

Key Lessons for Preventing Hydraulic Shock in Industrial Refrigeration Systems

Anhydrous Ammonia Release at Millard Refrigerated Services, Inc.

January 2015

32 Hospital Admissions,

4 Placed in Intensive Care

No. 2010-13-A-AL

KEY LESSONS SUMMARIZED:

- For the design of ammonia refrigeration systems, avoid grouping multiple, large-capacity evaporators to a single set of control valves.
- Program the defrost control sequence to automatically depressurize or bleed the coil upon restart after an outage or interruption, prior to opening the suction stop valve to set the evaporator into cooling mode.
- Avoid the manual interruption of evaporators while in defrost and equip control systems with password protected controls to ensure only trained and authorized personnel have the authority to manually override system processes.
- For time-initiated hot gas defrost systems, ensure pump-out times are long enough to remove all liquid refrigerant from the evaporator coils prior to introducing hot gas, especially after low-load periods or power outages.
- In the event of an ammonia release, activate the emergency shut-down switch to de-energize pumps, compressors and valves instead of attempting to isolate leaking equipment while the refrigeration system is running.



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1.0 INTRODUCTION

On August 23, 2010, at the Millard Refrigerated Services facility in Theodore, Alabama, hydraulic shock caused a roof-mounted 12-inch suction pipe to catastrophically fail leading to the release of more than 32,000 pounds of anhydrous ammonia. The hydraulic shock was enabled during the restart of the plant's ammonia refrigeration system following a 7-hour power outage. In addition to the catastrophic failure of roof-mounted piping, the pressure developed by the hydraulic shock event also caused an evaporator coil inside the facility to rupture.

The ammonia cloud released from the roof-mounted pipe and traveled 0.25 miles across the river adjacent to the plant. Downwind of the ammonia release were crew members on the ships docked at Millard and over 800 contractors working outdoors at a clean-up site for the Deepwater Horizon oil spill. One Millard employee sustained injuries after briefly losing consciousness from ammonia inhalation.

Nine ship crew members and 143 of the offsite contractors downwind reported exposure. Of the exposed victims, 32 required hospitalization, and 4 were placed in intensive care.

Caused by a rapid deceleration of liquid, “hydraulic shock” is an abnormal transient condition that results in a sharp pressure rise with the potential to cause catastrophic failure of piping, valves, and other components. Hydraulic shock can occur in industrial refrigeration systems and is often preceded by audible “hammering” in refrigeration piping. In low-temperature systems, the combination of high-pressure hot gas (commonly used for defrost) and cold liquid ammonia can result in hydraulic shock with the potential for ammonia-containing equipment to suddenly and catastrophically fail. Equipment failures can lead to a hazardous release of anhydrous ammonia. In addition to health and safety risks from ammonia exposure, these types of large-scale releases can result in deflagration¹ if an ignition source is present with concentrations of ammonia in the flammable range.² In 2007, hydraulic shock caused a similar ammonia release incident that resulted in an explosion at another cold storage company. Electric arcing from a nearby water fountain provided an ignition source when the ammonia cloud reached an explosible concentration.³

This bulletin describes the mechanism of hydraulic shock involved in the 2010 ammonia release at Millard Refrigerated Services and summarizes the investigation's lessons learned that aim to prevent future occurrences of hydraulic shock in the ammonia refrigeration industry.

¹ Deflagration is a type of explosion in which the shock wave propagates at a velocity less than the speed of sound.

² Anhydrous ammonia is considered slightly flammable with a lower flammability limit of 16 percent and an upper flammability limit of 25 percent by volume in air. In cases where ammonia may be released in an aerosolized form with lubricating oil from the refrigeration system, the flammable range can be significantly wider increasing the possibility of ignition.

³ Wienke, Bent., A Case Study of Pipe Work Fracture due to Hydraulic Shock in an Ammonia System. International Refrigeration Consortium. 2009 Forum. Madison, Wisconsin

2.0 INCIDENT DESCRIPTION

Shortly before 9:00 am on the morning of August 23, 2010, Millard was in the process of loading two international ships with frozen poultry when the facility's refrigeration system experienced a hydraulic shock event that led to a catastrophic piping system failure and the release of 32,100 pounds of anhydrous ammonia. The majority of the ammonia released in this incident occurred through a compromised portion of the system's 12-inch suction pipe located on the roof (Figure 1). The resulting cloud of ammonia vapor traveled 0.25 miles to the south across the Theodore Industrial Canal, exposing a Millard employee and offsite contractors working outdoors.⁴ At approximately the same time, alarms sounded within the plant due to the detection of high concentrations of ammonia indoors by air-monitoring equipment in the freezers. The ammonia detected within the facility was the result of a second leak that developed because a portion of the system's blast freezer⁵ evaporator header ruptured (Figure 2).

FIGURE 1

Ruptured 12-inch diameter end cap of low-temperature suction line piping on the roof of Millard facility (OSHA).



FIGURE 2

Freezer 5 evaporator coil weld failure after the incident (OSHA).



After the Operations Manager announced the release on the Millard facility intercom, three Millard employees went onto the roof in an attempt to mitigate the leak by closing manual valves that supplied ammonia to the blast freezer. All other Millard employees evacuated the facility to a location upwind from the ammonia release. Millard employees on the roof closed valves and reported the release secured by 1:20 pm, about 4 hours after the initial release. Ammonia released within the blast freezer due to the failed evaporator coil contaminated 8 million pounds of poultry and packaging material. Industrial hygiene technicians contracted for post-incident remediation recorded ammonia concentrations as high as 7,275 parts per million (ppm) in the contaminated blast freezer later that day.⁶

⁴At the time of the incident, nearby weather stations reported that the wind was mild but blowing in a southerly direction at 3.5 miles per hour.

⁵In this facility, the "blast freezer" was a 24,000 square foot space that operated at extremely low temperatures to rapidly chill or freeze product.

⁶According to the American Industrial Hygiene Association (AIHA) Emergency Response Planning Guidelines (ERPG), 150 ppm is the maximum airborne concentration below which nearly all individuals can be exposed for up to 1 hour without experiencing life-threatening health effects or other serious adverse health effects of symptoms that could impair an individual's ability to take protective action.

2.1 EMERGENCY RESPONSE

Approximately 15 minutes after being notified of the release, the Millard Plant Manager called 9-1-1, triggering a response from the Mobile Fire Department (MFD), which arrived on scene 16 minutes later with hazardous materials technicians to assess and mitigate the release. The Theodore Volunteer Fire Department also responded on the south side of the canal (Figure 3). The MFD called the Mobile County Emergency Management Agency and advised shelter-in-place for the surrounding community and the U.S. Coast Guard halted water traffic on the industrial canal. Shortly after the release occurred, contract employees working at the Deepwater Horizon (DWH) vessel and boom decontamination site,⁷ approximately 0.25 miles south of Millard, became engulfed in the ammonia cloud and immediately started experiencing symptoms of ammonia exposure. The workers were advised to go to their personal cars and evacuate the facility. The Mobile County Fire and Rescue set up an impromptu triage site at a gas station about 2 miles from the DWH clean-up site where exposed workers gathered upon evacuation. Most of the offsite contractors went to the triage site for medical evaluation, and some were transported to the hospital.

The MFD conducted air monitoring after arriving on scene. According to the MFD report on the incident response, colorimetric gas detection tubes used to sample ammonia on the dock detected ammonia concentrations between 250 and 450 ppm. The U.S. Coast Guard conducted air monitoring later that afternoon and reported concentrations of 500 to 600 ppm inside the Millard facility.

FIGURE 3

Overhead view of Millard and DWH boom cleanup site.



⁷ The DWH vessel and boom decontamination worksite was established as part of the Gulf of Mexico oil spill response. Workers at this site cleaned booms (large floating barriers used to collect oil) between uses. The CSB's investigation of the Macondo blowout and explosion in the Gulf of Mexico that resulted in 11 deaths and a significant oil spill is currently ongoing.

2.2 INJURIES

One Millard employee and more than 152 offsite workers, including 9 ship crew members docked at the Millard facility, sustained injuries as a result of exposure from the ammonia release. The exposed Millard employee was operating the ship's loading crane on the Millard dock when, as he attempted to self-evacuate to a safe location, he was overcome by ammonia. During his descent from the crane, he briefly lost consciousness and fell to the ship's deck, injuring his leg. A second Millard employee on the emergency response team was not directly exposed to ammonia, but sought medical treatment for heat exhaustion that he experienced while he was working to mitigate the ammonia leak. Nine crewmembers assigned to the two foreign-flagged ships docked at Millard also sought medical attention for ammonia exposure. One hundred and forty three of those affected by the ammonia vapor plume were offsite contractors associated with the DWH decontamination site.⁸ Of the 153 reported ammonia exposures from this incident, a total of 32 workers were admitted to the hospital, and 4 were placed in intensive care.

2.2.1 Ammonia Exposure Survey

The Center for Disease Control and Prevention (CDC) and the Agency for Toxic Substances and Disease Registry (ATSDR) conducted an Assessment of Chemical Exposure (ACE) survey of all persons offsite who were affected by the ammonia release. The purpose of the ACE survey was to determine the severity of the health effects from the ammonia release and make public health recommendations. ATSDR epidemiologists and staff members conducted field investigations for two weeks following the ammonia release, beginning on August 25, 2010. During the field investigations, the ATSDR conducted interviews of DWH workers and reviewed hospital medical charts to characterize the exposures. According to the ATSDR, people affected by the ammonia release reported shortness of breath, headaches, coughing, eye irritation, nausea, chest pain and dizziness within 24 hours of exposure. Of the 800 people working across the river from Millard on the day of the incident, 116 people that reported symptoms participated in the ACE survey (14.5%). Within the first 24 hours following the release, 71% reported headache, 64% reported shortness of breath, and 62% reported coughing. About 40% of the victims still reported those symptoms two weeks following the release. The ACE survey made recommendations to the local health department to monitor the long-term health effects of the exposed workers. The CSB followed up with the Mobile County Health Department in 2014 and found that there were no long-term health effects reported from the exposed victims.

3.0 HYDRAULIC SHOCK

Hydraulic shock is a sudden localized spike in pressure that can occur in piping or equipment when there is a rapid change in the velocity of a flowing liquid. Often referred to as “water hammer,” hydraulic shock is a well-understood phenomenon that has occurred in water and steam systems found in both domestic and industrial settings. In ammonia refrigeration, hydraulic shock events can generate extremely high pressures with the potential to cause the catastrophic failure of piping, valves, and other equipment. The highest pressures often occur when vapor and liquid ammonia are present in a single line and are disturbed by a sudden change in volume.⁹ Moderate hydraulic shocks can generate pressures that are evidenced by knocking sounds emanating from piping or valves.

⁸ The DWH vessel and boom decontamination worksite was decommissioned and ended operations in fall 2010.

⁹ American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE): ASHRAE Handbook - Refrigeration (SI Edition); Section 2.27, “Safety Considerations” (Atlanta; ASHRAE, 2010).

TYPES OF HYDRAULIC SHOCK:

Three common disturbance mechanisms can cause hydraulic shock in ammonia refrigeration systems:

- **Sudden Liquid Deceleration or “Water Hammer”:** Hydraulic shock is caused by the rapid closing of a valve in a pipe carrying flowing liquid. When the flow of liquid stops suddenly, a spike in pressure within the valve body and connected piping occurs.
- **Vapor-Propelled Liquid Slug (VPLS):** High pressure vapor flowing in a line partially filled with liquid may entrain a sufficient volume of liquid to fill the pipe circumference; thereby, creating a liquid “slug.” These liquid slugs move rapidly until they encounter an obstruction such as a valve or pipe end-cap. Momentum from the flowing liquid is imparted to the obstructing component, resulting in a rapid rise in pressure or hydraulic shock event.
- **Condensation-Induced Shock (CIS):** High pressure refrigerant vapor rapidly condenses in lines containing both liquid and vapor. As ammonia vapor condenses, it undergoes a large decrease in volume (a reduction of approximately 1,000 times) and the large reduction in volume causes liquid locally to accelerate. When the accelerated liquid encounters adjacent

Damaging hydraulic shock events are typically the condensation-induced type and frequently occur in low-temperature ammonia systems.¹⁰ Condensation-induced shock events are often associated with the transition from high temperature and pressure to low temperature and pressure, during and after the defrosting of evaporators with hot gaseous refrigerant. Failed system components typically include evaporators, associated piping components (e.g., suction stop valves), evaporator suction piping, and suction header mains downstream of the evaporators. Based on an examination of the failed components and a review of the evaporator defrost system at the time of the incident, the ammonia released at Millard was likely a result of condensation-induced shock, vapor-propelled liquid, or a combination of both, that ruptured the evaporator piping manifold and suction header. Vapor-propelled liquid and condensation-induced shock are two forms of undesirable transient events that can occur in piping conveying both liquid and vapor. These two mechanisms often occur together during a hydraulic shock event.¹¹

¹⁰ASHRAE; 2010 ASHRAE Handbook - Refrigeration (SI Edition); Section 2.27, “Safety Considerations” (Atlanta; ASHRAE, 2010).

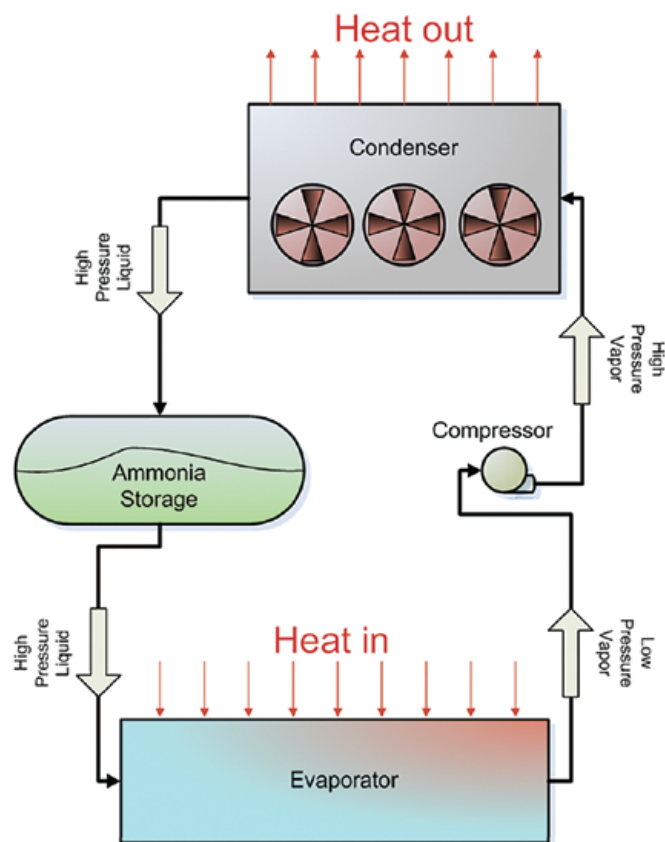
¹¹Industrial Refrigeration Consortium (IRC). “Understanding Hydraulic Shock.” The Cold Front. Vol. 9 No. 1. 2009.

4.0 AMMONIA REFRIGERATION

Millard Refrigerated Services operated a 143,000-pound ammonia refrigeration system that supplied five product storage freezers and three blast freezers.¹² Millard operated as a marine export facility that sent frozen meat abroad.¹³ The refrigeration system at the Millard facility was designed to handle liquid ammonia at a minimum temperature of -40°F to a maximum temperature of 110°F , and the normal design system operating pressure ranged from 8.8" of mercury (Hg) vacuum to 210 psig.

The refrigeration system removed heat from the freezers when the ammonia in the system changed phase, from a liquid to a vapor. The ammonia vapor was then compressed and condensed back into a liquid, cycling continuously through the system. The refrigeration system is a closed system that does not generate or consume ammonia during the refrigeration cycle (Figure 4).

FIGURE 4
Simplified
refrigeration cycle



¹² Millard's storage freezers held already frozen product at -5°F and blast freezing cells functioned to freeze incoming fresh product from an initial temperature of $+40^{\circ}\text{F}$ to a final temperature of 0°F in period of 24 hours.

¹³ At the time of the 2010 incident, Millard Refrigerated Services, Inc. operated as a refrigerated warehouse and distribution company, with 36 facilities located in the United States and Canada. In March 2014, Lineage Logistics acquired Millard Refrigerated Services. The Theodore, Alabama facility became a privately owned port facility called Millard Maritime Services in April 2013, providing bulk loading and unloading material.

4.1 CHARACTERISTICS OF ANHYDROUS AMMONIA

Anhydrous ammonia (NH₃) is a colorless gas at normal temperature and pressure, with a characteristic pungent odor. As a vapor, it is lighter than air and very soluble in water. When liquid ammonia is released into the atmosphere, it forms an aerosol with the moisture in the air and produces a visible white cloud. The resulting cloud is dense and tends to travel along the ground, which is especially dangerous to workers and the public in the surrounding area. Ammonia is irritating to the eyes and respiratory system and can be fatal upon exposure to elevated concentrations.¹⁴ Additionally, anhydrous ammonia-air mixtures can deflagrate if their concentrations are in the flammable range and if they are in the proximity of an ignition source.

4.2 THE DEFROST CYCLE

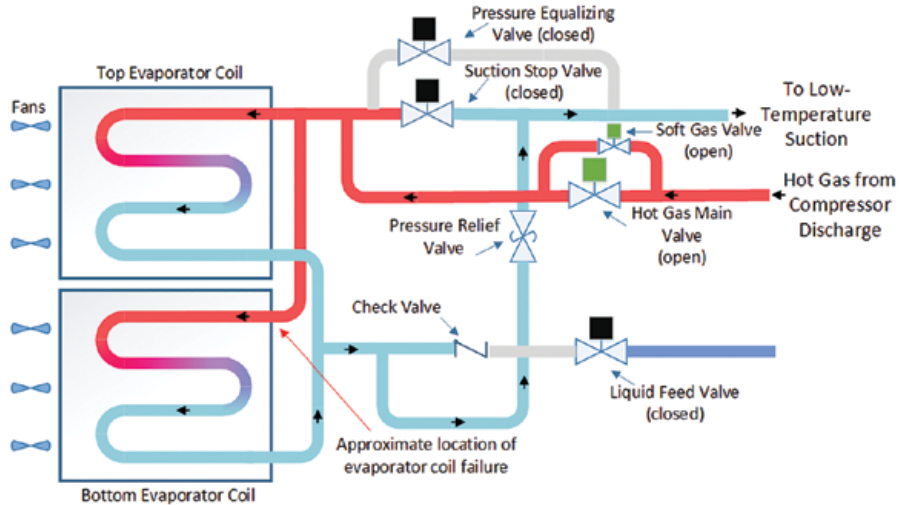
In large refrigeration systems, low-temperature, liquid ammonia is pumped through evaporator coils located in the cold storage and blast freezers to cool air within those respective spaces. The air temperature in the freezer decreases as it transfers heat to colder refrigerant evaporating within the coils. During cooling mode operation, moisture from the air builds up on the external surface of the evaporator coil in the form of frost. If not periodically removed, the frost accumulating on the evaporator coil surfaces eventually reduces its heat transfer and a significant reduction in the evaporator's cooling capacity results. A hot gas defrost cycle is a common technique used to periodically melt the accumulated frost from the evaporator coil surfaces by interrupting the normal cooling mode and circulating hot gaseous refrigerant from the compressor discharge through the coil to warm the evaporator surface. This process causes the temperature of the coil surfaces to rise sufficiently high to melt the accumulated frost. The defrost cycle can be initiated either manually or automatically by appropriate programming into the refrigeration system's controls to activate the defrost cycle at a set time or interval.

When the defrost process begins, the system stops feeding liquid ammonia to the evaporator by closing the liquid feed valve while allowing the evaporator fans to continue operating; thereby, evaporating residual liquid refrigerant in the coil (Figure 5). Next, the suction stop valve closes to isolate the evaporator coil from the low-temperature part of the system, and the hot gas valve on a branch connection (or bypass) opens to introduce hot ammonia gas (110°F and 100 psig) from the compressor discharge into the evaporator coil. The introduction of hot gas to the coil is typically performed in two steps. The first step, known as "soft gas," uses a smaller valve to gradually introduce the higher pressure hot gaseous refrigerant into the evaporator coil before opening the main hot gas valve. After the "soft gas," the second step involves introducing a higher rate of hot gas flow into the coil by opening a larger hot gas valve. The higher rate of gas flow warms the evaporator coil surfaces and the accumulated frost melts on the outside of the coil while the high-pressure refrigerant gas condenses to a liquid inside the coil. The condensed liquid refrigerant (along with gaseous refrigerant that may not have fully condensed) returns to the plant's intermediate pressure level – usually through a defrost relief valve. After defrost is completed, the hot gas valves close, and a pressure equalizing valve opens to slowly depressurize (or bleed) the coil. Next, the suction stop valve is opened and the valve feeding low-temperature liquid to the coil is opened to re-chill the evaporator. Finally, the fans reenergize and the normal cooling mode refrigeration cycle continues.

¹⁴The Immediately Dangerous to Life or Health exposure limit established by the National Institute of Occupational Safety and Health is 300 ppm for 30 minutes of exposure. Ammonia exposure can immediately result in life-threatening effects at 2,700 ppm in 10 minutes of exposure, based on the Environmental Protection Agency's Acute Exposure Guideline Levels.

FIGURE 5

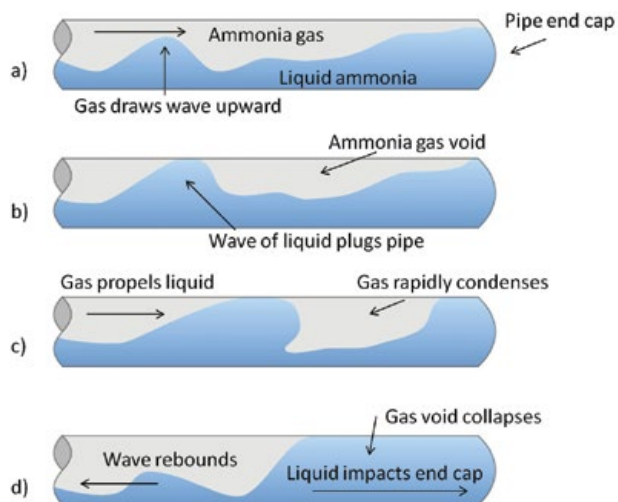
Simplified flow diagram of hot gas defrost



During hot gas defrost, the evaporator coils are isolated from the low-temperature suction line by closing the suction stop valve. The evaporator piping (upstream) of the suction stop valve is pressurized while the downstream low-temperature suction piping contains low pressure vapor and liquid returning from other evaporators in service. A cause of shocks more common in ammonia systems is the rapid opening of a valve from high pressure to low pressure.¹⁵ If the coil rapidly depressurizes, refrigerant liquid and vapor will accelerate through the suction stop valve and into the downstream suction piping. The gas will suddenly condense to a liquid, which can lead to condensation-induced shock when voids of trapped gas build up pressure and rapidly condense, creating a vacuum (Figure 6).¹⁶ The reduction in volume produces an inrush of fluid from other parts of the system. The liquid accelerates at a high velocity and when it arrives at an obstruction, such as an end cap, it abruptly stops and exerts a force on the piping. The exerted force stresses the pipe and joints and, in severe cases, results in component failure. The failure at Millard was likely caused by a combination of condensation induced shock and vapor-propelled liquid. These two mechanisms often work together during hydraulic shock events in ammonia refrigeration systems.

FIGURE 6

Progression of a condensation-induced shock event.



¹⁵Loyko, L. Hydraulic Shock in Ammonia Systems. IIAR 11th Annual Meeting March 12-15, 1989 Austin, TX

¹⁶The ratio of vapor volume to liquid volume for ammonia at -40°F is 1,073. Ammonia will undergo a change in volume of 1,000 times as it changes state from a vapor to a liquid at -40°F.

5.0 INCIDENT ANALYSIS

5.1 POWER OUTAGE

On the afternoon before the incident, the Millard facility and its refrigeration system experienced a loss of power that lasted more than 7 hours. While attempting to troubleshoot equipment issues after the system regained power, the Millard refrigeration system operator manually cleared an alarm in the system. This resulted in an interruption of a defrost cycle that was in progress for a blast freezer evaporator. The evaporator switched directly from defrost mode into refrigeration mode without bleeding hot gas from the evaporator coil. The bleed phase is necessary to prevent a rapid reduction of pressure in the coil when the low-temperature suction stop valve opens. Rapid depressurization in the coil increases the risk for hydraulic shock in the evaporator coil and connected suction header.¹⁷

Because the operator manually intervened to clear the alarm and thus reset the control system, the control system did not recognize that the blast freezer evaporator unit contained high-pressure hot gas when it allowed the suction stop valve to open during the system restart. Rather, the control system signaled the suction stop valve and liquid feed valves to simultaneously open in order to return the evaporator to cooling mode operation. This manual bypass of the programmed defrost sequence allowed the low-temperature liquid and hot gas to mix in the same pipe, causing the hot gas void to collapse as it rapidly condensed to a liquid. This created pressure shocks that ruptured the evaporator piping manifold and the low-temperature suction piping on the roof.

According to Millard documentation, the control system contained a programming error that permitted the system to go from soft gas directly to refrigeration mode without bleeding the high pressure from the coil or preventing the low-temperature suction valve from opening. The error with the software logic in the control system went undetected because under normal operations, in its programmed sequence, the defrost cycle would not allow the ammonia liquid to enter the evaporator until the coil was properly depressurized via the bleed cycle.

In Millard's investigation report for the 2010 incident, the company found that the manual clearing of an ammonia alarm in the control system interrupted the defrost cycle. This was enabled by a lack of restricted access to control system modifications. Had password-protected controls been in place, they could have been used to restrict access to only authorized personnel trained to modify the refrigeration system sequence and pump-out times. Because the reduction or omission of the bleed down cycle during hot gas defrost can result in a shock event,¹⁸ a severe release of ammonia can occur if manual operation during defrost is not properly executed. The probability of improperly sequencing manual defrost increases when workers are not trained on how to appropriately modify the control sequence.¹⁹

After an unintended interruption, process upset, or power outage, refrigeration system operators can avoid the need for manual intervention to the defrost cycle sequence by programming the control system to automatically bleed any coil that was in defrost prior to the power outage upon restart. Refrigeration control system designers can program the control sequence logic on a restart following a power outage to identify evaporators in defrost prior to the power outage. Next, the sequence would be programmed to assume that those coils are pressurized and thus initiate a bleed cycle prior returning the evaporator

¹⁷ Reindl, D.T. and Jekel, T.B. 2009. "Defrosting Industrial Evaporators." ASHRAE Journal: August 2009. pg 30-40.

¹⁸ Loyko, L. Hydraulic Shock in Ammonia Systems. IAR 11th Annual Meeting March 12-15, 1989 Austin, TX

¹⁹ Ma, Yitai. Gu Haoxiang., Research on Risk of Hot Gas Defrosting and Liquid Hammer in Ammonia Refrigeration. Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, MOE, No.92 in Tianjin, China. 2013

to refrigeration mode. These defrost control programming features will reduce the need for manual intervention and the risk of hydraulic shock after an unplanned shutdown.

5.2 MILLARD REFRIGERATION SYSTEM DESIGN

5.2.1 Evaporator Configuration

Another contributing factor in this incident was the design and configuration of the blast freezer evaporators at the Millard facility—specifically, connecting multiple evaporator units onto a single control valve group. This design approach allowed for an excessively large volume of high-pressure gas to be introduced to the suction line when the suction stop valve was prematurely opened. Millard and the designers of the refrigeration system designed the blast freezer evaporators at the Theodore facility with four evaporator coils grouped to one set of control valves. With this design, one set of valves controlled the liquid feed, hot gas, and suction for all four evaporator coils during cooling mode and the defrost cycle. The evaporator assembly at Millard consisted of a pair of evaporators with two coils each, stacked vertically. Liquid ammonia fed into the coils from the bottom of the coil and the hot gas fed the coils from the top (see Figure 5 for stacked evaporator configuration).

Designing the system with multiple evaporator coils controlled by a single valve arrangement reduced the overall number of valves that needed to be installed for each evaporator; therefore, reducing the initial system cost. Because of the poor controllability and the large internal coil volume, the practice of ganging multiple evaporators onto a single valve group should be avoided. The risk of hydraulic shock failure during hot gas defrost increases as coil volume increases and temperature decreases.²⁰ Accordingly, larger coils at lower temperatures have a higher risk of component failure, as exhibited at Millard. A large volume of hot gas will condense on a cold surface into a small volume of liquid.²¹ The greater the volume of hot gas, the larger the gas void created during the rapid condensation of vapor in the suction line, contributing to catastrophic failure.

Each evaporator coil at Millard had an aggregate capacity of 15 cubic feet of liquid ammonia or gas with a total of 60 cubic feet of ammonia for each blast freezer valve control bank. Because two evaporators (4 coils total) were assigned to the same set of control valves, when the suction valve suddenly opened, the total volume of each evaporator (totaling 60 cubic feet of hot gas at a pressure of 70 psig) was introduced into the low-temperature suction line. The large amount of energy stored in the four coils rapidly condensed to a liquid in the suction line, creating the condensation-induced shock that ruptured the evaporator piping manifold and rooftop piping. By grouping four large blast freezer evaporators together with one set of control valves, the opportunity for a large volume flow through the suction line enabled the catastrophic failure. The risk of such failure can be reduced by configuring each evaporator with its own individual set of control valves.

As the capacity of the evaporator coil increases, the hot gas defrost system requires a more detailed engineering analysis.²² Refrigeration system designers should avoid grouping multiple evaporators to one set of control valves. Had Millard assigned each evaporator to an individual set of control valves, only 15 cubic feet at 70 psig would have been released to the header when the control system reset signaled the suction stop valve to open. The lower volume of hot gas may have resulted in a minor shock event, such as an audible hammering or shaking, instead of a pipe rupture.

²⁰ Read, George. Design Practices to Prevent Hydraulic Hammer. IRC Workshop May 13 and 14 2009. Page 6 of 42.

²¹ Loyko, L. Hydraulic Shock in Ammonia Systems. IIAR 11th Annual Meeting March 12-15, 1989 Austin, TX

²² Briley, G.C., Hot Gas Defrost Systems for Large Evaporators in Ammonia Liquid. Overfeed Systems, IIAR 14th Annual Meeting, Miami, FL, March 1992.

5.3 OPERATIONAL ISSUES

5.3.1 Short Pump-out Time

“Pump-out” is the first step in the defrost cycle. It is intended to remove residual liquid ammonia in the evaporator by using heat from the room air to vaporize, or boil off the liquid ammonia resident in the coil prior to the introduction of hot gas. Removing the liquid from the coil increases the efficiency of the defrost process by allowing the heat from the hot gas to be applied directly to warm the coil surfaces instead of warming residual liquid refrigerant remaining in the coil. During shutdowns or low-load periods, liquid refrigerant can accumulate in the bottom evaporator coils. If hot gas defrost is initiated on an evaporator that has been operating under light load conditions for an extended period, the evaporator may be vulnerable to shock.²³ Therefore, it is important to ensure pump-out times are long enough to remove the majority of liquid ammonia from the coils. If the evaporator piping isn’t thoroughly pumped out, any standing liquid in the evaporator can cause hydraulic shock when the hot gas is introduced.

Though it is likely the bleed cycle omission directly resulted in the hydraulic shock at Millard, the short pump-out time at the beginning of the defrost cycle likely did not fully clear the residual liquid ammonia from the evaporator coil, creating another condition that may have contributed to the event. According to Millard documentation, the blast freezer evaporator defrost timer was originally intended to run the pump-out cycle for 20 minutes; however CSB investigators reviewed control system data for the evaporators and found that it only lasted 15 minutes on the days leading up to the incident. Though 15 minutes may have been sufficient during normal operations, the power outage, followed by a low-load period in the middle of the night, allowed for the low-temperature liquid ammonia to fill the coils and settle in the bottom evaporator. When the hot gas was introduced to the blast freezer evaporator minutes before the manual interruption, the hot, high-pressure gas may have propelled the remaining liquid through the evaporator coil, resulting in a rupture on the piping manifold. A longer pump-out time would have cleared a greater quantity of liquid refrigerant from the coil prior to the hot gas cycle.

5.4 AMMONIA SYSTEM EMERGENCY SHUTDOWN

Immediately after discovering the release, two Millard employees went to the roof to mitigate the release by manually closing valves to isolate the associated equipment and processes. The employees attempted to isolate the source of the leak, but all other equipment connected to the low-temperature suction header was still in operation. Based on a review of control system data, other blast cell evaporators kept operating and ammonia fed to the ruptured suction line. This caused an intermittent expulsion of ammonia as pressure from the evaporators increased upstream of the failure, as evidenced by security camera footage and reported by emergency responders. Based on a review of security footage, the ammonia cloud continued to travel to the south of the Millard roof until about 11:00 that morning, about 2 hours after the initial release.

The use of the emergency stop button (e-stop), located in the Millard control room, would have shut down the compressors and pumps, and de-energized valves. Shutting down these components would have stopped the circulation of ammonia into the other evaporators and decreased the quantity of ammonia that flowed out to the failed suction line located

²³International Institute of Ammonia Refrigeration (IIAR). IIAR-116 - Guidelines for Avoiding Component Failure in Industrial Refrigeration System Caused by Abnormal Pressure or Shock. (1992).

on the roof. Because the employees attempted to isolate the release to avoid shutting down refrigeration for the entire facility, the release quantity was significantly greater than it would have been had they simply shut the system down.

Millard identified that the e-stop button should have been activated earlier by the Plant Engineer in their internal investigation report of the incident. The Millard emergency procedure instructed personnel to “locate the leak” and attempt to isolate the leak. The procedure stated that “control of an ammonia leak will require that the leak be stopped by valving off a pipe or piece of equipment.” The procedure went on to define criteria for when the e-stop button could be activated including natural disasters or any other emergency when shutdown is deemed necessary by authorized personnel.²⁴ However, on the day of the incident, the plant engineer made the decision to locate and isolate the release instead of shutting down the ammonia system. The activation of the e-stop would have reduced the volume and the duration of the ammonia release, and lessened offsite consequences.

6.0 LESSONS LEARNED

Anhydrous ammonia refrigeration systems are susceptible to hydraulic shock mechanisms during the transition between hot gas defrost and normal cooling in the refrigeration process. Damaging hydraulic shock events can result in a release of highly toxic and flammable ammonia. Hydraulic shock events and ammonia releases can be avoided by adhering to the following lessons learned from the Millard incident:

REFRIGERATION SYSTEM DESIGN:

1. For the design of ammonia refrigeration systems, avoid grouping multiple evaporators to a single set of control valves. This is especially important for large capacity evaporators in excess of 20 tons. Evaporators with hot gas defrost systems should be controlled by individual valve control groups dedicated to each evaporator coil.

REFRIGERATION SYSTEM OPERATION:

2. Program or configure defrost control systems with interlocks to ensure the low-temperature liquid feed and hot gas remain isolated during the initiation and termination of the hot gas defrost cycle in the event of a power outage, cycle interruption, or other abnormal situation. Program the defrost control sequence to automatically depressurize or bleed the coils in defrost upon restart after an outage or interruption, prior to opening the suction stop valve to set the evaporator into cooling mode.
3. Avoid the manual interruption of evaporators in defrost and equip control systems with password protected controls to ensure only trained and authorized personnel have the authority to manually override system processes.
4. For time-initiated hot gas defrost systems, ensure pump-out times are long enough to remove a sufficient amount of residual liquid refrigerant in the evaporator coils prior to introducing hot gas, especially after low-load periods or power outages.

²⁴ OSHA cited Millard for not having a procedure for activating the emergency stop button during an emergency shutdown as required by PSM; however, it was later determined that the Millard Theodore plant Emergency Action and Response Plan included shutdown procedures for the control of ammonia releases. Accordingly, the OSHA violation was vacated.

RESPONDING TO AN AMMONIA RELEASE:

Design and operational considerations are most important in the prevention of hydraulic shock incidents and other events that could result in an ammonia release. If an ammonia release does occur from ruptured equipment, lessons learned from the Millard incident can also be applied to reduce the quantity of released ammonia from the refrigeration system.

5. In the event of an ammonia release that cannot be promptly isolated, activate the emergency shut-down switch to de-energize pumps, compressors and valves instead of attempting to isolate leaking equipment while the refrigeration system is running. Shutting down the equipment will stop the circulation of ammonia and limit the release of additional ammonia from components running upstream of failed equipment or piping.

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