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Mechanical Integrity and Carbon Steel Refrigerant Piping

By **Daniel J. Dettmers**, Member ASHRAE; and **Douglas T. Reindl, Ph.D., P.E.**, Member ASHRAE

The goal of the U.S. Occupational Safety & Health Administration's process safety management (PSM) standard (29 CFR 1910.119, *Process Safety Management of Highly Hazardous Chemicals*) is to protect people from large-scale catastrophic incidents that can occur in systems using hazardous or flammable chemicals. A portion of the PSM standard requires that end-users develop and implement mechanical integrity (MI) programs capable of managing the ongoing safe operation of systems that use hazardous chemicals, including the ammonia used in many large-scale industrial refrigeration systems.

The intent of the mechanical integrity provision in the PSM standard is to ensure the safety of plant personnel by preventing releases that result from equipment

failure. This rule has produced significant changes in the industrial refrigeration community from reactive maintenance to proactive or predicted maintenance

in an effort to meet the requirements of this standard.

The PSM standard has driven many industrial refrigeration end-users to develop and implement mechanical integrity programs that include regular equipment inspections and tests. An effective mechanical integrity program pays dividends in protecting people but can also deliver collateral benefits to the business including: decreased likelihood of unscheduled downtime, reduced insurance rates, and improved public image (by fewer chemical releases). Less downtime for the refrigeration system allows higher production rates while fewer uncontrolled refrigerant releases improves plant relations with both their communities and regulatory agencies.

About the Authors

Dan Dettmers is associate researcher and **Douglas T. Reindl, Ph.D., P.E.**, is a professor and director at the University of Wisconsin-Madison's Industrial Refrigeration Consortium in Madison, Wis.



Photo 1 (left): Uniform corrosion on the exterior of refrigerant piping. **Photo 2 (center):** Pitting corrosion on the exterior of refrigerant piping. **Photo 3 (right):** Erosion on the inside of a valve due to change in direction of a two-phase refrigerant.

An important part of developing and implementing an effective mechanical integrity program is identifying those areas of industrial refrigeration systems that present risk of refrigerant releases. Historically, refrigerant piping has been the system component involved with larger scale releases making it a priority to address as part of a plant's mechanical integrity program. In comparison, compressors, refrigerant pumps, and vessels also require attention and preventive maintenance but these components tend to be centrally located making inspections and tests easier. The distributed nature of piping (including valves) as it runs throughout the facility makes inspection and testing to insure its mechanical integrity more challenging.

Because the first step in establishing an effective MI program is recognizing the common failure modes of carbon steel refrigerant piping, our emphasis here is on introducing basic mechanisms of mechanical integrity failures applicable to carbon steel piping (and vessels). We also provide some basic information on practices that can be taken to prevent loss of mechanical integrity of piping systems. Armed with this information, industry professionals can work with end-users to facilitate the implementation of more robust mechanical integrity programs.

While the focus of this article is on ammonia refrigeration systems, most of the failure modalities discussed also apply to refrigeration systems with carbon steel piping and vessels using other refrigerants. An MI program should be implemented whether the refrigerant is ammonia, carbon dioxide, R-22, R-507 or any other halocarbon refrigerant. Using other materials, such as stainless steel or copper, introduces a whole new set of failure mechanisms. For example, stainless steel is extremely susceptible to stress corrosion cracking in the presence of chlorides. Anyone dealing with copper should be aware of formicary (ant's nest) corrosion.

Pipe Wall Material Loss

By far, the most common failure mode for carbon steel piping is by wall material loss from external corrosion (rusting) due to prolonged exposure to water, and most often occurring

under the piping insulation system. Corrosion is defined by the National Association of Corrosion Engineers (NACE) as “*the deterioration of a material, usually a metal, by reaction with its environment.*”¹ The two most common forms of corrosion found in ammonia refrigeration systems include uniform corrosion and pitting corrosion. A third mechanism of wall material loss is attributable to “erosion.” The first two are found on the external surface of the pipe, while the last is mostly internal.

Uniform corrosion is the gradual thinning of wall material due to the oxidation of material by progression of the corrosion process. Visual examination of the surface alone may not yield an adequate indication of the corrosion's severity since the entire surface is being uniformly removed. If uniform corrosion is suspected, a wall thickness measurement using an ultrasonic thickness gauge or similar device is recommended to quantify the material loss. *Photo 1* shows uniform corrosion on the exterior section of carbon steel pipe.

Many factors can conspire to increase the rate of corrosion including oxygen (presence of dissolved oxygen in water accelerates corrosion), solutes (presence of acids accelerate corrosion), and temperature (corrosion rates double for every 18°F [10°C] rise in temperature). Unfortunately, several of these variables are largely uncontrolled in refrigeration applications.

Pitting corrosion is the localized material loss of a pipe forming one or more cavities or pits in the surface. Visual identification of pitting corrosion is easy and obvious but only if the pitting exists in the vicinity of the pipe being examined. The severity of the pitting is dictated by the density of the pits and by the depth of the deepest pit. Failure usually occurs when a pit fully penetrates the wall. *Photo 2* shows the variability of wall material loss by pitting corrosion.

Erosion is the loss of material due to the repeated impingement of suspended solids or of high momentum two-phase refrigerant flow impinging on internal surfaces. One of the highest risk areas for erosion occurs on the outer radius of an elbow when suspended solids (i.e., weld slag, dirt, or other debris) impinge due to the change in direction of flow. Similarly, ammonia liquid droplets entrained in ammonia vapor and

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Photo 4 (left): Corrosion to the pipe surface is not limited to the point of the insulation system failure. The piping down to the elbow and beyond also should be inspected. Photo 5 (above): The ever-present ice on the jacket of this pipe indicates possible failure of the insulation system.

accelerated to higher velocities can erode the interior portions of a vessel (e.g., wet return or makeup inlet nozzles) or piping elbows in the same method as the debris-laden refrigerant. One example illustrating the effects of erosion is shown in *Photo 3*, which shows the internal loss of wall material on a globe valve caused by the change in direction of two-phase refrigerant flow through the valve. Once eroded, these valves become unable to stop refrigerant flow.

Since it occurs internally, erosion of piping is difficult to detect without the use of ultrasonic thickness gauges, radiography or other nondestructive inspection technologies suitable for quantifying wall thickness. Inspections aimed at identifying the extent of erosion should be concentrated on areas of a piping system with directional changes such as elbows, valves or nozzles where the refrigerant flow is high velocity, two-phase or particulate-laden.

External Corrosion/Corrosion Under Insulation

Corrosion under insulation (CUI) is not a distinct form of corrosion; rather it refers to the location where wall material loss is occurring—underneath the insulation material and on the external surfaces of piping (and vessels). Because it is one of the most common and most difficult to detect modalities of mechanical integrity loss in industrial ammonia refrigeration systems, we consider it separately here. The difficulty in detecting CUI is attributed to the fact that visual inspection techniques are not capable of positively locating those portions of a piping system actively losing wall material by the corrosion process due to insulation system's presence.

The occurrence of CUI is opportunistic and usually occurs when water or water vapor migrates into an insulation system and reaches underlying carbon steel surfaces. The source of moisture is variable but often originates from rain, a water leak,



Photo 6: This pipe carried subcooled, high-pressure liquid ammonia. At installation, only the portion of pipe on the right was painted. When the insulation became saturated with water, corrosion reduced the pipe on the left to one-sixth its original thickness while the painted pipe suffered little damage.

excessive sanitation overspray, discharge from a sprinkler system, or by the water vapor pressure difference between the pipe surface and the environment pulling ambient moisture into the insulation system. Once water has infiltrated the insulation system and migrated to the pipe surface, uniform or pitting corrosion can readily occur.

The best method to inhibit CUI is to prevent moisture from contacting the pipe surface. This protection starts with an insulation system that features a suitable outer jacket layer along with a properly applied vapor retarder. In addition, specifying and installing a good closed cell insulation material that is tightly bound to the pipe further inhibits moisture migration. Once placed in service, the insulation system must be properly maintained. Unfortunately, most insulation systems are not promptly repaired or replaced until there is an externally obvious failure of the insulation system (e.g., punctured), which is often preceded by an undetected failure of the insulation. As a secondary defense, it is imperative to coat the piping with more than just the protection applied at the time of manufacture. Several options exist including prime-paint, two-part epoxy, enamel paints, and others. Lack of a protective coating on insulated components

can result in a premature failure without warning because the water causing the corrosion may enter the insulation system several yards away, flowing down to the point of failure.

Somewhat related to CUI, is the corrosion that can occur on uninsulated piping concealed in piping chases and

behind walls. The hidden location of this piping makes it difficult to visually inspect, making it susceptible to uniform or pitting corrosion.

Surfaces at the greatest risk of premature failure are those whose temperatures fluctuate above and below the freezing point of water. This temperature fluctua-

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tion can pull moisture into the insulation where it condenses and, possibly, freezes. Once frozen, the ice expands and irreversibly damages the insulation. Upon melting, a larger gap exists, which allows an even larger amount of moisture to be trapped and do further damage to the insulation system during the next freeze-

thaw cycle. Examples of these surfaces include defrost condensate return lines, liquid transfer vessels and wet suction return lines.

Piping locations at high risk for corrosion under insulation include:

- Low points in a piping system, such as elbows and horizontal runs of pipe.

If the insulation system is compromised, gravity can force the moisture to migrate to the lowest point where it collects and has the highest potential to cause corrosion.

- Piping expected to cycle in temperature, especially above and below freezing or near the freezing point.
- Suction piping, especially wet suction returns. These often contain a mixture of refrigerant liquid and vapor below 32°F (0°C), but the low heat transfer coefficient of the ammonia vapor does not always keep the top of the pipe below freezing resulting in a freeze/thaw line along the length of the pipe.
- Ammonia defrost condensate return lines and liquid transfer lines from suction traps due to the temperature cycling.
- Locations requiring difficult insulation assemblies such as the connection point for instrumentation or a smaller pipe connecting to a larger diameter pipe.

Various methods are available for locating moisture or ice under insulation. The easiest is to perform a visual inspection for sections of damaged outer jacket on suspect piping. If damage is found, corrosion could be found immediately below the area with the damaged jacket or it could be “downhill” from the damaged area if the water has migrated to a lower section of the piping. Also, look for signs of deteriorated insulation beneath the outer insulation system jacket, such as continuous ice buildup, even during warm weather. Examples of these conditions are shown in *Photos 4* and *5*.

For owners who wish to inspect a system without removing the insulation, nondestructive inspection technologies are available. One approach is to use thermography to locate differences in the thermal conductivity and mass of the piping’s insulation caused by wet versus dry insulation, just as is done by the roofing industry. This is most effective when ambient temperature is changing rapidly at sunrise or sunset, but the aluminum outer jacket used on outdoor piping reduces the effectiveness of this technique.

Another nondestructive inspection technology relies on the use of a digital radiographic profiler. This method uses a radia-

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tion source and detector to determine changes in the density of the pipe and insulation system. When the device detects an increase in the density of the pipe and insulation, it is probable that this is due to the presence of water or ice trapped in the insulation. This technology has proven very effective at locating failed insulation.

Because insulation systems will fail at some point in their service life, underlying piping and vessels are at risk of CUI if left unprotected. At a minimum, insulated piping and vessels should be primed and painted to provide an additional layer of protection from corrosion should an insulation system fail. More robust coatings can also be applied that yield a greater level of protection as well. The need for base preparation of piping and vessels is illustrated by *Photo 6*, which shows a section of a subcooled high pressure liquid line whose insulation system previously failed. The segment of pipe shown on the right photo was primed and painted prior to being insulated while the photo on the left shows the same pipe where no paint was applied. Corrosion under the insulation reduced the wall thickness in the unpainted pipe to one-sixth that of the original painted pipe.

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Stress Corrosion Cracking

Stress corrosion cracking (SCC) is the initiation and propagation of microcracks caused by the combined effects of tensile stress coupled with direct surface contact with an enabling chemical.⁵ The stress can be externally applied, thermal, or residual from the manufacturing process. Interestingly, the onset and propagation of SCC does not require that the applied or residual stress be above the material's yield point. This stress, coupled with a susceptible materials and environment, causes small cracks inherent or formed in the material to propagate; thereby, relieving the material's stress. If the stress level is low, the cracks will self-limit (stop propagating) prior to reaching the outside surface of the pipe (or vessel) wall. If the stress level is high, the cracks have the potential to propagate completely through the entire wall thickness resulting in a leak. The propagation of SCC cracks is usually a slow process, 0.004 to 4.0 x10⁻¹¹ in./s.²

Iron-based alloys are particularly susceptible to SCC when subjected to a number of chemicals, including the combination of ammonia and oxygen. The mixture of anhydrous ammonia with oxygen appears to be a synergistic combination that can cause/contribute to SCC in low carbon steel and low alloy ferritic steels.^{3,4} In addition to carbon steel, systems that utilize copper and stainless steel can also suffer from SCC. Copper and copper alloys experience SCC in the presence of aqueous nitrates, nitrites, ammonia and steam. Likewise, the interaction of stainless steel and chlorides leaching from insulation, depositing from seaside air or introduced from human perspiration was one of the first instances where SCC was discovered.⁵

In a piping system, welds and the adjacent heat affected zones are areas potentially susceptible to stress corrosion cracking. Preexisting cracks and defects such as pitting can also serve as points of increased stress and therefore have heightened potential for SCC initiation. Detection of SCC is very difficult since

it originates on the interior of piping or vessels. With care, the internal cracking from SCC can be found using ultrasonic or radiographic inspection, but is most often discovered when the component either develops a pinhole leak resulting from the complete breakthrough of cracks to the outer surface. If SCC occurs in a vessel, it usually occurs within the first 18 months of construction.⁶ Most likely, this is because any residual manufacturing stresses that remained relived themselves through noncatastrophic internal cracking.

Bansch⁶ and others⁷ provide recommendations to prevent SCC including post weld heat treatment of vessels, limiting material minimum yield stress to no more than 55 ksi (379 MPa), and minimizing the accumulation of non-condensable gases (by regular purging or by the use of automatic. These recommendations have been made for the protection of vessels, but similar recommendations have not been developed specifically for piping. It is likely that similar measures also will protect refrigerant piping.

Weld Discontinuities

Discontinuities in welds, which can be considered “defects” by the refrigerant piping code (ASME B31.5, *2006 Refrigeration Piping and Heat Transfer Components*), are practically unavoidable due to the many influencing factors that are difficult or impossible to control during the welding process in either a shop or field under varying conditions. Weld discontinuities can be created by the improper joint preparation, improper weld technique, inappropriate selection of weld materials, or from welder ineffectiveness. Proper inspection by both the welder and inspector during the entire fabrication process, beginning with joint fit-up prior to welding, can significantly reduce weld discontinuities and defects.

Since radiographic or ultrasonic inspection is not explicitly required under the refrigerant piping code (ASME B31.5) on newly constructed piping for most refrigerants, two common weld defects that go unidentified are the lack of penetration (or lack of fusion) and slag inclusion. Performing a visual inspection of the final weld only provides an indication on the condition of the last pass. Many recommend visual inspection of the root pass(es) on butt welds and ultrasonic or radiographic inspection of a small percentage of all welds upon completion.

Developing a Visual Inspection Procedure

Unlike other inspection techniques, no standard for the visual inspection of refrigerant piping currently exists. Some guidance can be found in Article 9 of Section V of the ASME Boiler and Pressure Vessel Code, which was written for the construction of pressure vessels. The code provides recommendations for creating a visual inspection procedure including a test to establish the adequacy of the program. It also specifies a minimum light intensity of 100 foot-candles (1,000 lux) on the surface and lists the physical requirements of the inspector.

IIAR Bulletin 110⁸ recommends that a visual inspection of all pressure vessels be performed annually. Many MI programs have adopted this same time frame for the inspection of their

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piping. The inspection is typically conducted by plant personnel and performed in conjunction with other activities such as verifying valve tags, inspecting valves and other duties that would also require walking the length of the piping system.

Additional information may be found from inspection documents from other industries. A list of probable CUI locations is provided by the American Petroleum Institute⁹ while welding inspection advice originates with the American Welding Society.¹⁰ For assistance in determining the condition of surface corrosion, the Society for Protective Coatings¹¹ provides a picture book of various types and severity of corrosion.

Conclusion

Many industrial ammonia refrigeration system owners are continuing to develop and refine their mechanical integrity programs as part of their overall efforts aimed at having effective PSM programs. Because resources devoted to inspection and testing are limited, owners must prioritize their efforts based on the risks of failure. As an equipment class, refrigerant piping is a vulnerable area and corrosion under insulation the primary concern. Proper prevention, in the form of a good insulation system including a coating on the pipe, will help extend the life expectancy of carbon steel piping, but a thorough inspection and testing program should also be implemented.

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