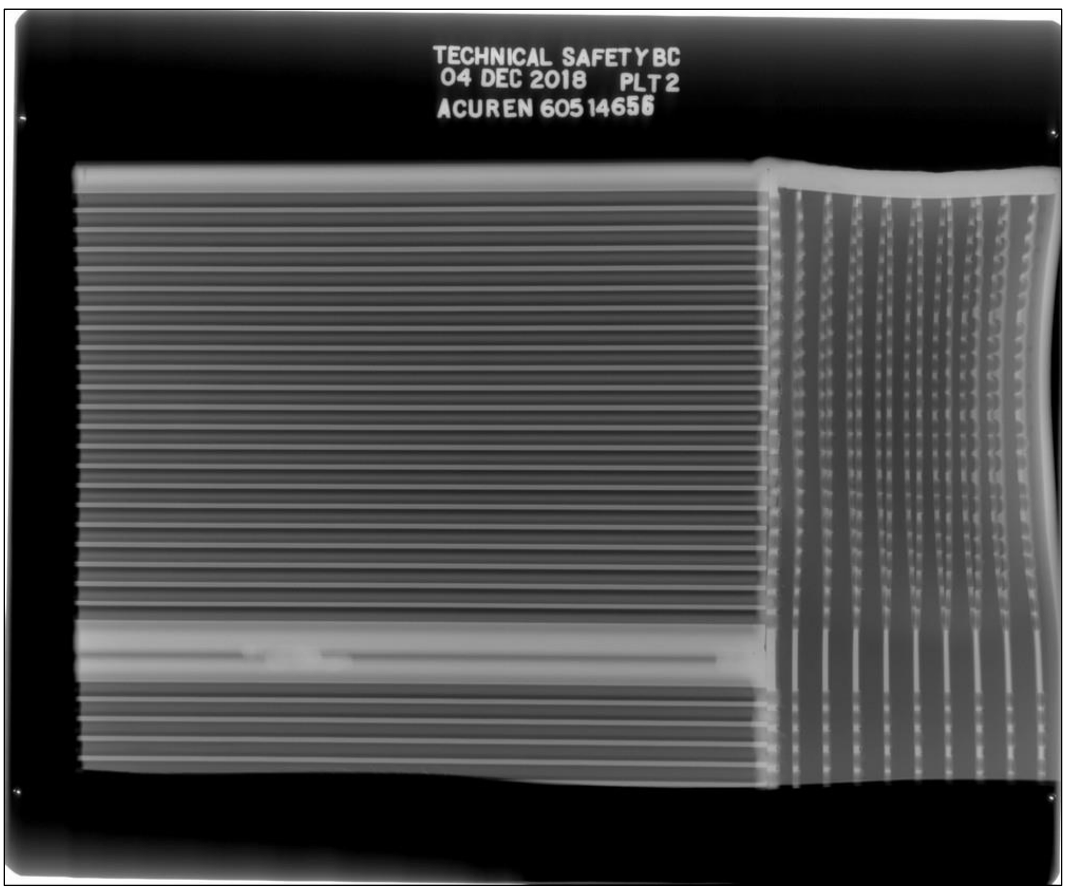

Figure 8 X-ray of bulged plate showing deformation and varying thickness between drilled holes. No obstructions are present.

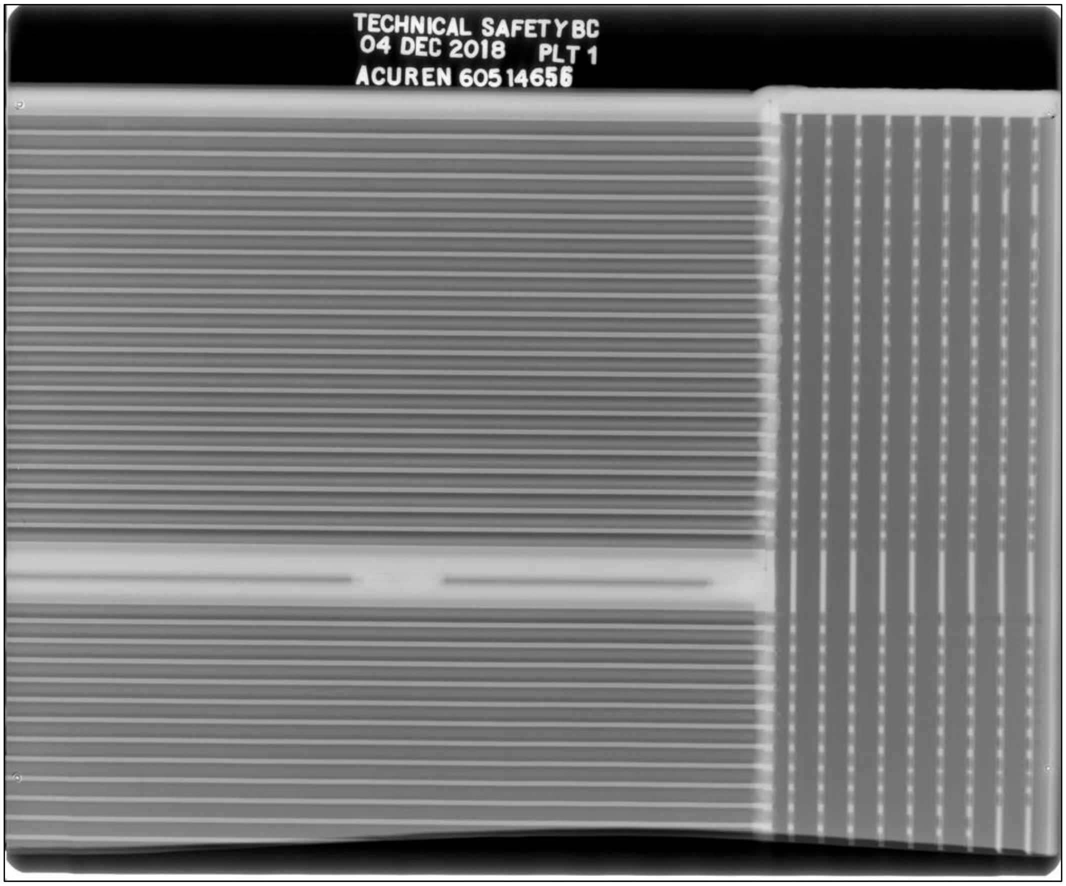

Figure 9 X-ray of exemplar plate showing variability between drilled holes. No obstructions are present.

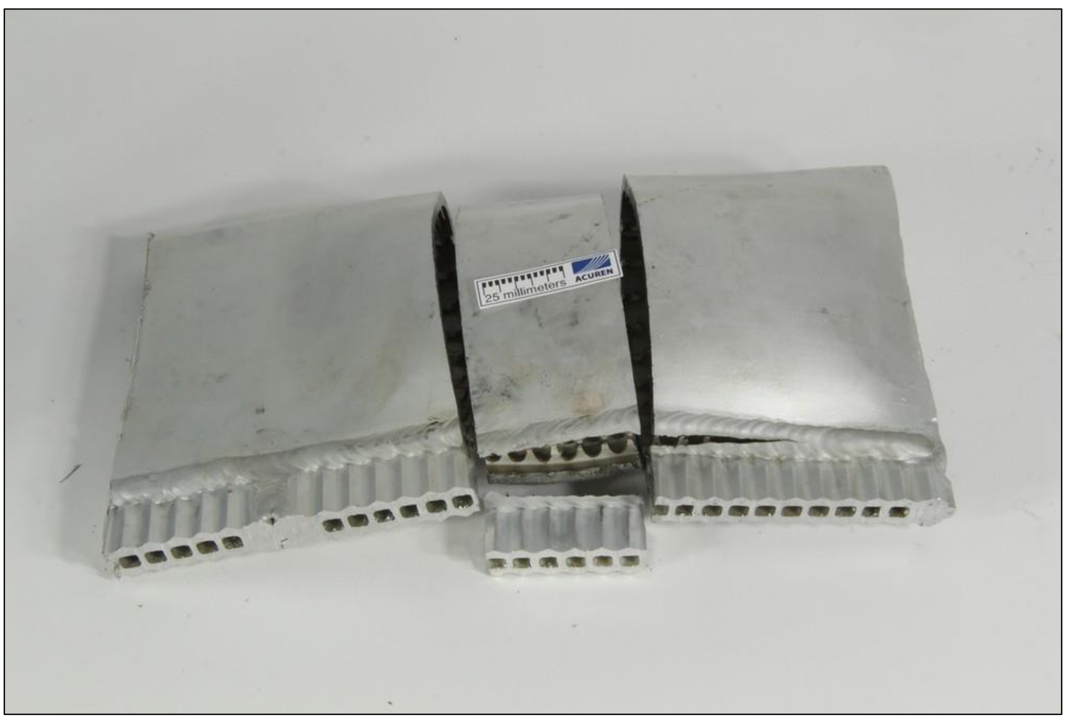

Figure 10 Bulged plate cut to reveal internal construction.

Figure 11 Bulged plate integral surface. The legs between each hole have fractured.

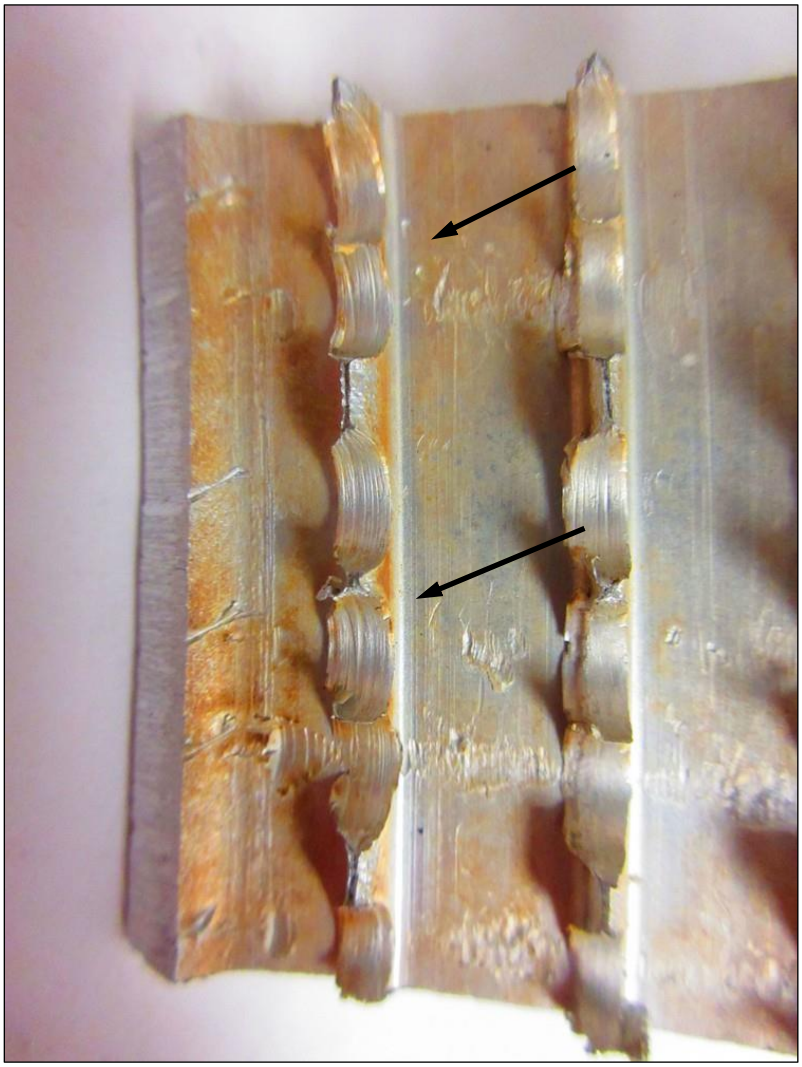

Figure 12 Close up view of internal leg fractures. Each fracture appears ductile.

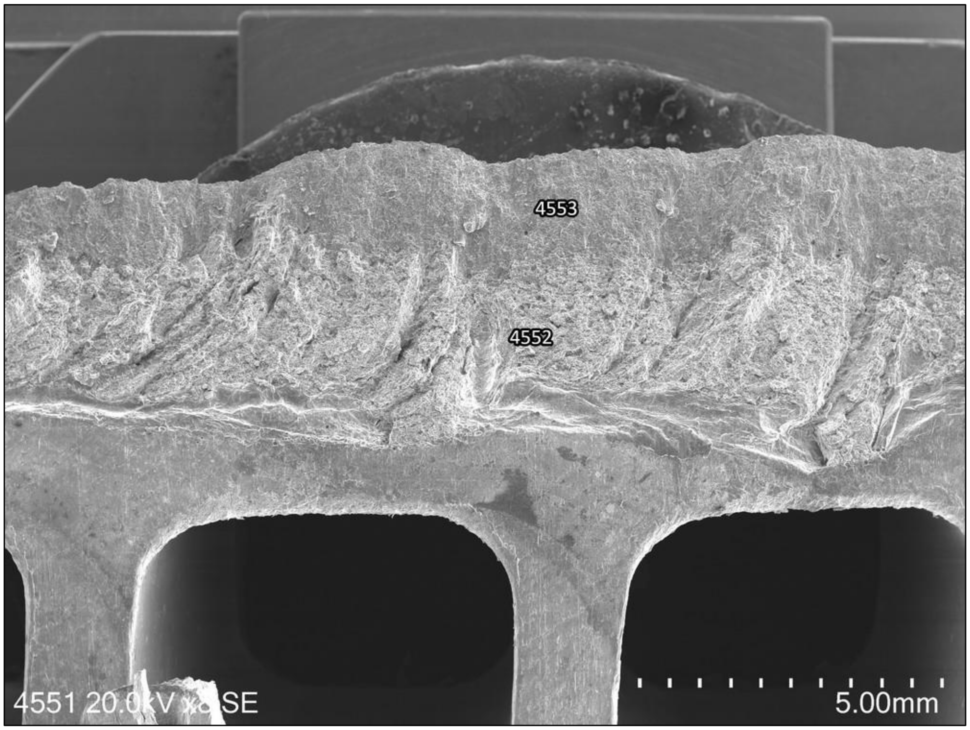

Figure 13 Low magnification SEM view of fractured plate to header weld.

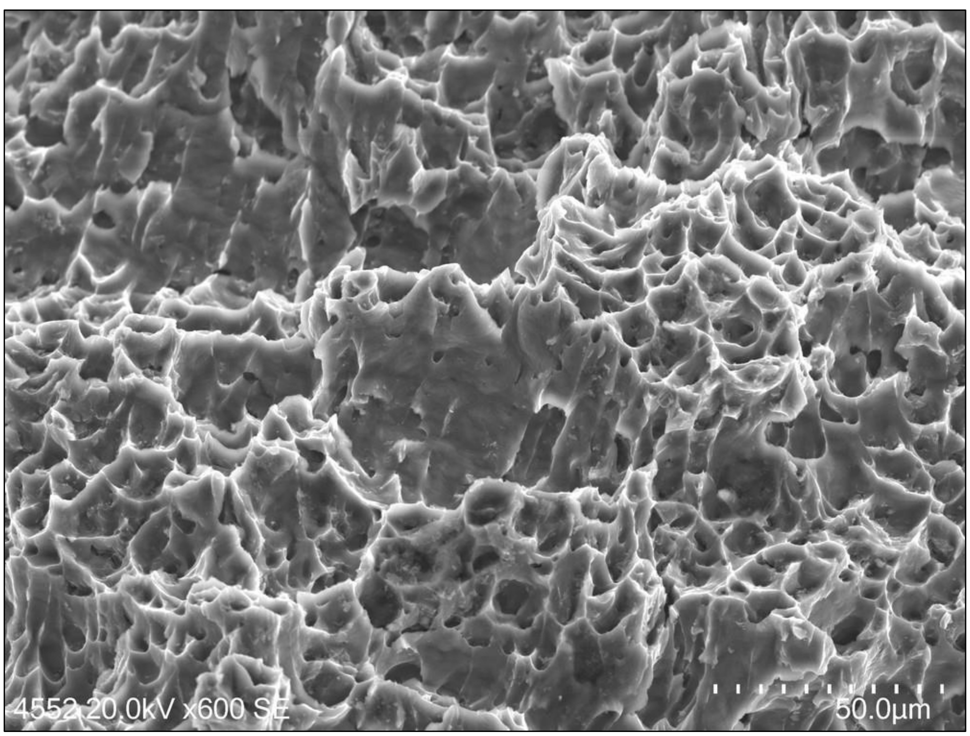

Figure 14 High magnification SEM view of features nearest the plate.

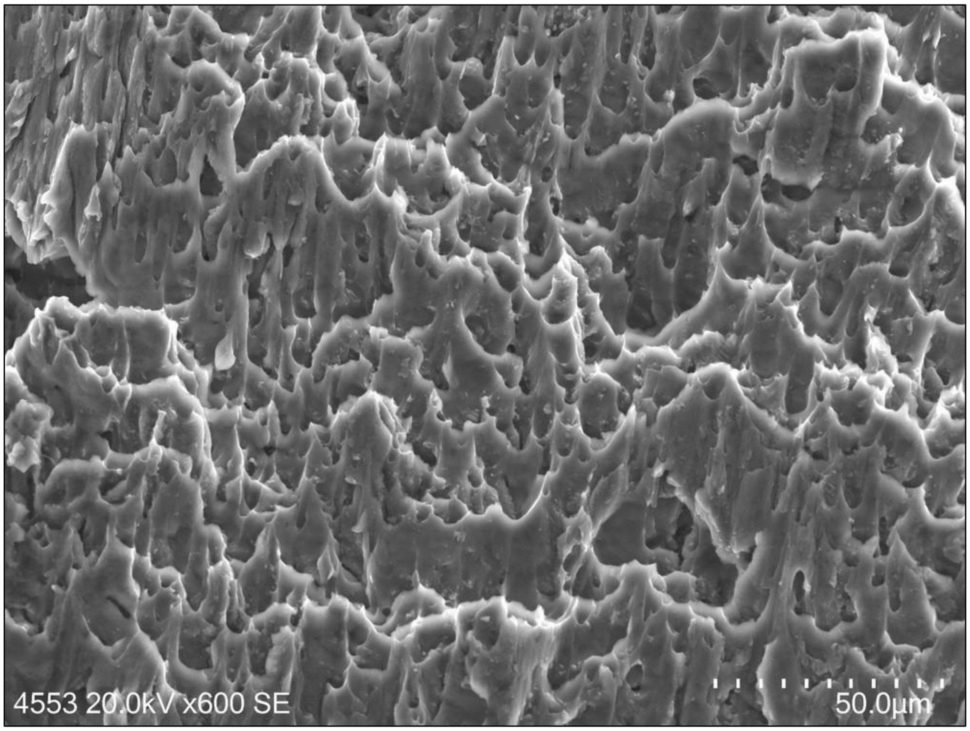

Figure 15 High magnification SEM view of features nearest the header.

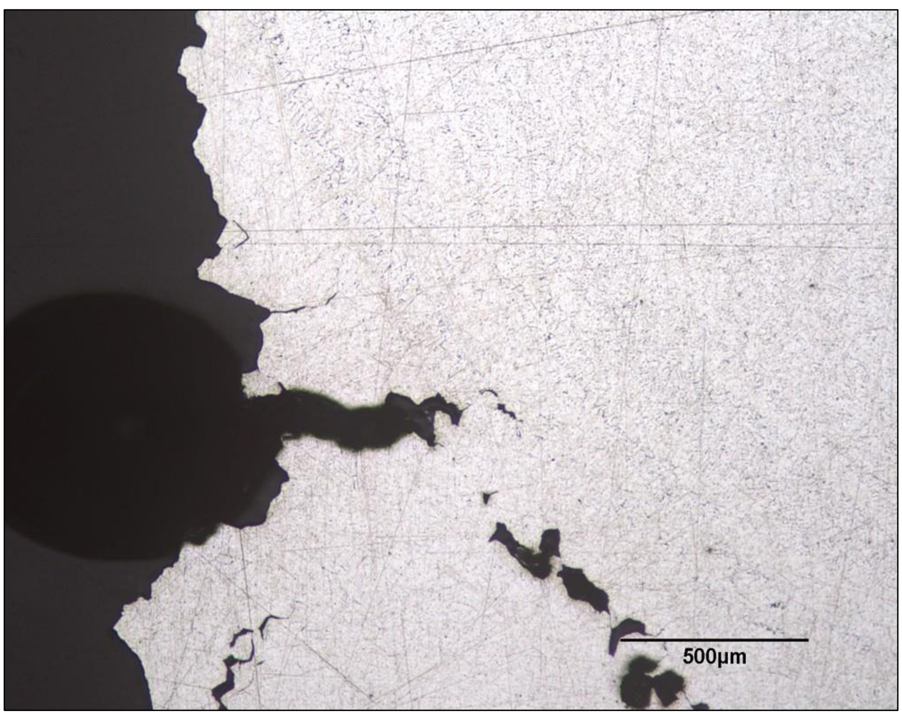

Figure 16 Metallographic view of fracture cross section. Note secondary cracking and porosity in weld metal. (unetched; max 50x.)

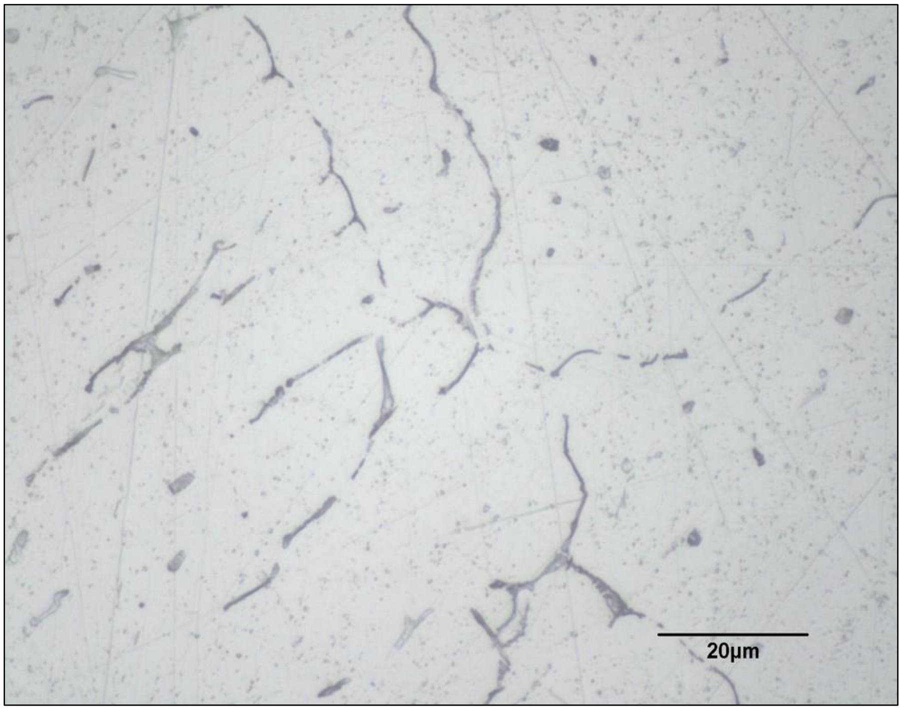

Figure 17 Metallographic view of typical dendritic 2nd phases in weld metal. (unetched; mag 1000x)

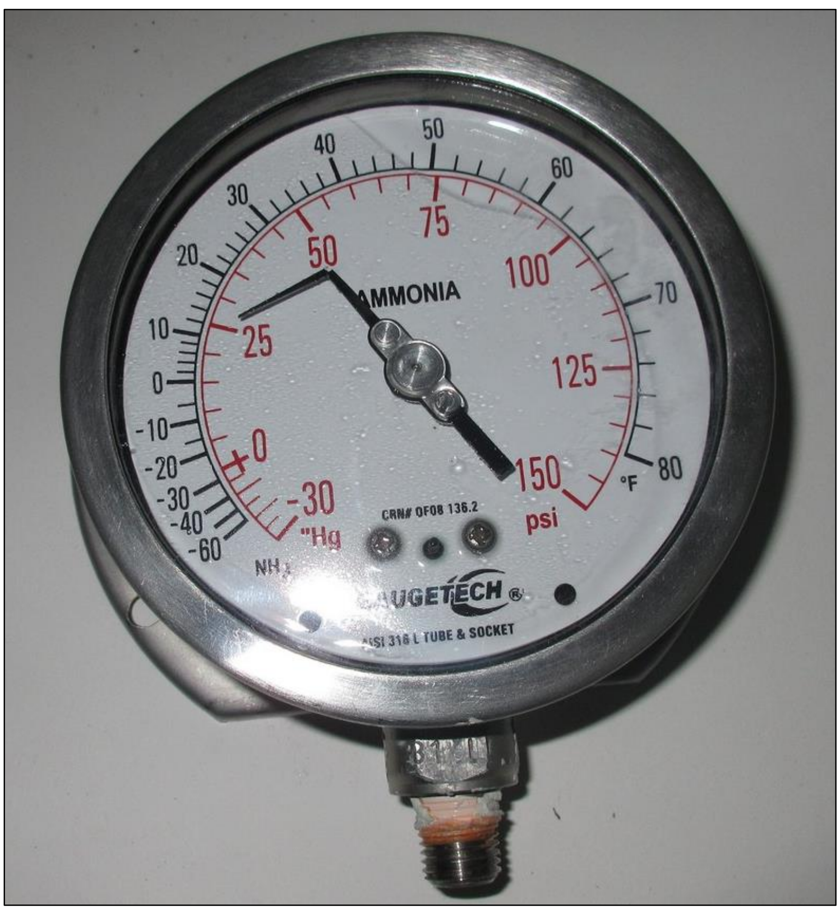

Figure 18 Overall view of damaged pressure gauge attached to cold trap.

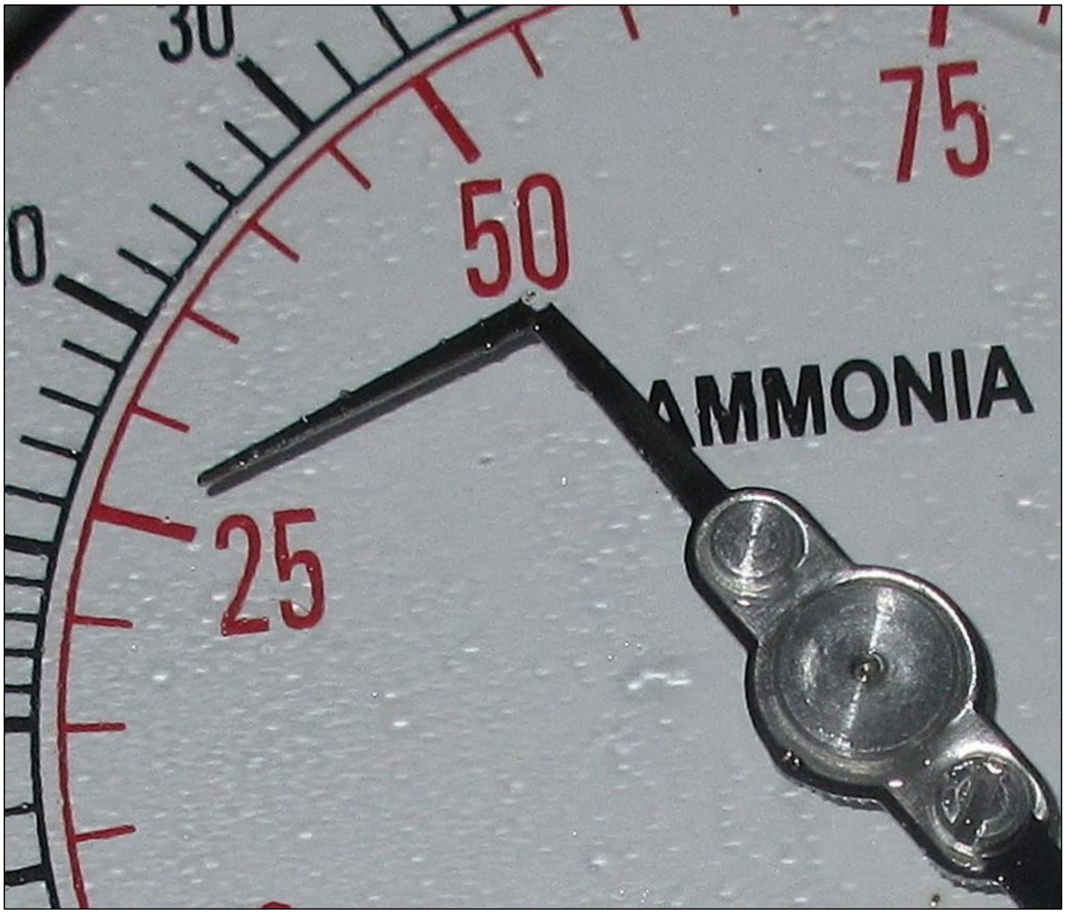

Figure 19 Closer view of fractured needle.

Figure 20 Overall view of internal components.

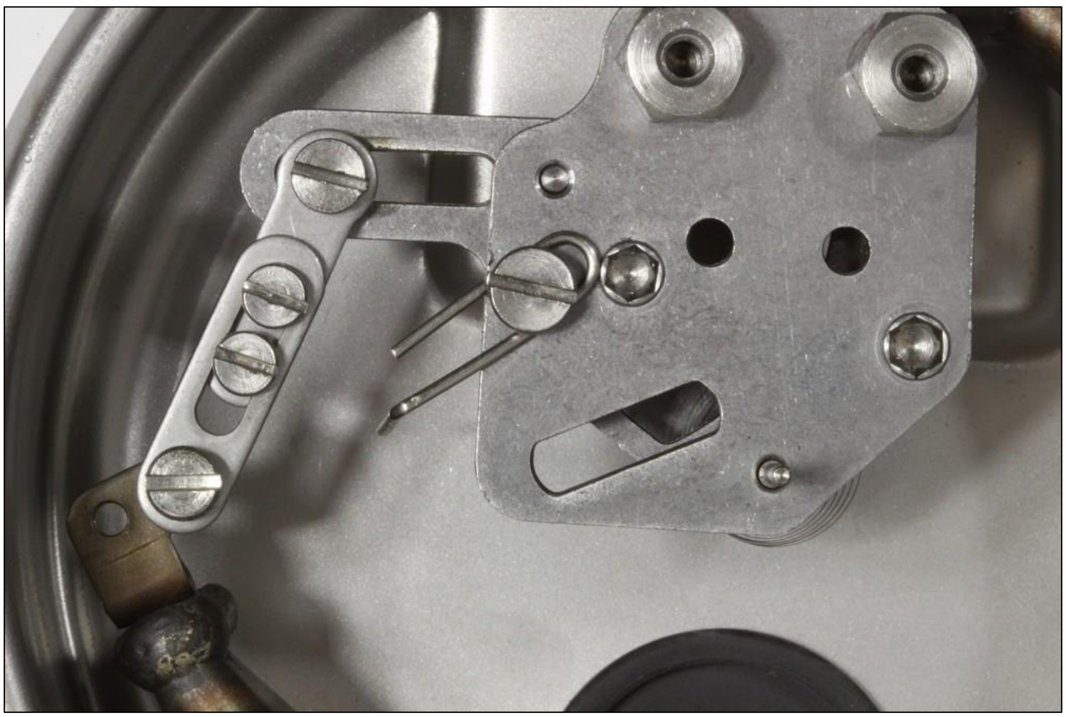

Figure 21 Closer view of linkages and adjustment screws within damaged gauge.

ACUREN

APPENDIX B

REPORTS

ACUREN

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A Higher Level of Reliability

ISO 17025:2005 ACCREDITED CERT #3977.03

ISO 9001 : 2015 REGISTERED Acuren: An ISO 9001 certified company

CHEMICAL ANALYSIS REPORT

TECHNICAL SAFETY B.C.
600-2889 EAST 12TH AVENUE
VANCOUVER, B.C.
V6M 4T5

DATE: January 11, 2019
OUR FILE NO: 60514656
PO NO: Pending
REPORT NO: 1 (Appendix B)
PAGE: 23 of 27

ATTENTION: **ERIC LALLI, P.ENG.**

DESCRIPTION: Chemical Analysis of Cold Trap Components

SAMPLE ID: Plate; Header
TEST METHOD: Optical Emission Spectrometer (OES)

TEST RESULTS

ELEMENT	CHEMICAL COMPOSITION (WT %)		
	HEADER	PLATE	6063
Si	0.430	0.418	0.20-0.60
Fe	0.095	0.153	0.35 max
Mn	<0.0003	<0.0003	0.10 max
Mg	0.590	0.600	0.45-0.90
Cr	0.0005	0.0007	0.10 max
Ni	0.005	0.007	0.10 max
Zn	0.012	0.011	0.10 max

Reported by: ______________________
[redacted]

Reviewed by: ______________________
[redacted]

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ISO 9001 : 2015 CWB REGISTERED Acuren: An ISO 9001 certified company

TENSILE TEST REPORT

TECHNICAL SAFETY B.C.
600-2889 EAST 12TH AVENUE
VANCOUVER, B.C.
V6M 4T5

DATE: January 11, 2019
OUR FILE NO: 60514656
PO NO: Pending
REPORT NO: 2 (Appendix B)
PAGE: 24 of 27

ATTENTION: **ERIC LALLI, P.ENG.**

DESCRIPTION: Aluminum Alloy Extrusion Plates and Header

TEST SPECIFICATION: ASTM B209

MATERIAL SPECIFICATION: Aluminum Alloy 6063

SPECIMEN IDENTIFICATION	YIELD STRENGTH 0.2% OFFSET (PSI)	TENSILE STRENGTH (PSI)	% ELONGATION (IN 2")
Extruded Plate	24,606	31,647	14.5
Header	30,240	34,551	14.0
6063 (Rod and Bar)	24.500	31,000	10.0
Specification Requirements			

- Technical Safety BC Certificate of Recognition Registration No. CR-5
- Test machine calibrated to ASTM E4 and CSA A23.2-9C specifications.
- Specimens will be disposed of after 30 days unless alternate provisions are made.

Reported by: ____________________
[redacted]

Reviewed by: ____________________
[redacted]

ACUREN

APPENDIX C

PRESSURE CALCULATIONS

ESTIMATE OF PRESSURE CAUSING FRACTURE IN HEADER PLATE WELDS

THERE ARE A NUMBER OF WAYS IN WHICH THE PRESSURE CAN BE ESTIMATED BASED ON THE BULGE SIZE, THE FRACTURE LENGTH AND TYPE AT THE WELDED JOINT, AND THE CROSS NETWORK OF HOLES EXTRUDED AND DRILLED IN THE HEADER PLATE. AT THE END OF THE EVENT, THE PLATE TO HEADER WELD FRACTURED UNIFORMLY ON TWO SIDES OF THE JOINT. THESE FRACTURES ARE UNIFORM ON BOTH SIDES OF THE PLATE, INDICATING THAT THE PRESSURE WAS HYDROSTATIC AT THE TIME THE FRACTURE TOOK PLACE. THE FOLLOWING ASSUMPTIONS ARE MADE:

- Tensile strength of aluminum alloy header plate is 34,500 psi (measured);
- As bulging began, the connecting tendons between the drilled holes and the extruded channels fractured, allowing bulging to increase in accordance with the strength of the aluminum and the pressure in the bulge area;
- Fracture of the weld occurred along the welded joint between the extruded plate and the header plate. Half of the fracture appeared tensile in nature (straight dimples), the remaining half (outside half) appeared to be caused as a combination of tensile and shear stress (horseshoe shaped dimples);
- Fractures on both sides of the header were 3.5” long by the width of the weld throat (0.20 “);
- Assume maximum pressure attained caused the tensile failure of the welds **AFTER** initial bulging and fracture of the internal tendons between the extruded channels and drilled holes;

a) Assume tensile failure of 3.5” of weld metal:

Weld metal strength approximately 24,000 psi in tension, 16,000 psi in shear

Total area fractured: 3.5”x 2 x 0.2” = 1.4 in^2

Total tensile load required to fracture = 20,000 psi x 1.4 in^2 = 28,000 lb

b) Assume tensile load on fracture area results from hydrostatic pressure pushing on plate end in area of bulge;

Plate end bar thickness - 0.40” (10mm)

Plate end over length of bulge - 7” (178 mm)

Pressure acting on area of 7” x 0.4” = 2.8in^2

Total pressure to cause fractures = 28,000 lb/2.8 in^2 = 10,063 psi

c) Pressure Required to Fracture Tendons

Number of tendons 20x10 = 200

Total area tendons = 0.08” x 0.08” x 200 = 1.3 in^2

Load required to fracture = 34,551 psi x 1.3 in^2 = 44,916 lb

Hydrostatic pressure acting on 7” x 5” = 35 in^2

Required pressure = 44,916 lb/35 in^2 = 1283 psi

Therefore, tendons fractured before welds as the pressure built.