VESSELS AND PIPING

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1.0 SCOPE

This document contains loss prevention recommendations and supporting information for vessels, piping, and systems used in the storage, transfer, or processing of solids (powders, granules, etc.), liquids, and gases.

The term “vessels” includes pressure-retaining process vessels, unfired pressure vessels, storage vessels, heat exchangers, isostatic presses, as well as atmospheric tanks, silos, bins, etc. The term “system” as used in this data sheet refers to the combination of a vessel or vessels and the connected piping and piping components.

For vessels, piping, and systems that contain ignitable liquids, see Data Sheets 7-88, *Ignitable Liquid Storage Tanks*, and 7-32, *Ignitable Liquid Operations*. Note that the hazards of explosion, detonation, deflagration, and fire are beyond the scope of this data sheet. See Data Sheet 7-46, *Chemical Reactors and Reactions*, for reactor guidance.

The recommendations in this document are minimums established by FM to ensure optimum performance of vessels, piping, and systems for intended service. Implementation of alternative practices that provide equivalent property protection is also acceptable.

1.1 Hazards

Vessels, piping, and systems represent varying magnitudes of exposure depending on their service and environment. Vessels, piping, and systems are present in many occupancies and in various processes in each occupancy, containing many different process fluids. Therefore, the vessels, piping, and systems of the different processes at each location need to be evaluated independently. Failure to evaluate the vessels and piping for each process or system at a location may lead to unidentified exposures.

Additionally, due to the wide use of this equipment, vessels, piping, and systems are constructed from many different kinds of materials and are subject to various types of damage mechanisms. This means the inspection, testing, and maintenance of vessels, piping, and systems will change depending on their service and environment.

1.2 Changes

October 2024. Interim revision. Made editorial changes for additional clarity. Added power and process piping definitions to the glossary of terms.

2.0 LOSS PREVENTION RECOMMENDATIONS

2.1 Introduction

The range of applications in which that the equipment covered by this data sheet may be used is very broad. As a result, recommendations are usually also very broad. In the cases of a few vessel and piping types, more specific advice is provided. For more information, see the data sheets applicable to the specific service of the vessel or piping system.

The following recommendations are, in general, for the vessel and associated piping “system.” Recommendations applicable to specific vessels are also usually applicable to the associated piping. Note that in some systems there may be relatively large diameter piping of comparatively thin wall used for collecting vapor or dust. This piping is commonly known as “ducting.”

Use FM Approved equipment, materials, and services whenever they are applicable. For a list of products and services that are FM Approved, see the *Approval Guide*, an online resource of FM Approvals.

2.2 Construction and Location

2.2.1 For pressure vessels, consider pressure vessel rupture damage potential in the design of and location of vessels and the surrounding building. Vessels containing pressurized liquid above its ambient boiling temperature or above its critical pressure may fail catastrophically, with extensive collateral damage. See Data Sheet 1-44, *Damage-Limiting Construction*, for guidance on design and construction of buildings.

2.2.2 Where possible, locate equipment to limit collateral damage in the event of equipment failure (loss of containment).

2.2.3 Provide secondary containment (e.g., a dike or barrier that will contain the liquid, or floor drains and piping to holding tanks) for tanks and vessels that hold liquids that will damage property if released.

2.3 Occupancy

2.3.1 Remove accumulations (dust, debris, snow, etc.) from vessels, tanks, and piping to prevent structural overloading and to eliminate any potential hinderance or obstruction of operation.

2.4 Equipment and Processes

2.4.1 Design and construct equipment to a recognized code (see Section 4.2) or have an engineering analysis performed to ensure the equipment is fit for the intended service. In addition to the operational loads, include in the analysis provision for external loads on the equipment due to natural hazards or other location specific concerns (wind, earthquake, precipitation, flood, surface water, freeze, etc.).

2.4.1.1 Where feasible, design and construct equipment or systems that may be subject to vacuum for full vacuum to avoid having to provide and maintain vacuum-relief devices.

2.4.1.2 For metallic equipment operating above 3000 psig (20.7 MPa), provide a fatigue analysis for vessels and piping. Follow practices described in a recognized code such as EN 13445 or ASME BPVC, Section VIII, Division 2 or 3 (whichever is more applicable).

2.4.1.3 For equipment with quick-actuating closures, see Appendix D.

2.4.2 Use materials and fabrication or construction processes that are less susceptible to the known damage mechanisms of the intended service of the equipment, even if such processes are not required by jurisdictional code or construction code (e.g., post-weld heat treatment [stress relief] of welds in carbon steel vessels).

2.4.3 Implement a QA/QC program on site to ensure equipment is fabricated and installed properly. When fabricating and installing equipment with various grades and compositions of material on site, use a form of positive material identification (PMI) to ensure the correct materials are being used.

2.4.4 Retain all design documentation, including material specifications and baseline inspection, as well as QA/QC and repair records. Use these records in developing the asset integrity program. Also use them to evaluate the condition of the equipment, determine if corrective action is needed, determine appropriate repair methods, and determining remaining service life.

2.4.5 For systems intended for operation at atmospheric pressure, provide the greater of the following: the relief vent capacity required for overpressure relief during filling, or the relief vent capacity required for relief during fire exposure. Also provide sufficient relief vent capacity to prevent vacuum collapse during use (contents extraction, draining or collapse of vapor in the system) unless the system is designed for full vacuum service.

For equipment containing ignitable liquid see Data Sheet 7-88, *Ignitable Liquid Storage Tanks*.

2.4.6 Provide overpressure protection for systems intended for pressure operation set at or less than the maximum allowable working pressure (MAWP) of the weakest system component. There are many ways to achieve overpressure protection. Three common options are listed below.

A. Provide pressure-relief devices with sufficient relieving capacity to prevent exceeding the MAWP. This includes vacuum relief for systems not designed for full vacuum that may be subjected to vacuum. Install these relief devices so plugging by system contents is avoided. See Data Sheet 12-43, *Pressure-Relief Devices*.

B. Implementation of overpressure protection by system design. Design the equipment and system to be able to withstand any credible overpressure scenario. An example of this type of system is described in *ASME Boiler and Pressure Vessel Code* (BPVC) VIII, Division 1, (Rules for Construction of Pressure Vessels) UG-140, “Overpressure Protection by System Design.”

C. Provide a process protection scheme to begin shutoff of system inputs at 90% of system MAWP, and to open vents at 95% of MAWP. The intent of this arrangement is to permit operation at the necessary process pressure and avoid operation of safety relief valves or rupture disks, which may force interruption of the process.

2.4.7 Provide instrumentation, controls, and safety devices to ensure equipment does not experience pressure, temperature, or flow in excess of the intended design conditions during normal and transient operation. If instrumentation and controls are used without passive safety devices to control the process variables, see Data Sheet 7-45, *Instrumentation and Control in Safety Applications*.

2.4.8 Where corrosion or erosion is predicted by the asset integrity program (see Data Sheet 9-0, *Asset Integrity*), specify a corrosion/thinning allowance or use materials (base materials, liners, claddings or coatings) which are resistant to corrosion or erosion in the design of the equipment. This will help extend system life by extending the amount of time it will take for the wall thickness to be reduced below the minimum required for continued safe operation of the system components (consider material loss from both internal and external means).

2.4.8.1 When constructing a steel-reinforced or pre-stressed concrete vessel, apply the cement to at least the designer's specified thickness. Typically, a minimum of 1 in. (25 mm) is needed to minimize corrosion.

2.4.8.2 For buried metallic piping, provide a cathodic protection system.

2.4.9 Provide appropriate external corrosion protection for vessels, piping and systems.

2.4.9.1 Select and apply a protective coating material that will resist the expected ambient environment. This is the best way to prevent external corrosion. Effective coatings for prevention of corrosion are those that are suitable for immersion in water. Technical documents produced by industry organizations, such as the National Association of Corrosion Engineers (NACE), can be of assistance in determining the right type of coating to use for a specific application.

It is not uncommon for component surfaces to be cleaned and have a primer applied in preparation for insulation. Primers are not designed to be protective coatings. Generally, only coatings designated for immersion under water provide adequate corrosion protection. Use of such coatings will also be beneficial for protection of the material during periods when insulation must be removed.

2.4.9.2 If insulated, select an insulation material that contains a low concentration of elements that could damage the pipe if moisture is present (e.g., leachable chlorides). Provide a weather-tight covering for the insulation. To avoid corrosion under insulation, it is vital that no moisture enter the insulation system from pipe system leaks or external sources.

Installing and properly maintaining insulation is critical to preventing corrosion under the insulation. Select and install insulation to prevent moisture from entering the system. Install insulation as follows:

A. Face all seams downward so water will be shed rather than providing a path for moisture to enter the system.

B. Install only dry insulation. If insulation becomes wet while in storage, dry it out thoroughly before installing.

C. Install insulation only during dry conditions to prevent water from becoming trapped inside during installation.

D. If installation is halted, seal off all openings to prevent wetting of the partially exposed insulation.

E. If insulation is removed, cover the exposed surfaces to prevent wetting, and keep the insulation dry if it is to be reused.

F. Reinstall insulation as soon as possible, being sure to dry previously exposed surfaces.

2.5 Operation and Maintenance

2.5.1 General

2.5.1.1 Post the system operating instructions and precautions where operators can refer to them. Ensure instructions address any operating actions that could damage the system (e.g., maximum fill level or maximum withdrawal rate).

2.5.1.1.1 Develop a system startup procedure to ensure the equipment is vented, drained, filled, and/or pressurized properly. Ensure all drain traps are clear to prevent liquid accumulations. Also ensure that the equipment is not pressurized until the shell temperature is well above the nil ductility transition temperature for the material (to avoid brittle fracture).

2.5.1.1.2 Develop and enforce pressure boundary flange bolting procedures. Ensure specific bolting procedures are in place for pipe and vessel flange connections containing hazardous, ignitable, corrosive, high-temperature, and/or pressurized fluids. Include the following bolting procedures for pressure boundary flanged connections:

- Bolt tightening sequence
- Torque or tension requirements and any allowed lubrication
- Flange joint alignment
- Procedure to ensure the use of proper bolts, studs, nuts, gaskets, and any necessary electrical isolation
- All bolts in place
- Nuts engage the thread for full depth of the nut
- Written instructions and training program
- Audit program and routine inspection of work completed

2.5.1.1.3 Where potential open routes to atmosphere exist (e.g., nozzles for draining, mixing, sampling, etc.) ensure the potential open route is properly controlled to prevent inadvertent discharge from a leaking or slightly open valve. This could include using two isolation valves, caps, plugs, blind flanges, etc. Ensure vents intended to be open to atmosphere are not isolated.

2.5.1.2 Calibrate and functionally test system interlocks and protective devices in accordance with FM data sheets, as recommended by the system supplier, the local jurisdiction, or in accord with accepted industry practice. Where no other guidance is available, functionally test every 12 months. Document all testing.

2.5.1.3 Develop and implement layup procedures to prevent corrosion or freeze damage during idle or shutdown periods. Some potential layup strategies are passivation, filling with inert gas, dehumidification, venting corrosive gases from high points, heat tracing and draining from low points. See Data Sheet 9-18, *Prevention of Freeze-Ups*, for additional guidance on preventing freeze damage.

Include the following layup procedures:

- Intended duration of layup for given methods
- Necessary inspection, testing, and maintenance (ITM) activities to ensure continuous effective layup of the equipment
- Necessary ITM activities after layup period has concluded to ensure equipment is in good operating condition.

2.5.1.4 Develop and implement a program to verify the equipment is adequately designed, installed, operated, maintained, and protected during its service life in accordance with Data Sheet 9-0, *Asset Integrity*. Include all physical methods of protecting the equipment or system from the process medium (e.g., coatings, cladding, and/or linings), dead legs, valving and instrumentation. Maintain written records of all inspection, testing and maintenance activities.

A. Visually inspect all vessels and piping externally for obvious signs of deterioration at least annually, or when upset events occur. More frequent inspection may be recommended in other data sheets or necessary due to service conditions. Include the support structure or system for the equipment (e.g., hanger supports on piping systems, structural steel, concrete foundations for vessels or fireproofing). Maintain a record of support structure or system inspection during full load and cold conditions for conformance to specified settings.

B. Perform detailed inspections of all vessels and piping materials at intervals using techniques as determined by the asset integrity program. Inspection intervals and nondestructive examination (NDE) techniques may be recommended in other data sheets, OEM guidelines, industry documents, or required by jurisdictional authorities. Have the scope of the assessment program developed by a qualified person familiar with both industry practice and the specific system, and executed by a person having demonstrated the ability to assess vessel and piping condition.

C. Reassess the inspection program for any needed changes if system service conditions are modified in any way.

D. Implement an inspection program to identify corrosion under external coating, fireproofing, or insulation at facilities with susceptible vessels or piping. While the mitigation practices can greatly reduce the probability of CUI/CUF occurring and reduce the need for inspection of CUI/CUF, inspection is still required to confirm the mitigation practices are working properly. Ensure the program can do the following:

1. Identify compromise of primary protective barrier (e.g., the coating, fireproofing or insulation jacket).
2. Identify moisture intrusion under the primary protective barrier.
3. Confirm thickness of the pressure-containing material.
4. Promptly correct any deficiencies.

2.5.1.5 Evaluate equipment or systems that have experienced an excursion beyond design parameters. Base the scope of the evaluation on the extent of the excursion (pressure, temperature, flow, displacement of the system component, or combination). For relatively minor excursions, an expert may be able to determine the condition of the system by analyzing operating records. For other excursions any of a variety of NDE techniques may be employed and, for some excursions, material may need to be removed from the component for evaluation. In some cases, other systems or structures associated with the affected system may also require evaluation.

2.5.1.6 If hydrostatic (liquid pressure) or pneumatic (gas pressure) testing is required, use the lowest test pressure necessary. Confirm the temperature of both the component being tested and the test fluid is maintained above the component material nil ductility transition temperature (to avoid brittle fracture during the test).

2.5.1.7 If adverse conditions are identified on equipment or systems, implement a deficiency management process to resolve the condition. See Data Sheet 9-0, *Asset Integrity*, for information on deficiency management programs.

2.5.1.8 For equipment with quick-actuating closures, see Appendix D.

2.5.2 Concrete Equipment

2.5.2.1 Examine concrete vessels internally and externally for indications of cracking, spalling, or crushing of the vessel and to evaluate the condition of external or internal steel reinforcement to determine the condition of the steel-reinforcing elements.

2.5.3 Metal Equipment Open, Vented, and Operating at Atmospheric Pressure

2.5.3.1 Inspect accessible interior walls, floor, and roof of metal tanks. This is particularly important when the tank is subject to corrosive or abrasive influence.

2.5.3.2 Examine fasteners securing the joints of bolted steel tanks. Tighten any loose fasteners. Restore the corrosion barrier on any fasteners that have corroded. Replace fasteners having cross-sectional area reduced more than 25% by corrosion.

2.5.4 Metal Equipment Operating ≥ 3000 psig (≥ 20.7 MPa)

2.5.4.1 Do not exceed system design process condition limits when operating. Provide instrumentation to monitor these process conditions. If these limits are inadvertently exceeded, suspend operations until the vessel is examined, and a new fatigue or fracture mechanics study is conducted. Use the results of the new analysis to determine remaining cyclic life and new NDE frequency. If deterioration is revealed during NDE, determine the dimensions (length, width, and depth) and orientation of imperfections for accurate results of the fatigue or fracture mechanics study.

2.5.4.2 Maintain records of operating data, including number of cycles and the maximum pressure and maximum temperature during each cycle. Record any unusual conditions during each cycle. Retain these records throughout the life of the system.

2.5.4.3 Completely inspect the vessel at installation or when resuming operation after an extended period of inactivity. Corrosion is likely in an idle system, particularly for systems utilizing water as process fluid.

2.5.4.4 Conduct at least annual visual and dimensional vessel inspections and examine high-stress areas with an appropriate NDE method to ensure that the surfaces are free of defects.

2.5.4.5 Conduct ultrasonic examination (UT) of the vessel after every 25% of the design cycle life or every five years, whichever comes first.

2.5.4.6 If indications of deterioration (cracks, corrosion, or other) are revealed, perform appropriate corrective measures and complete an evaluation of any potential repaired components using fracture mechanics techniques. This is to determine MAWP, cyclic life, and NDE frequency.

2.5.5 Wood Equipment

2.5.5.1 Maintain fluid levels in wood systems to prevent wood shrinkage and potential for leaks.

2.5.5.2 Examine hoops or bands encircling wood vessels and piping at least annually for evidence of deterioration. This is particularly important when the vessel or pipe is subject to a corrosive atmosphere or when any protective coating has outlived its useful life. When appreciable deterioration is discovered, replace the hoops or bands. If corrosion has already begun, remove the corrosion and coat the metal with corrosion-resistant paint.

2.5.5.3 Periodically examine staves of older wood vessels and piping for signs of deterioration and replace them as necessary.

2.5.6 Steel Coal Silos

2.5.6.1 Perform external visual inspections of steel coal silos for any obvious signs of damage, including cracking, deformation, and corrosion, focusing on the shell-to-cone joint. Where the silo design permits, perform inspections to assess the integrity of the shell-to-cone joint, as well as the cone and shell walls, from the exterior of the silo.

2.5.6.2 Conduct a design review of all steel coal silos in service. Determine silo age, history, design specifications, plus past and current operating conditions to help determine and prioritize further actions.

Determine the welding procedures and quality control programs used to confirm weld quality during original fabrication, repairs, or alterations performed on the silos. Include documentation of the implementation of these programs. If none were used or exist, establish them for future work.

2.5.6.3 Determine the scope of inspection, testing, and maintenance of steel coal silos in the current asset integrity program. Evaluate the implementation and results of any inspection, testing, and/or maintenance activities previously performed on the silos (including past inspection results and any repair/alteration activities).

2.5.6.4 If conditions or deficiencies are (or have been) identified that could reduce steel coal silo integrity, remove the silos from service or reduce the load of the silos until they can be fully inspected and any deficiencies repaired. When reducing load, the lower silo capacity should not interfere with the boiler operation.

2.5.6.5 For steel coal silos where failure of the silo presents an exposure to plant operations, perform internal inspections on the silo to assess the integrity of the silo supports, weldments, and wall plates. Perform internal inspections using an appropriate nondestructive examination method of the shell-to-cone welded joint. Once this preventive maintenance is established, reinspection intervals should be condition-based (inspection results, vessel design, operating history, etc.), but they should not exceed 10 years.

2.5.6.6 Review the asset integrity program to ensure critical assets, including steel coal silos, are evaluated and included in the program to assess their integrity and reliability.

2.6 Training

The scope of the training program will be highly dependent on the system service. See specific service data sheets, industry standards, and jurisdictional requirements for additional guidance.

2.6.1 Establish operator training programs in accordance with Data Sheet 10-8, *Operators*, and include the following aspects:

- The hazards of the materials and equipment used in the process.
- The plant’s procedures for jumpers, forces and temporary modifications of control systems.
- Scenarios that involve potential variances from normal operation, including the worst-case scenario.

- Understanding standard operating procedures (SOPs), alarm management, and emergency operating procedures (EOPs).

Additional guidance is provided in Data Sheet 10-8, *Operators*, including guidance for permit-to-work (PTW) systems.

2.1.6.2 For equipment with quick-actuating closures, see Appendix D.

2.7 Contingency Planning

2.7.1 Equipment Contingency Planning

When a vessel or piping system breakdown would result in an unplanned outage to site processes and systems considered key to the continuity of operations, develop and maintain a documented, viable vessel or piping system equipment contingency plan per Data Sheet 9-0, *Asset Integrity*. See Appendix C of that data sheet for guidance on the process of developing and maintaining a viable equipment contingency plan. Also refer to sparing, rental, and redundant equipment mitigation strategy guidance in that data sheet.

In addition, include the following elements in the contingency planning process specific to vessels and piping systems:

- Unique design/materials of construction, including vessels and piping purpose built for the intended service due to pressures, temperatures, and/or operating conditions
- Lined or coated vessels and piping (rubber/glass/epoxy/metal clad/explosion bonded)
- Possible contamination of a sterile environment/products or solidification of process materials
- Presence of unique or hard-to-obtain catalyst
- Remaining useful life/fitness for service of the vessel or piping system impacting replacement lead time

3.0 SUPPORT FOR RECOMMENDATIONS

3.1 Equipment and Processes: System Construction

Constructing vessels, piping, and systems to a recognized code better ensures the equipment will function as intended over the planned equipment life and will facilitate future repairs. Construction codes typically provide minimum safety requirements for construction of the equipment. They generally address minimum material thickness required for containing pressure, but do not provide specific guidance on material allowance for corrosion and erosion for specific service applications.

Process fluids may be caustic or acidic, leading to rapid corrosion. Process fluid may contain erosive material (dirt, sand) that may accelerate thinning of vessel walls and piping (erosion-corrosion and FAC). Additionally, specific requirements for structural loads beyond pressure containment are generally not provided in construction codes. These factors need to be considered to minimize damage to the equipment

3.1.1 Common Materials of Construction

3.1.1.1 Concrete

Commonly used for construction of silos, bins, hoppers, and tanks primarily for holding solid materials. While piping associated with these vessels may be concrete, it is more likely to be metallic, with some being plastic.

3.1.1.2 Metal

May be comprised of vessels or piping having square, rectangular, or circular cross sections. System elements may be formed by stamping, welding, bolting, or some combination. Quick-actuating closures may be provided on these vessels, particularly if operated in a batch mode.

Vessels ≥3000 psig (20.7 MPa) are typically comprised of vessels or piping having a circular cross section. System elements are typically fabricated by forging or welding. Wire-wound vessels are also relatively common. A system may incorporate bolted joints. Quick-actuating closures may be provided on these vessels, particularly if operated in a batch mode.

3.1.1.3 Wood

Wood vessels, piping, and system (penstocks) for liquid service are uncommon. Construction is typically wood stave with external metal hoops, bands, or cables.

3.1.1.4 Claddings and Linings

Materials such as Glass, Rubber, brick, ceramic or exotic metals may be used as internal claddings or liners in order to prevent the process media from coming in direct contact with the pressure boundary material. The cladding or liner require ITM activities to ensure they still provide the protection intended. Additionally, the cladding or liner material coupled with the construction techniques used to fabricate the equipment may lead to long lead times for repair and replacement options.

3.1.2 Metallic Systems

There is the potential for unanticipated failures even in equipment designed and fabricated to industry recognized codes and standards. Faulty layout and support design, poor welding practices, erosion or corrosion thinning due to poor material choice, and system design limits not consistent with process operating limits are a few of the more common root causes of loss. When released, pressurized fluid can cause collateral damage to nearby systems and equipment.

The photographs below show the potential collateral damage from the failure of a vessel at pressure (Figure 1) and under vacuum (Figure 2).

Fig. 1. Collateral damage following catastrophic failure of a hot isostatic press

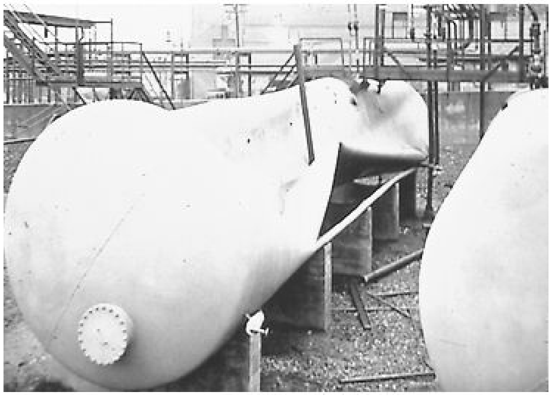

Fig. 2. Imploded tank caused by inadequate design

3.1.3 Bolting

Bolting is commonly used to connect sections of piping and fittings together as well as to attached valving, instrumentation and safety devices to different systems. These bolted connections are critical for ensuring the integrity of the pressure retaining boundary and preventing release of the process medium. An improperly bolted joint does not provide the same pressure retaining capability as a joint that is bolted as intended. Flanges are designed to sit in proper alignment to each other and for the nut-bolt assembly to transfer the forces on-to the flange.

Common deficiencies in bolted flange joint assemblies include misalignment of the joint, not tightening the bolts in the proper sequence to evenly distribute the clamping force, using incorrect torque specifications leading to increased stress in the bolts or inadequate pressure retaining capability, and not providing full thread engagement of the nut-bolt assembly, otherwise known as short bolting. A photograph of a bolted flange with missing bolts is provided below in Figure 3.

A loss of containment event created by a pressurized bolted flange failure will, at minimum, lead to an interruption to production. If the medium being retained under temperature and pressure is ignitable then an uncontrolled release to atmosphere could result in a serious fire or explosion. .

Fig. 3. Bolted connection on pressure vessel pressure boundary showing missing bolt

3.1.4 Buried Pipe

Buried piping systems present a unique concern within facilities. Since the piping system is not physically accessible without excavation, other measures need to be taken to ensure the integrity of the piping system. In some situations, remote visual examinations and/or in-line inspection (ILI, also known as “smart pigging”) may be feasible for inspecting the condition of the system. However, not all systems are able to be subject to remote visual and ILI and therefore you may not be able to directly determine the condition of the systems.

It is industry standard for new buried metallic piping to have exterior coatings provided to isolate the piping material from the soil environment. Additionally, cathodic protection (CP) is typically provided to ensure the potential difference between the piping material and the soil does not cause corrosion. Air to soil interface is one of the most prevalent locations for corrosion to occur on systems that span both aboveground and underground.

3.2 System Operation and Maintenance

3.2.1 Avoiding Temperature-, Pressure-, and Support-Related Failures

Due to operation within a process, vessels, piping, and systems are subject to pressure and thermal transients. These operating stresses can result in fatigue (possibly from inadequate or improper support or from cyclic service), adverse metallurgical changes over time (e.g., operation in or near the creep regime) or other deterioration of the equipment materials.

Operating and environmental factors may accelerate the rate of deterioration seen by the equipment. The accumulation of creep (formation of voids in the microstructure of the material from exposure to elevated temperature and stress), deterioration from inadequate support or cyclic service, and corrosion damage can lead to initiation and propagation of cracking conditions. If not detected by appropriate inspection, testing and maintenance activities and addressed by appropriate repair, the result may be catastrophic failure.

Periodic inspection of a system, including valving and sensors, and its supports assures the design bases are maintained, the equipment nozzle loads (forces and moments transferred to equipment by the piping system as a result of operation dynamics) are within limits and helps form a basis for remaining-life evaluations. Additionally, pressure and vacuum relief devices are typically installed in order to prevent damage from pressure excursions outside of normal operation. A photograph of a vacuum relief valve installed on a piping system is provided as Figure 4.

Inspection techniques are selected to ensure an acceptable probability of flaw detection. The success of any necessary repairs is ensured by employing experienced and qualified personnel who follow appropriate repair procedures.

Fig. 4. Eighteen in. (450 mm) diameter, weighted pallet vacuum relief valve (set pressure on order of inches of water [mm of water] with relief capacity on order of 20,000 scfm [566 m^2/min] air)

Piping support systems must be inspected and maintained to ensure stresses on critical equipment do not exceed the design limits and the piping is pitched properly to permit draining. Systems normally are designed to be equipped with low-point drains to permit the elimination of condensation. Long term operation of high temperature steam piping may lead to pipe creep and sag. When sag occurs or piping supports are damaged, new low points can develop. Condensation can then accumulate in these new low points. Internal corrosion and ″steam hammer″ during startup are common when condensation is allowed to accumulate.

The high impact stress from steam hammer may cause cracking or rupture of system components. A piping system typically moves during steam hammer, placing unplanned stress on the piping support system (hangers and snubbers). The supports, which may include major structural steel members, may be damaged and the pipe may be cracked at welded attachments for the supports. Piping components such as pipe spools and fittings may also rupture, especially at changes in direction. Common causes of this phenomenon in piping are rapid stoppage of flow, such as closure of steam turbine emergency stop valves, or the introduction of a large quantity of water into a hot steam line. In the former case, the energy in the momentum of the flowing steam must be absorbed by the piping system. In the latter case, the water flashes to steam, causing shock waves in the pipe. Pipe systems are provided with snubbers at changes in direction to reduce the amount of displacement, but resultant forces are transmitted to the structure. Water hammer is similar to steam hammer except water is incompressible, which can increase shock forces. Proper vent, fill, drain, and pressurization can mitigate steam or water hammer in piping systems.

Inadvertent entry of water into a hot steam pipe is a common cause of steam hammer in power generating facilities that incorporate reheat cycles. This typically results from leakage through a block valve. Leak-tight block valve integrity can be extended by operating practice (i.e., terminating flow using a control valve, which is designed for throttling service) before closing the block valve. Again, regular inspection, testing, and maintenance of these piping system components can mitigate this hazard.

Fig. 5. Utility reheat steam line failure along a pipe spool seam weld joint; timely inspection could have provided opportunity for corrective action

Effective inspection of in-service systems, with appropriate repair or replacement of damaged components, can mitigate critical system failures. This is a lesson some electric generating companies learned the hard way, after suffering catastrophic failures of seam-welded hot reheat piping in 1985 and 1986. A photograph of a seam-welded pipe after failure is provided in Figure 5. Subsequent investigations revealed that in some plants, seam-welded pipe had been substituted for the specified seamless pipe, and experience demonstrated seam-welded pipe was likely to develop cracking conditions associated with the seam-weld. Inspection programs for seam-welded pipe were initiated and reliable examination techniques have been developed. Many electric generating companies have replaced extensive seam-welded piping systems to avoid disastrous failures due to creep. Additionally, some design codes (ASME B31.1, B31.3) have introduced factors to account for the reduction in long-term creep strength as a result of having a seam weld.

3.2.2 Avoiding Corrosion- and Erosion-Related Failures

Corrosion and erosion reduce the thickness, and thus the strength, of vessels, piping, and systems. Corrosion can damage fasteners holding piping together, and when combined with stress, can result in cracking. Without timely detection and corrective action, the affected areas of the piping materials or joints will fail. This may lead to site production being interrupted and nearby equipment or structures being damaged.

Corrosion and erosion occurring inside critical components is not readily apparent during normal operations. External corrosion of insulated components also is not readily apparent. Without an inspection program, undetected thinning leads to failure and an unplanned outage.

Corrosion is a process of deterioration of metal. A common example is rusting of steel. The process is electrochemical in nature, involving the transfer of electrons from the metal to the surrounding environment. Corrosion may be general, occurring over a large area and appear uniform, or be local, occurring over a small area and appear as pits.

High fluid velocities, solid particles, or bubbles in the process fluid as well as high temperature and extremes in pH (acid or caustic) can increase the susceptibility or rate of corrosion.

Corrosion that occurs on insulated external surfaces is driven by trapped moisture and may be accelerated by constituents in the insulation, or water that has leaked into the insulation. This type of corrosion is commonly known as corrosion under insulation (CUI).

Erosion is a mechanical process. Typically, solid particles have an abrasive effect when they impact the metal surface. This abrasiveness can break the protective film on the material or scrape away material. The simultaneous combination of both the chemical corrosion process and the mechanical erosion process is known as erosion-corrosion and is often called flow-accelerated corrosion (FAC) in steels. A photograph showing the condition of a pipe after failure from solid particle erosion is provided as Figure 6.

Fig. 6. Solid particle erosion at a change in direction led to the failure of this pipe at a power generating station

3.2.3 Repair Methods

Metallic vessel and piping equipment may be required to be subject to repair as a result of deterioration that has occurred to the system or equipment during its operational life. The steps involved with the repair process may change based on the type of deterioration that has occurred, the materials the equipment was fabricated from, the process medium, and the size of or accessibility to the location requiring repair. Repairs should be performed in accordance with the requirements of the authority having jurisdiction, the original/most recent code of construction, or other recognized and accepted engineering standards.

Typical repairs on metallic systems involve repair welding. Welding is the same process often used in the fabrication of vessels, piping, and systems. In these types of repairs, the equipment is taken offline; the deterioration is identified, quantified, and removed; then welding is performed in order to bring the equipment back into a condition as good or better than when the equipment was newly constructed. The repair welding process can include many steps such as deterioration removal, initial non-destructive examination, preheating, welding, intermittent non-destructive examination, post-weld heat treatment and final non-destructive examination. The need or feasibility of these steps depends on the materials being repaired and the environment in which the repair is occurring.

There are also situations in which a repair is necessary and it is not feasible to remove the equipment from service. These repairs may be referred to as “on-stream,” “temporary,” or “emergency.” In these situations, a form of a secondary containment system is installed on to equipment while the equipment is still in operation. This secondary containment system is commonly referred to as a “leak clamp.” These leak clamps are typically only used when the risk of shutting down a process is considered unacceptable to the owner. Leak clamps can be found in many different types and sizes. Specific and dedicated procedures should be developed for any leak clamp repair. These procedures should include when each type of repair can be used, a timeframe for inspection/revalidation, specifics on installation, acceptable temperature and pressure conditions, and any supplemental requirements.

Depending on how the leak clamp is designed and installed, it can be considered a temporary or permanent repair. Temporary repairs are performed in order to be able to operate until the next available maintenance opportunity. At that next maintenance opportunity, the temporary repair is removed, and a permanent repair solution is implemented. If designed as a permanent repair, the repair solution would not be required to be removed at the next maintenance opportunity. The life cycle of both of these types of repairs should be considered and properly evaluated.

Any type of repair, other than replacement in kind, should use a management of change (MOC) program and should be incorporated in to the asset integrity (AI) program. For additional guidance on MOC programs, see Data Sheet 7-43, *Process Safety*. For additional guidance on AI programs, see Data Sheet 9-0, *Asset Integrity*. This MOC program should assess the specific situation to ensure that any additional hazards introduced from the repair are identified and addressed and that change in the existing hazards of the system are identified and addressed. All affected personnel should be notified of the change and documentation of identifying, tracking and monitoring the changes should be kept up-to-date until the change is considered complete.

3.3 Loss History

Loss experience with vessel and piping related incidents is extensive in industry. FM loss data for a recent 10-year period indicates vessel and piping exposures are present in many industries and can lead to significant losses.

3.4 Illustrative Losses

3.4.1 Pressure Vessels

3.4.1.1 Insufficiently Sized Vacuum Breaker Leads to Damage to Deaerator Tank

The site is a fully integrated solid bleached sulfate (SBS) paper mill that produces SBS paperboard from logs and chips with on-site power generation. A deaeration process is used to remove entrained air from the steam, consisting of two vertical deaerators known locally as No. 1 Deaerator Head and No. 2 Deaerator Head. The deaeration process normally operates with the No. 1 Deaerator Head in service and the No. 2 Deaerator Head normally isolated. The deaerator storage tank is 38 years old.

The black liquor recovery boiler (BLRB) was being flushed with feed water to clean out a black liquor contamination. The main feed water line that normally supplies the deaerator storage tank had two leaking gaskets. A supervisor and operator decided to isolate this line to replace the gaskets. It was decided to supply the deaerator storage tank through another line and manually control the feed rate and tank level to continue flushing the boiler. The deaerator storage tank was alternatively filled with deionized water (not the usual fill line) while No. 1 Deaerator Head operated with steam.

The water level in the storage tank became so high it began to fill the heater. This resulted in what Witnesses heard as a hammering event caused by the steam and water mixing in the No. 1 Deaerator Head. Within seconds a second water hammer type sound occurred followed by the sound of large amounts of rushing water. One witness observed that the deaerator storage tank footing was swaying. Reportedly, within 15 seconds, the space began to fill with steam/water vapor. It was reported that the High-Level Dump valve was not open. Procedures were initiated for normal shutdown of the operating systems to secure any steam and water flow.

While operators worked to lower the deaerator storage tank level, a vacuum was produced. This vacuum imploded the lower half of the deaerator storage tank, which disabled the tank. The deaerator storage tank appeared distorted on its lower half and showed signs of vacuum collapse. There were six holes of various sizes appearing to fish mouth inwardly. All adjacent piping and instrumentation were damaged. Photographs of the damage to the deaerator are provided in Figures 7 through 9.

Fig. 7. Photograph of failure location at center of tank

Fig. 8. Photograph of failure location at center of tank

Fig. 9. Photograph of shifted support

Improper operation of the deaerator unit (the bypass of the high-level dump valve and manual control of the water feed rate and water level allowing the deaerator storage tank water level to fill into the No. 1 Deaerator Head) led to the scenario that produced the vacuum on the vessel. The adequacy of the vacuum protection on the equipment will be considered.

3.4.1.2 Lack of Inspection, Testing, and Maintenance on a Deaerator Leads to an Explosion

A paper products manufacturing facility produces corrugated cardboard boxes from linerboard. The equipment involved in the incident was the Deaerator vessel that supplies feed water to the facilities two 500 HP, 250 psi (1.7 MPa) firetube boilers. The deaerator had been in operation for 6 years and was designed for 150 psi (1 MPa) at 400°F (204°C). It was protected by two safety valves set at 150 psi (1 MPa). The deaerator normally operates at 60 psi (0.4 MPa).

As the boilers were being brought up to pressure, the deaerator tank ruptured, causing the water inside to flash into steam, causing a large explosion. The explosion caused significant damage to the boiler room shutting down facility operations.

The facility was shut down for three days until a rental boiler could be up and running. Customer orders were able to be sent to their client owned facilities to ensure orders were met on time. The estimated rebuild time for the boiler room was 3 months. Photographs of the failed vessel and ensuing damage are provided as Figures 10 through 12.

The deaerator had not been inspected and the weldments suffered from cracking and wall loss that routine inspection, testing, and maintenance would have been able to identify. Additionally, it was revealed that the original welding of the vessel did not achieve complete penetration of the weld joints. It was unsure if there was complete joint penetration in the location of the failure.

Fig. 10. The boiler building showing the rear walls; the red arrow shows the area where the deaerator exited the building

Fig. 11. The boiler room, showing the two front walls completely blown to the ground

Fig. 12. The deaerator after colliding with the dumpster; part of one head is attached to the shell (the other head went out the front of the boiler room)

3.4.2 Piping

3.4.2.1 Lack of ITM Leads to Damaged Steam System

Lack of proper inspection, testing, maintenance and repairs of a university steam system results in escaped liquids, damage to boilers, and an extended steam outage. The lack of steam during freezing weather resulted in further damage to domestic and fire protection piping.

A university campus uses a central utility plant (CUP) housing multiple boilers to supply steam via underground steam piping to a multi-building campus. Steam is distributed through underground tunnels. Much of the piping system had deteriorated over time with lack of routine ITM activities, some of the equipment was more than 80 years old.

Water leaks from condensate return pipes resulted in a large makeup water demand, such a high make up water demand could not be properly treated by the system in place. Due to the lack of enough condensate return caused by leaking pipes, domestic water was added directly to the deaerator tank.

The boilers were overdue for internal inspections and had suffered significant amounts of tube leaks in the past. Operators discovered water leaking from one of the boilers and shut down the unit as they reported the CUP was filling with steam. Upon investigation they found portions of the steam tunnel had filled with six feet of water.

Other boilers also started showing signs of tube fouling and eventually suffered tube failures. Insufficient chemical treatment caused excessive scale to build up in the boiler water circuit tubes. This caused a fouling of heat transfer surfaces leading to localized overheating and water tube failure. To supplement steam production, rental boilers were installed to maintain the campus in operation.

Insufficient maintenance and haphazard repairs of an already deteriorated steam and condensate system led to the severe failures. The poor quality of the steam only added to the ongoing corrosion and subsequent leaks within the piping installed in the underground tunnels. Several buildings sustained steam releases from corroded steam piping into the buildings from openings from the tunnels, resulting in extensive damage to interior finishes and contents. Some buildings lost adequate heat resulting in frozen sprinkler or domestic water piping and subsequent leaks. Photographs of the dehumidification process and interior damage to the buildings are provided in Figs. 13 and 14.

Fig. 13 Dehumidication efforts

Fig. 14. Interior building damage

3.4.2.2 Water Hammer Causes Damage to Cold Re-Heat (CRH) Piping and Supports

This site is an electrical generation station with a total generating capacity of 626 MVA from a single steam turbine generator. Steam used to power the steam turbine generator is produced in a single coal fired boiler. The turbine consists of a High Pressure (HP) turbine, Intermediate Pressure (IP) turbine, and two coupled Low Pressure (LP) turbines to drive the generator. Steam from the boiler’s superheater is supplied to the HP turbine via a 25-inch (635 mm) main steam pipe. Exhaust steam from the HP turbine is carried by a 36-inch (914 mm) diameter Cold Re-Heat (CRH) pipe back to the reheater section of the boiler, where additional heat is added to the steam. A 42-inch (1067 mm) diameter Hot Re-Heat (HRH) pipe carries the steam from the reheat section of the boiler to the IP turbine. The IP turbine exhausts directly to the LP turbines.

A check valve was added to the CRH pipe to prevent the turbine blades from overheating due to windage. The check valve was installed at the bottom of the vertical section of CRH pipe just below the CRH attemperator spray connection. The CRH attemperator spray is used to control the steam temperature in the reheat section of the boiler and HRH steam to the IP turbine.

During a normal start-up of the turbine, the turbine is latched prior to being given the signal to start. Latching the turbine means that the Throttle Valve (TV) is closed, the governor valve (GOV) is open, the Hot Reheat Stop valve (RSV) is open, and the reheat Intercept Valve (IV) is open. The start-up rate and target speed are entered into the Digital Control System (DCS) system and the “Go” button is pressed on the DCS screen. The DCS system then opens the TVs and controls the speed increase of the turbine within the target start-up rate until the target speed is reached. When the turbine is tripped, the TVs, GOVs, RSVs, and IVs all shut. The RSVs are not designed to be opened against a high differential pressure.

During a restart of the boiler, the Control Room Operator (CRO) attempted to start the turbine from the control room, but the turbine failed to latch when the RSVs and IVs failed to open. The Shift Supervisor went out to the turbine to attempt to latch the turbine locally. The first attempt to latch the turbine failed to open the RSV and IV. A second attempt was made to latch the turbine, and the IVs and then the RSVs were opened.

The turbine speed increased from 0 to approximately 800 rpm even though the throttle valve remained shut. The CRO pushed the “Go” button, which allowed the DCS to start the turbine. The DCS was programmed to automatically bring the turbine to 3,450 rpm using a 300 rpm per minute ramp rate. As the TVs opened, the turbine speed suddenly increased from approximately 800 rpm to approximately 1,870 rpm. This was accompanied by high turbine and power plant building vibrations. The CRO then manually tripped the turbine. The boiler was not tripped. The CRO, Shift Supervisor, and Operations Manager discussed the turbine start issue. It was decided that leakage past the TVs was likely the cause of the turbine rolling prior to the “Go” switch being pressed and the sudden speed increase was also attributed to a problem with the TVs.

A decision was made to re-start the turbine. During the second attempt to start the turbine, the turbine could not be latched from the control room via the DCS. Several attempts were made to latch the turbine locally, but the RSVs failed to open on each attempt.

An Instrument and Control Technician forced the IVs to close, allowing the RSVs to be opened. Then the IVs were opened, and the turbine started rolling again prior to the TV being opened and reached a speed of about 1,300 rpm. The turbine speed began to decrease from 1,300 rpm before the TV indication indicated that the TVs were open. Approximately 10 seconds after the TV indication indicated that the TVs were open, the turbine speed again increased rapidly from about 1,300 rpm to approximately 2,700 rpm in a couple of seconds, which is faster than the design ramp rate. A loud bang was heard in the control room and rumbling was felt in most areas of the plant. It was discovered that the CRH pipe had broken free from its hangers and had come to rest on the concrete deck of the 2nd floor. Bent structural members for the building, broken air and water lines, and damaged cable trays were also discovered. Photographs of the damage are provided in Figures 15 through 17.

Approximately 280 ft (85 m) of CRH piping moved in this incident. Based upon the deformation of the structural steel, the vertical section of the CRH pipe moved significantly vertically, resulting in all of the pipe hangers and supports for the CRH piping being bent or broken. No piping ruptured due to overpressure.

The addition of the check valve in the CRH line allowed water that had leaked past the attemperator spray valves to collect on top of the valve. When the RSV was opened, steam was introduced into the system causing a “hammer” event.

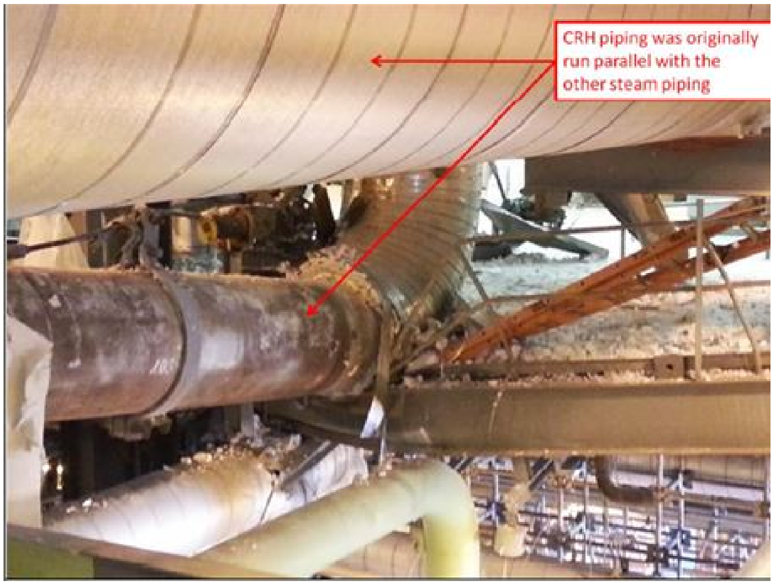

Fig. 15. Uunsupported CRH pipe

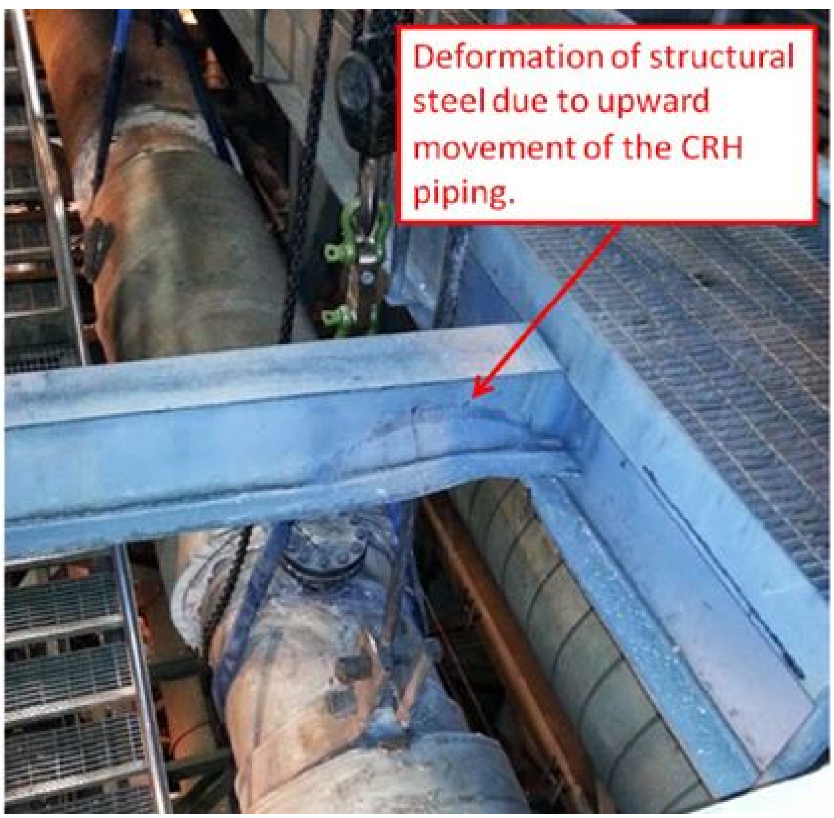

Fig. 16. Damage to the structural steel due to pipe movement

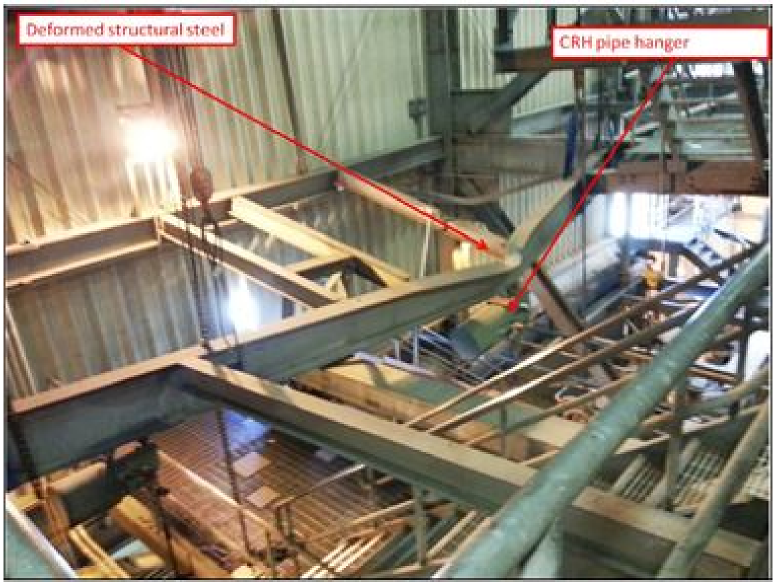

Fig. 17. Damage to the structural steel due to pipe movement

3.4.3 Heat Exchangers

3.4.3.1 Lack of Inspection, Testing, and Maintenance Leads to Rupture of a Heat Exchanger

A coal-fired electric power generation facility can produce 2,484 MW at full load, (621 MW per unit). The facility is split into two main buildings, the boiler building and the turbine/generator building. The boiler building houses the boilers, pulverizers, deaerators, bunkers, etc. The turbine/generator building houses four turbines generators and auxiliary equipment side by side for each unit (units 1-4). Feedwater heaters no. 4 and no. 6 for each unit sit on the turbine deck. The turbine deck is a large shared high bay area. Feedwater heaters no. 1, 2, and 3 sit on the mezzanine level. The feedwater system is similar for each unit. The condensate is pumped at 3,900 psi through a series of eight feedwater heaters. These feedwater heaters heat the water up to 560°F (293°C).

The feedwater heater pre-heats the feedwater with steam extracted from the turbine. The high-pressure feedwater runs inside of the tube bundle while the steam surrounds the tube bundle inside the shell of the heat exchanger. Normal and emergency drains are provided to ensure the condensate level in the heat exchanger (from the steam being cooled by the feedwater) is able to be controlled. The heat exchangers are set up in parallel strings to allow maintenance on one while the other remains in service. Electricity production reduces by 20% when only running one string of heat exchangers.

Several hours prior to the event, the normal drain for heat exchanger 1A3 was opened more and more to accommodate additional condensate. The normal drain for Heat Exchanger No. 1A3 drains to Heater No. 4, therefore Heater No. 4 was also having trouble with extra condensate. The emergency drain valve for Heater No. 1A3 was opened due to the normal valve being at 100% open and still having rising condensate. The emergency drain was opened from 24% to 100% by the DCS within 2 minutes of opening. After 10 minutes of the emergency drain being open to 100%, the decision was made to isolate the “A” string of heaters. After being unsuccessful in trying to isolate the heat exchangers for 22 minutes, Heat Exchanger No. 1A3 ruptured.

Lack of inspection of the heat exchanger tube bundle let deteriorated tubes fail during service. Additionally, the lack of testing and maintenance of the isolation valves used during the bypass process led to inadequate closure of the valves. This allowed the pressure to build in the No. 1A3 heat exchanger since the unit was not taken offline.

The water/steam flash damaged the turbine deck and mezzanine as well as major structural beams, adjacent feedwater heaters, various metal wall panels (~60,000 sq. ft [5,574 m^2]), brick walls (~20,000 sq. ft [1,858 m²]), doors, motor control centers, piping, switchgear, etc. Temporary bracing was required to allow personnel in for clean up/repairs. A photograph of the damage is provided in Fig. 18.

Fig. 18. Damage due to heat exchanger failure

Unit 1 was taken down because of the interruption of feedwater flow. Unit 2 was taken down because of the damage to the switchgear. Unit 3 was offline at the time and Unit 4 was taken down as precaution. Units 3 and 4 were able to be restarted

3.4.3.2 Inadequate Inspection Leads to Failure of a Heat Exchanger

A site mines phosphate ore and coverts it to phosphoric acid and phosphate fertilizers. Large amounts of sulfuric acid are needed in the process and this plant produces sulfuric acid using sulfur burning technology. The sulfur burning process is exothermic and excess heat is collected in waste heat boilers and economizers. The plant normally operates at 99.5% sulfuric acid concentration and they receive alarms when this concentration falls to 97%. Under these conditions, the corrosion rate of the stainless steel used gives an expected life of 10 years. When the concentration of the acid falls below the above-mentioned range, the corrosion rate of the steel increases exponentially (at 80% concentration, the corrosion rate can increase by a factor of 200,000).

The loss involves a medium pressure boiler for the heat recovery system. The boiler consists of a U-tube bundle constructed of 310 stainless steel. The shell of the boiler is carbon steel. The heat exchanger has 783 tubes with an outside diameter of 1 inch (25.4 mm). The bundle is 40 feet (12 m) long and produces 50 psi (0.35 MPa) steam. The waterside pressure is higher than the acid side pressure. Any failure would cause water to enter the acid side.

The tube bundle was originally installed in 1993 and is tested with eddy current every year. The original tube bundle was replaced in 2003. In 2011 the eddy current testing performed indicated 26 tubes needed to be plugged. This was completed with 310 stainless steel plugs and compatible welding material.

One evening, operators noted an irregularity in the concentration of acid going to the diluter. Over several hours, additional irregularities began to show (low water induction on the boiler and low concentration throughout the system) which caused the operators to press the emergency stop on the process. Once safe boiler was opened and the damage to the tube bundle was found. The heat recovery system pumps were started to remove dilute acid from the system and high strength acid was flush through the plant to dry and cool the system to stop any ongoing corrosion.

The damage was a result in failure of a seal weld of a previously plugged tube on the heat exchanger. These were not part of the yearly heat exchanger testing being performed. Photographs of the damage are provided below in Fig 19 and 20.

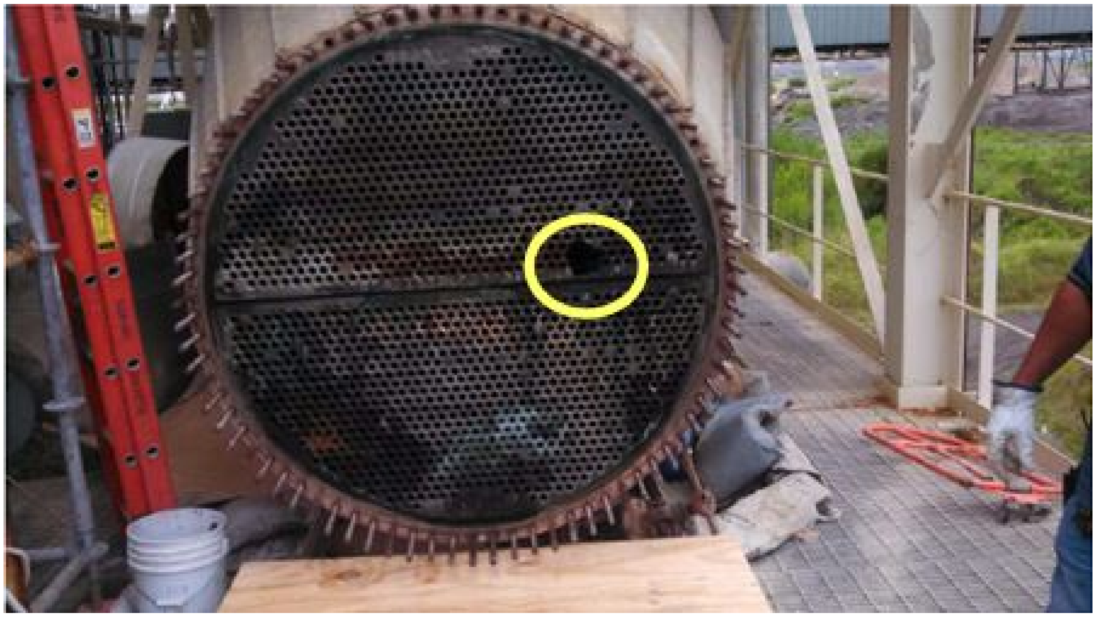

Fig. 19. Tube bundle; damage is circled in yellow

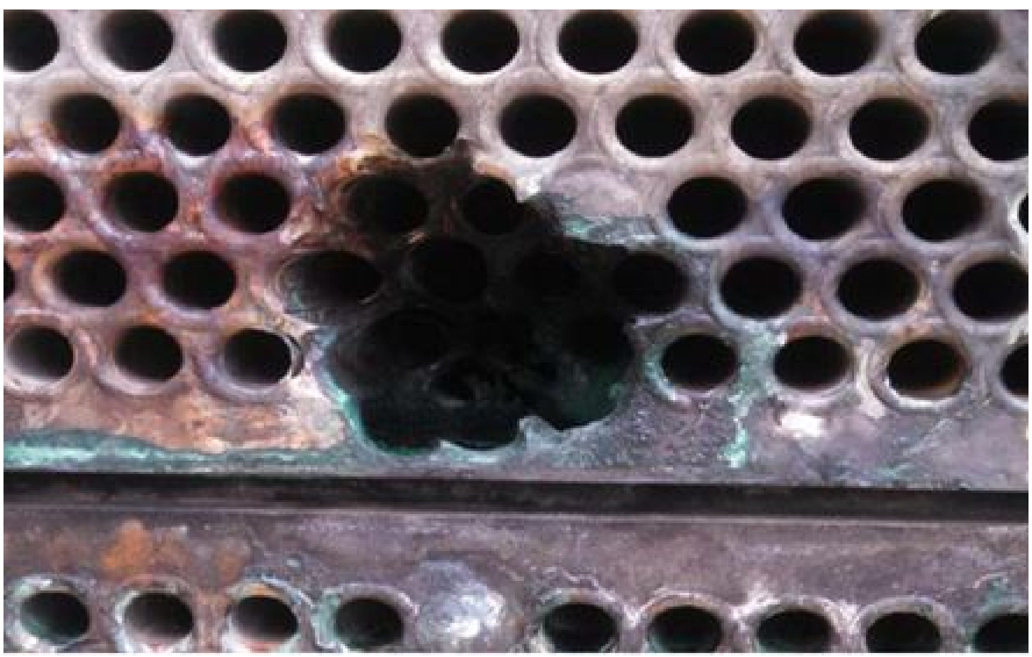

Fig. 20. Closeup of damage to the tube bundle

Replacement of the tube bundle was necessary since the damage was not repairable. Cleaning and inspection of the plant vessels was performed. Damage was revealed on the acid circulation pump and heat recovery system tower boot. Acid had also entered the gas side of the plant and damaged brick work, mist eliminators, ducting, and the heat recovery system tower distribution equipment. The plant was able to resume operation at a reduced rate (88% of normal). A total of 23 days of acid and steam production were lost.

3.4.4 Tanks and Silos

3.4.4.1 Delayed Inspection and Maintenance Leads to Roof Collapse

An ethanol plant produces fuel-grade ethanol and distiller dried grains with soluble (DDGS) that are used for livestock, and CO_2. that produced a nominal daily production of 22,954 ft^3 (650 m^3) for the entire plant. The plant typically operates 7 days a week, 350 days per year.

Six outdoor fermenters of identical construction (40 ft (12 m) diameter, 65.6 ft (20m) height). The fermenter tanks were built from black steel and had been in service for 9 years. The batch process is 60 hours duration between filling a fermenter and cleaning it for 12 hours after operation.

An inspection program is in place at the location and generated internal inspection of the fermenters and repair work to be carried out on fermenter B in October 2015. Corrosion pits on the welds of the black steel were rebuilt and an epoxy lining was sprayed on the internal surface to prevent further corrosion.

In May of the next year, another fermenter was stopped for a similar maintenance outage. During that outage, an electrical issue caused the fermenters to stop operations. However, fermenter C was being filled by transfer from another fermenter and had to be stopped manually due to a very high-level alarm (97% full)

Upon starting the circulation pump to avoid sedimentation in the fermenters, fermenter C suddenly failed at the upper collar, leading to roof collapse. While falling, the roof damaged the structures supporting electrical cables, the CO_2 piping, and the cleaning-in-process piping system supplying the surrounding fermenters. This caused loss of use of 50% of production for 20 days, 25% loss of production for an additional 47 days.

The cause of the failure was likely a combination of significant corrosion that was not detected and increased pressure from the fermentation process.

Fig. 21. Fermenter configuration

Fig. 22. Upper portion of fermenter after failure

Fig. 23. The roof of the fermenter after failure

3.4.4.2 Lack of Silo Inspection Leads to Collapse

A coal-fired electric power generation facility with four units produced electricity using large steam turbine generators. Two of the four units were decommissioned. Unit 1, the unit that suffered the failure, produced 347 MW. Fuel for the Unit 1 boiler that produced the steam for the Unit 1 turbine was supplied by a group of four bottom-cone, suspended silos. The silos were 45 years old and were originally fabricated on site from carbon steel.

There had been no inspection, testing, and maintenance activities for the coal silos from the time of commissioning until the loss. None of the coal silos at the site were part of the site’s asset integrity program.

One Saturday evening, one of the cone sections of the silos separated from the remainder of the silo. Five hundred to 800 tons of coal and the cone landed on the feeder deck, which caused a 50 x 50 ft (15.24 m x 15.24 m) section of the deck to collapse. This covered the pulverizer and surrounding area with coal.

The release of the coal and the collapse of the feeder deck also led to damage of the UPS system, switchgear control DC power system, turbine DC motor system, battery chargers, UPS inverters, several distribution panels, the high-pressure steam line, and 2 in. (50.8 mm) service water piping. AC power was immediately cut off from the DCS control system, but the emergency bearing oil pumps and hydrogen seal oil pumps started automatically and allowed the turbine to coast down normally.

Immediately following the collapse, a coal dust deflagration occurred and blew off the metal wall panels and roof vents of the building. A fire did not follow. The building panels that were blown off hit the Unit 1 start up transformer deluge sprinkler piping and broke the piping fittings. Photographs of the deflagration and subsequent damage are provided in Figs. 24-26.

Unit No 4 was able to stay in operation. Significant wall thinning, and weld cracking were revealed on the failed silo.

Fig. 24. Deflagration fireball erupting from the silo enclosurecollapsed feeder deck

Fig. 25. Collapsed feeder deck

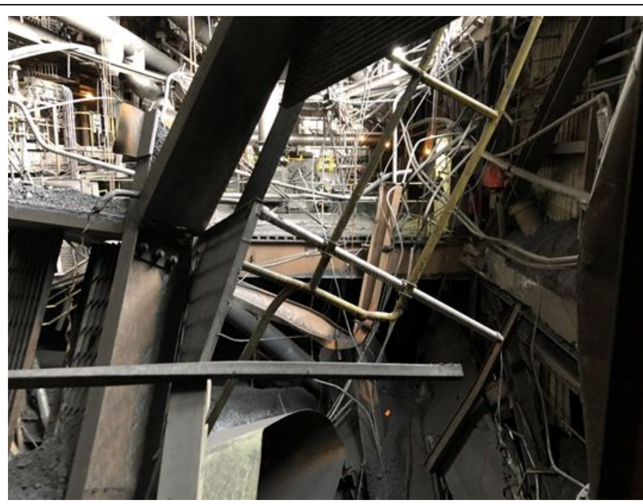

Fig. 26. Structural damage as a result of the silo failure

3.4.5 Pressure Vessels Equipped with Quick-Actuating Closures

3.4.5.1 Improper Inspection of the Quick-Closing Device leads to Failure during Pressure Test

A large manufacturer of medical products for the health care industry produced sterile IV solutions. The IV solution, container, tubing and other components were steam sterilized and water-rinsed as a single unit using 12 autoclaves. The sterilization process consisted of loading the autoclave with the product, closing the unit, filling it half full of water and then introducing steam to pressurize the unit. The products were sterilized for two hours and then removed. Each autoclave was approximately 25 ft long and 8 ft in diameter. The normal operating temperature and pressure was approximately 300°F (149°C) and 35 psi (0.24 MPa), respectively. The autoclaves had a maximum allowable working pressure of 50 psi (0.35 MPa).

The door closure device consists of two flanges with a split capture band ring and a toggle locking device. The over-center locking device expanded and contracted the locking band to engage the two flange surfaces, which were sealed with a gasket in the shell flange. The autoclaves were located in a one-story building with a 40 ft (12 m)high roof that was fully sprinkler protected.

An autoclave was undergoing scheduled maintenance performed by site personnel. The pressure relief valve was being tested using pressurized air. At approximately 48.4 psi (0.34 MPa), the door of the vessel ruptured at the door clamps, and the pressure tore the door and hinge from the vessel. The door was blown to the ceiling and landed approximately 59 ft (18 m) from the vessel. When the door hit the ceiling, it impacted a fire sprinkler line, rupturing it.

The roof above the autoclave suffered damage from impact. Water from the ruptured sprinkler pipe damaged the electrical box and control panel for the involved autoclave and damaged the electrical box for an adjacent autoclave. Water from the ruptured sprinkler pipe damaged 21 pallets of work in process, a segment of the packing line, and a section of the gypsum board partition wall.

Positive factors relating to this loss included an extra autoclave that was able to pick up some production and the affected area was not congested with equipment that could have been impacted by the door or damaged by sprinkler water. Additionally, installed drainage prevented the water from the broken sprinkler pipe to cause significant damage to the room and contents.

The root of the failure was the quick-actuating closure not being in a condition which was able to withstand design pressure. Regular inspection of the quick-actuating closure was not included in the autoclave maintenance program. This allowed the condition of the quick-actuating closure to deteriorate over time unknown to the operators. Photographs of the damage to the autoclave are provided as Figs. 27 and 28.

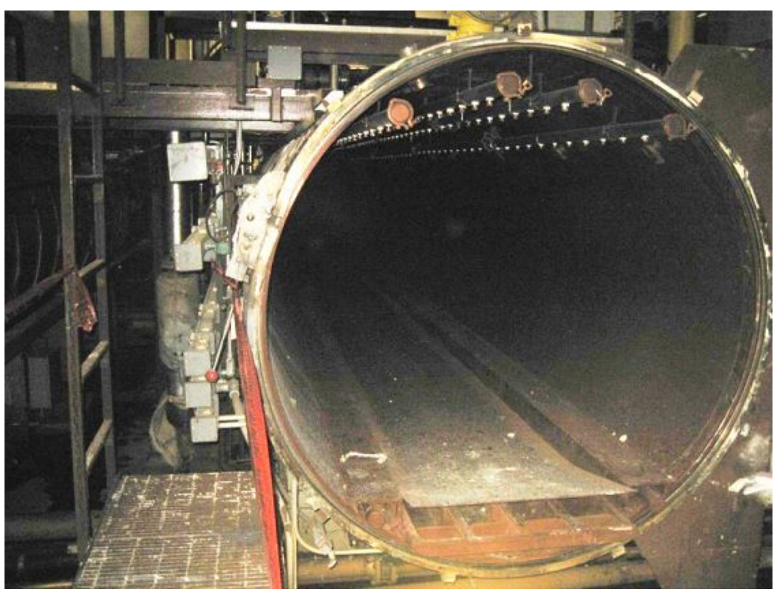

Fig. 27. Autoclave front seal area with remains of locking rings

Fig. 28. Autoclave door that failed and separated from the autoclave

3.4.5.2 Inadequate position indication leads to Autoclave Door Explosion

A manufacturing and sterilizing plant provided saline solutions in bags and bottles for medical applications. The sterilization process used two autoclaves for their parenteral fluids products, which represented 45% of sales for the site.

The autoclaves operated in 2-hour 40-minute cycles, which included heating, sterilization and cooling. The autoclaves were built in 2002 and measured approximately 8 ft (2.4 m) in diameter and 18 ft (5.5 m) in length. They had two sliding rectangular doors approximately 4 ft (1.2 m) by 6 ft (1.8 m), one door for loading and one door for unloading at the back end of the cylindrical vessel. All components of the autoclave were made of stainless steel. A pressure safety valve was installed on the top of the vessel at the unloading side. The autoclave had automated temperature, pressure, and water flow sensors, controlled by a PLC control system. During the cycle, the operator manually records any alarms in the batch log. Prior to the incident, there were no reported abnormal operating conditions.

The autoclave operates at 44 psig (0.33 MPa) and 292°F (144°C). During the heating portion of the cycle, approximately 57 minutes after the autoclave started operating, a failure occurred that caused leakage of the contained water. Leakage leading to a rapid cascade of events led to the complete failure of the autoclave door. The failure of the door led to a steam explosion (rapid vaporization of the hot water in the vessel). The steam and shockwave liberated from the explosion sent the 1,320 lb. (600 kg) door approximately 50 ft (15.2 m) across the room and landed in an office area. The autoclave was displaced 6 in. (154 mm) back from its original position and rotated slightly counterclockwise. The welds and bolts were torn apart at the base of the autoclave. The door was projected horizontally and caused damage to in-process containers to be sterilized, gypsum walls, ceiling tiles and the epoxy floor. Fortunately, it did not damage other critical equipment. The autoclave required full replacement. The facility was completely shut down for six days. Partial operations started four weeks later (50% of the Parenteral Fluids line), and it took 12 months to restore the facility to full production. Photographs of the damage to the Autoclave are provided as Figs. 29 and 30.

The autoclave manufacturer had previously reported an issue with a position limit switch used to serve as an interlock to prevent pressurizing of the vessel unless the closing mechanism was fully engaged. This was found at another installation (not specified), where the position switch did not properly detect that the closing mechanism was not fully engaged. The manufacturer sent two bulletins regarding this issue and recommended to install a second position switch to ensure the autoclave doors closed completely, and the sides engaged adequately in the side rail. These had not been installed prior to the explosion and may have prevented this loss from happening. Secondly, NDE should have been done on the horizontal lower and upper edges of the sliding door of the autoclave to identify any cracks.

Fig. 29. Autoclave after the steam explosion

Fig. 30. Autoclave door and internal trays that were propelled 50 ft (15.2 m) across the room

4.0 REFERENCES

4.1 FM

Data Sheet 1-44, *Damage-Limiting Construction*
Data Sheet 7-32, *Ignitable Liquid Operation*
Data Sheet 7-45, *Instrumentation and Control in Safety Applications*
Data Sheet 7-88, *Ignitable Liquid Storage Tanks*
Data Sheet 7-109, *Fuel Fired Thermal Electric Power Generation*
Data Sheet 8-10, *Coal and Charcoal Storage*
Data Sheet 9-0, *Asset Integrity*
Data Sheet 9-18, *Prevention of Freeze-Ups*
Data Sheet 10-8, *Operators*
Data Sheet 12-43, *Pressure Relief Devices*

APPENDIX A GLOSSARY OF TERMS

Brittle fracture: A fracture that occurs suddenly, with little or no plastic deformation such as stretching or bulging.

Caustic: Any of the hydroxide compounds, most commonly sodium hydroxide. Aqueous caustic solutions are extremely basic, usually having a high pH of between 10 and 14.

Corrosion: The electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material.

- **Corrosion, local:** Occurs in a relatively limited area. Pitting and crevice corrosion are common examples. Erosion-corrosion, FAC, and cavitation are also examples.
- **Corrosion under insulation (CUI, may also occur as corrosion under fireproofing, CUF):** External corrosion due to moisture within the insulation system. The moisture remains in contact with the pipe for an extended period of time, or may condense under the insulation covering and diffuse to the pipe wall. The insulation may contain chloride ions, making the moisture much more corrosive. Process fluids containing chlorides, acids, or caustics also may penetrate the insulation system.
- **Critical pressure:** The pressure required to liquefy a gas at the maximum temperature a substance can be at before liquefication is no longer possible no matter how much pressure is applied.

Critical pressure: The pressure required to liquefy a gas at the maximum temperature a substance can be at before liquefication is no longer possible no matter how much pressure is applied.

Creep: A form of (permanent) plastic deformation that typically occurs over a long period of time at an applied stress level that is below the yield strength of the material. Occurs in materials from exposure to elevated temperature.

Erosion: A mechanical process resulting in thinning of pipe material. The rate of thinning for specific materials is dependent on flow velocity and the water, steam, and/or solid particles impacting the pipe.

- **Cavitation:** A specific type of erosion caused by formation of bubbles in a liquid stream that impact the pipe (collapse at the pipe surface). Likely to occur at change in pipe size or direction.
  - **Erosion-corrosion (EC):** Thinning from combined mechanical and electro- chemical process. The rate of thinning is more rapid than for either erosion or corrosion alone.
  - **Flow accelerated (or assisted) corrosion (FAC):** A specific type of erosion-corrosion affecting carbon steels. The normally protective oxide coating is dissolved by the combination of flow velocity and fluid chemistry. The fluid may be a liquid or liquid- vapor combination. The rate of thinning for a particular carbon steel is dependent on chromium content, fluid velocity, fluid temperature, fluid pH, and two-phase flow.

FM Approved: Products and services that have satisfied the criteria for FM Approval. Refer to the Approval Guide, an online resource of FM Approvals, for a complete listing of products and services that are FM Approved (www.approvalguide.com).

Fracture toughness: A material property that indicates its ability to resist propagation of a crack and fracture from a flaw, such as a void, inclusion, or preexisting crack.

Isostatic processing: Batch processes completed at a constant pressure. May include heating of the processed material. Typically performed at high pressure in vessels having quick-actuating closures. Processing fluid may be liquid or gas. Examples are supercritical carbon dioxide extraction, diamond or quartz crystal growing, food and drink processing, ceramic processing, and metal processing. Vessels may be called extractors, autoclaves, reactors, or presses.

Low alloy steels: Those steel alloys with more alloying additions than carbon steels, and less than stainless steels. When compared with the less expensive carbon steels, some have higher strength, some better corrosion resistance, and some better high temperature properties.

Nondestructive examination (NDE): The application of analysis methods to determine the condition of materials without causing damage to the materials. The following are some types of NDE that may be applied to vessels and piping.

- **Visual (VT)**: Visual testing is the most common nondestructive testing method. If a component can be viewed, visual testing is the first method of testing in an NDT examination.
- **Liquid penetrant (PT):** A penetrating liquid is applied to the material surface to detect cracking. Can only detect discontinuities open to the surface.
- **Magnetic particle (MT):** A magnetic powder is applied to the material surface and a magnetic field is then generated in the material to detect cracking in magnetic materials. Wet fluorescent magnetic particle (WFMT) is the preferred method in most instances. Can only detect discontinuities open to or very near the surface.
- **Radiography (RT):** A radiation source is placed on one side of the vessel or pipe wall(s) and a sheet of film is placed on the other side. Variation in wall thickness affects exposure of the film. Best results require the film to be in contact with the examined surface. RT can be done through insulation, but the results are blurry and thus not conclusive. RT is more time-consuming and costly than UT.
- **Ultrasonics (UT):** A transducer transmits and receives an ultrasonic signal, revealing wall thickness, delamination, and cracks. A flaw detector-type instrument provides much more information than does a digital thickness gauge. UT requires access to a bare metal surface over the entire area to be inspected.

Overpressure: A pressure increase or vacuum beyond a vessel design pressure (or MAWP), or beyond the set pressure of a pressure relief device.

Plastic deformation: Deformation, such as stretching, bending, or bulging, that is permanent; i.e. is not recovered when the stress is removed. As opposed to elastic deformation, which is fully recovered when stress is removed.

Positive material identification (PMI): PMI is the name commonly given to the practice of physically testing a material in order to identify its chemical composition. PMI can be used to confirm that the materials of construction are consistent with the specified design either prior to or after being placed into service. PMI can be performed by various techniques. X-ray fluorescence is the most widely used portable method in the field. In a laboratory setting, a scanning electron microscope (SEM) with energy dispersive X-ray spectrometer (EDS), or optical emission spectroscopy (OES) are more common.

Power Piping (Also referred to as “High Energy Piping” by industry and “Critical Piping Systems” and “Covered Piping Systems” in ASME B31.1): Piping meeting the requirements of ASME B31.1 which includes piping in power generating stations, industrial and institutional plants, geothermal heating systems, central/district heating/cooling systems for steam, water, oil, gas, and air services. This also includes external piping for power boilers and high temperature/high pressure water boilers and piping operating at certain pressures and temperatures per ASME B31.1. Refer to ASME B31.1 for additional power piping information.

Process Piping: Piping meeting the requirements of ASME B31.3, which includes piping in petroleum refineries; chemical, pharmaceutical, hydrogen, textile, paper and pulp, power generation, semiconductor, and cryogenic plants; and related processing plants and terminals operating at certain pressures and temperatures. Materials and components, design, fabrication, assembly, erection, examination, inspection, and testing of piping are based on the type of fluid service/category. Refer to ASME B31.3 for additional process piping information.

Quick-actuating closure: A vessel closure designed to reduce the time to open and close the vessel, particularly for batch processing.

Vent, atmospheric: Pressure relief opening on a system to permit the intake and discharge of air during emptying and filling operations and to permit expansion and contraction of vapor due to temperature changes. Sometimes called breather vent.

Vent, emergency relief: Pressure relief opening on a system to prevent over pressurizing or pulling a vacuum on the system in the event of upset in system operation, fire exposure or other adverse condition.

Vessel: Generic term used in this data sheet for containers used for storage or processing of solids, liquids or gases. The general category of “vessel” is divided into subcategories of pressure vessel, silo and tank. Vessels may be constructed of a wide variety of materials.

- **Vessel, aboveground:** A vessel installed above grade, at grade or below grade having access to all external vessel surfaces.
- **Vessel, underground:** A vessel installed above grade, at grade or below grade not having access to entire external vessel surface due to earth mounding or backfill.
- **Fired pressure vessel:** A vessel above ambient pressure containing and liquid or gas exposed to products of combustion.
- **Process pressure vessel:** A vessel above ambient pressure containing a solid, liquid or a gas with materials used in a production process.
- **Unfired pressure vessel:** A vessel above ambient pressure containing a solid, liquid or gas with materials used in a support system for the production process.
- **Pressure vessel:** Generic term for vessel containing solids, liquid or gas at a pressure significantly exceeding ambient pressure. Pressure vessels addressed in this data sheet are limited to those constructed of metals and some plastics. Pressure vessels are typically designed for a minimum pressure of 15 psi (100 kPa) and up to full vacuum.
- **Autoclave:** A pressure vessel used in processing materials in a production process. Depending on occupancy, it may be known as a sterilizer, reactor, extraction vessel, or isostatic press. In batch processing applications, it will have a quick-actuating closure.
- **Silo:** Generic term for vessels containing solids. Silos addressed in this data sheet are expected to operate at ambient pressure only, not subject to application of either positive or negative (vacuum) pressure.
- **Tank:** Generic term for vessels containing solids, liquids or gases at essentially ambient pressure. Tanks addressed in this data sheet are primarily constructed of metals with some being plastic, wood or concrete construction. Tanks are typically designed for a maximum pressure of 15 psi (100 kPa) and up to full vacuum.
  - **Aboveground tank:**A tank that is installed above grade, at grade, or below grade without backfill.
  - **Atmospheric tank:**A storage tank that has been designed to operate at pressures from atmospheric through a gauge pressure of 1.0 psig (6.9 kPa) measured at the top of the tank.
  - **Double-skinned tank:** See “secondary containment tank,” a term used in European Standards (EN).
  - **Low-pressure tank:** A storage tank designed to withstand an internal pressure of more than 1 psig (7 kPa) but not more than 15 psig (100 kPa or 1 bar gauge) measured at the top of the tank.
  - **Secondary containment tank:** A tank that has an inner and outer wall with an interstitial space (annulus) between the walls and that has a means for monitoring the interstitial space for a leak.
  - **Storage tank:** Any vessel having a liquid capacity that exceeds 60 gal (230 L), is intended for fixed installation, and is not used for processing.

APPENDIX B DOCUMENT REVISION HISTORY

The purpose of this appendix is to capture the changes that were made to this document each time it was published. Please note that section numbers refer specifically to those in the version published on the date shown (i.e., the section numbers are not always the same from version to version).

October 2024. Interim revision. Made editorial changes for additional clarity. Added power and process piping definitions to the glossary of terms.

July 2022. Interim revision. Made editorial changes for additional clarity.

January 2021. Interim revision. Clarified the definition of nondestructive examination (NDE) and added visual testing (VT) as a means of NDE.

July 2020. Interim revision. Updated contingency planning guidance.

January 2020. Interim revision. Minor editorial changes were made.

October 2019. Interim revision. Minor editorial changes were made.

July 2019. This document was completely revised. The following major changes were made:

A. Reorganized document to improve readability and remove redundancies.

B. Combined quick actuating closure recommendations in an appendix.

October 2018. Interim revision. Minor editorial changes were made for this revision.

July 2018. Interim revision. Minor editorial changes were made for this revision.

October 2017. Interim revision. Existing recommendation 2.1.5.1 was modified for clarification.

January 2017. Interim revision. Minor editorial changes were made.

April 2015. Data Sheets 12-66, *High Pressure Forming Presses,* and 12-26, *Quick-actuating Closures,* have been incorporated into this document.

April 2014. This data sheet has been completely rewritten. Major changes include the following:

A. Changed the title from External Corrosion of Pressure Vessels and Piping to Vessels and Piping.

B. Incorporated all relevant information from Data Sheet 1-25, *Process Tanks and Silos.*

C. Incorporated all relevant information from Data Sheet 12-5, *Critical Steam and Water Piping.*

D. Added guidance on process and storage tanks, silos, bins, pressure vessels and piping, in addition to the hazard of external corrosion.

E. Added text to direct the user to seek recommendations in other FM Global data sheets for the specific service application.

F. For the Equipment and Processes section, made the primary recommendation to use a recognized vessel or piping construction code for new vessels and piping. A list of codes is provided in Section 4.2, Recognized Vessel and Piping Codes, which can be expanded as other codes are determined to be acceptable.

G. For the Operation and Maintenance section, made the primary recommendations to implement a system integrity program and included text to direct the user to Data Sheet 9-0 for methodologies. A list of acceptable industry inspection and repair codes is provided in Section 4.2, Recognized Vessel and Piping Codes.

H. Updated the Support for Recommendations section.

May 2003. Minor editorial changes were made for this revision.

January 2000. This revision of the document has been reorganized to provide a consistent format.

APPENDIX C RECOGNIZED VESSEL AND PIPING CODES

C.1 Vessel and Piping Construction Codes, Standards, Recommended Practices and Manuals

C.1.1 National Standards of the People's Republic of China

GB 150, *Pressure Vessels*

C.1.2 American Society of Mechanical Engineers (ASME)

PVHO-1, *Safety Standard for Pressure Vessels for Human Occupancy*

C.1.3 ASME Boiler and Pressure Vessel Code

Section VIII, *Rules for Construction of Pressure Vessels Division 1*

C.1.3 ASME Boiler and Pressure Vessel Code

Section VIII, *Rules for Construction of Pressure Vessels Division 1*

Section VIII, *Rules for Construction of Pressure Vessels Division 2 - Alternative Rules*

Section VIII, *Rules for Construction of Pressure Vessels Division 3 - Alternative Rules for Construction of High Pressure Vessels*

Section X, *Fiber-Reinforced Plastic Pressure Vessels*

Section XII, *Rules for Construction and Continued Service of Transport Tanks*

C.1.4 ASME B 31 Code for Pressure Piping

B31.1, *Power Piping*

B31.3, *Process Piping*

B31.4, *Pipeline Transportation Systems for Liquid and Slurries*

B31.5, *Refrigeration Piping and Heat Transfer Components*

B31.8, *Gas Transportation and Distribution Piping Systems*

B31.9, *Building Services Piping*

B31.12, *Hydrogen Piping and Pipelines*

C.1.5 American Water Works Association (AWWA)

C600, *Installation of Ductile-Iron Water Mains and Their Appurtenances*

C604, *Installation of Steel Water Pipe - 4 In. (100 mm) and Larger*

C605, *Underground Installation of Polyvinyl Chloride (PVC) and Molecularly Oriented Polyvinyl Chloride (PVCO) Pressure Pipe and Fittings*

C900, *Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings, 4 In. Through 60 In. (100 mm Through 1,500 mm)*

C950, *Fiberglass Pressure Pipe*

D100, *Welded Carbon Steel Tanks for Water Storage*

D103, *Factory-Coated Bolted Carbon Steel Tanks for Water Storage*

D107, *Composite Elevated Tanks for Water Storage*

D110, *Wire- and Strand-Wound, Circular, Prestressed Concrete Water Tanks*

D115, *Tendon-Prestressed Concrete Water Tanks*

D120, *Thermosetting Fiberglass-Reinforced Plastic Tanks*

D121, *Bolted Aboveground Thermosetting Fiberglass-Reinforced Plastic Panel-Type Tanks for Water Storage*

M9, *Concrete Pressure Pipe*

M11, *Steel Pipe: A Guide for Design and Installation*

M23, *PVC Pipe - Design and Installation*

M41, *Ductile-Iron Pipe and Fittings*

M55, *PE Pipe - Design and Installation*

C.1.6 Australian Standards

AS 1210, *Pressure Vessels*

C.1.7 European Standards

EN 13445, *Unfired Pressure Vessels*

EN 13923, *Filament-Wound FRP Pressure Vessels*

EN 13121, *GRP Tanks and Vessels for Use Above Ground*

EN 14931, *Pressure vessels for human occupancy (PVHO) - Multi-place pressure chamber systems for hyperbaric therapy - Performance, safety requirements and testing*

C.1.8 Japanese Industrial Standards

JIS B 8242, *Horizontal type cylindrical storage tanks used for liquefied petroleum gas - Construction*

JIS B 8265, *Construction of pressure vessel - General principles*

JIS B 8267, *Construction of pressure vessel*

JIS B 8266, *Alternative standard for construction of pressure vessel*

JIS B 8241, *Seamless steel gas cylinders*

JIS B 8248, *Cylindrical layered pressure vessels*

JIS B 8278, *Saddle supported horizontal pressure vessels*

JIS Z 2342, *Methods for acoustic emission testing of pressure vessels during pressure tests and classification of results*

C.2 Vessel and Piping Inspection and Repair Codes and Standards

C.2.1 The National Board of Boiler and Pressure Vessel Inspectors

National Board Inspection Code (NBIC)

C.2.2 ASME

PCC-1, *Guidelines for Pressure Boundary Bolted Flange Joint Assembly*

PCC-2, *Repair of Pressure Equipment and Piping*

PCC-3, *Inspection Planning Using Risk-Based Methods*

B31.8S, *Managing System Integrity of Gas Pipelines*

PVHO-2, *Safety Standard for Pressure Vessels for Human Occupancy: In-Service Guidelines*

C.2.3 American Petroleum Institute (API)

Publication 510, *Pressure Vessel Inspection Code: In-Service Inspection, Rating, Repair, and Alteration*

Publication 570, *Piping Inspection Code: In-service Inspection, Rating, Repair, and Alteration*

Recommended Practice 571, *Damage Mechanisms Affecting Fixed Equipment in the Refining Industry*

Recommended Practice 572, *Inspection Practices for Pressure Vessels.* (2016, November).

Recommended Practice 574, *Inspection Practices for Piping System Components*

Recommended Practice 576, *Inspection of Pressure-relieving Devices*

Recommended Practice 577, *Welding Inspection and Metallurgy*

Recommended Practice 578, *Guidelines for a Material Verification Program (MVP) for New and Existing Assets*

Standard 579-1/ASME FFS-1, *Fitness-for-Service*

Recommended Practice 580, *Risk-based Inspection*

Recommended Practice 581, *Risk-based Inspection Methodology*

Recommended Practice 583, *Corrosion Under Insulation and Fireproofing*

Standard 598, *Valve Inspection and Testing*

Recommended Practice 750, *Management of Process Hazards*

Recommended Practice 1160, *Managing System Integrity for Hazardous Liquid Pipelines*

C.2.4 American Society of Nondestructive Testing (ASNT)

SNT-TC-1A, *Personnel Qualification and Certification in Nondestructive Testing*

CP-106, *Nondestructive Testing - Qualification and Certification of Personnel*

CP-189, *ANSI/ASNT Standard for Qualification and Certification of Nondestructive Testing Personnel*

C.2.5 Materials Technology Institute (MTI)

Project 129-99, *A Practical Guide to Field Inspection of FRP Equipment and Piping*

Project 160-04, *Guide for Design, Manufacture, Installation & Operation of FRP Flanges and Gaskets*

C.2.6 National Association of Corrosion Engineers (NACE) International

SP0198, *Control of Corrosion Under Thermal Insulation and Fireproofing Materials - A Systems Approach*

SP0590, *Prevention, Detection, and Correction of Deaerator Cracking*

SP0169, *Control of External Corrosion on Underground or Submerged Metallic Piping Systems*

SP0170, *Protection of Austenitic Stainless Steels and Other Austenitic Alloys from Polythionic Acid Stress Corrosion Cracking During Shutdown of Refinery Equipment*

SP0274, *High-Voltage Electrical Inspection of Pipeline Coatings*

C.2.7 Australian Standards

AS/NZS 3788, *Pressure Equipment - In-service Inspection*

C.2.8 Welding Technology Institute of Australia (WTIA)

WTIA Guidance Note GN 001, *Deaerator Cracking*, May 1998

C.2.9 The Technical Association of Pulp and Paper Industry (TAPPI)

Recommended practice for prevention, detection, and correction of deaerator cracking, *TAPPI JOURNAL*, September 1991, Vol. 74(9).

C.3 Tanks and Silos Construction Guides, Codes, and Standards

C.3.1 European Standards

EN 1990, *Basis of structural design*

EN 1991, *Eurocode 1: Actions on structures*

EN 1992, *Eurocode 2: Design of concrete structures*

EN 1993, *Eurocode 3: Design of steel structures*

EN 1994, *Eurocode 4: Design of composite steel and concrete structures*

EN 1995, *Eurocode 5: Design of timber structures*

EN 1996, *Eurocode 6: Design of masonry structures*

EN 1997, *Eurocode 7: Geotechnical design*

EN 1998, *Eurocode 8: Design of structures for earthquake resistance*

EN 1999, *Eurocode 9: Design of aluminium structures*

EN 13121, *GRP Tanks and vessels for use aboveground*

EN 14620, *Design and Manufacture of Site Built, Vertical, Cylindrical, Flat-Bottomed Steel Tanks for the Storage of Refrigerated, Liquefied Gases with Operating Temperatures Between 0°C and -165°C*
C.3.2 American Concrete Institute (ACI)

ACI 376, *Code Requirements for Design and Construction of Concrete Structures for the Containment of Refrigerated Liquefied Gases and Commentary*

ACI 371R, *Guide for the Analysis, Design, and Construction of Elevated Concrete and Composite Steel-Concrete Water Storage Tanks*

ACI 372R, *Guide to Design and Construction of Circular Wire-and-Strand-Wrapped Prestressed Concrete Structures*

ACI 313, *Design Specification for Concrete Silos and Stacking Tubes for Storing Granular Materials and Commentary*

C.3.3 Japanese Industrial Standards

JIS B 8501, *Welded steel tanks for oil storage*

JIS B 8502, *Construction of welded aluminium and aluminium alloy storage tanks*

JIS A 4110, *Glassfiber reinforced plastic water tanks*

JIS K 7012, *Glass-fiber reinforced thermosetting resin chemical resistant tanks*

C.3.4 American Petroleum Institute (API)

Specification 12P, *Fiberglass Reinforced Plastic Tanks*

Specification 12B, *Bolted Tanks for Storage of Production Liquids*

Specification 12D, *Field Welded Tanks for Storage of Production Liquids*

Specification 12F, *Shop Welded Tanks for Storage of Production Liquids*

Standard 620, *Design and Construction of Large, Welded, Low-Pressure Storage Tanks*

Standard 650, *Welded Tanks for Oil Storage*

Recommended Practice 651, *Cathodic Protection of Aboveground Petroleum Storage Tanks*

Recommended Practice 652, *Linings of Aboveground Petroleum Storage Tank Bottoms*

Standard 2000, *Venting Atmospheric and Low-Pressure Storage Tanks*

Recommended Practice 2003, *Protection Against Ignitions Arising Out of Static, Lightning, and Stray Currents*

Standard 2610, *Design, Construction, Operation, Maintenance & Inspection of Terminal and Tank Facilities*

C.3.5 ASME

RTP-1, *Reinforced Thermoset Plastic Corrosion-Resistant Equipment*

C.3.6 ASTM International

ASTM D3299, *Standard Specification for Filament-Wound Glass-Fiber-Reinforced Thermoset Resin Corrosion-Resistant Tanks*

ASTM D4097, *Standard Specification for Contact-Molded Glass-Fiber-Reinforced Thermoset Resin Corrosion-Resistant Tanks*

C.3.7 Underwriters Laboratories (UL)

142, *Steel Aboveground Tanks for Flammable and Combustible Liquids*

142A, *Standard for Special Purpose Aboveground Tanks for Specific Flammable or Combustible Liquids*

C.3.8 American Water Works Association (AWWA)

D100, *Welded Carbon Steel Tanks for Water Storage*

C.4 Tanks and Silos Inspection and Repair Reports, Standards, and Guides

C.4.1 American Concrete Institute (ACI)

ACI 222R, *Protection of Metals in Concrete Against Corrosion*

ACI 228.2R, *Report on Nondestructive Test Methods for Evaluation of Concrete in Structures*

ACI 222.2R, *Report on Corrosion of Prestressing Steels*

C.4.2 American Petroleum Institute (API)

Standard 653, *Tank Inspection, Repair, Alteration, and Reconstruction*

Recommended Practice 575, *Inspection Practices for Atmospheric and Low-Pressure Storage Tanks*

C.4.3 Steel Tank Institute (STI)/Steel Plate Fabricators Association (SPFA)

SP001, *Standard for the Inspection of Aboveground Storage Tanks*

APPENDIX D VESSELS EQUIPPED WITH QUICK-ACTUATING CLOSURES

Table 1 is intended to provide the details for recommendations around design, ITM activities and procedures regarding vessels equipped with quick-actuating closures.

Table 1. Design, Inspection, and Testing, and Procedural Details for Vessels Equipped with Quick-Actuating Closures

DESIGN	
ITEM OR CONDITION	**CRITERIA**
Locking Mechanism	Design so that the failure of one locking element will not result in the release or failure of the other elements.
Locking and Holding Elements	Arrange so a visual external examination can be made of their condition and to confirm that the elements are fully engaged in the closed position.
Where the locking mechanism (or closure) is completely released by limited movement and is hydraulically operated (by other than manual operation)	Design the unit (or provide protective interlocking devices) so the vessel cannot be pressurized until the closure mechanism is confirmed fully engaged (closed position interlock), and the mechanism cannot be released until the vessel has been depressurized to ambient pressure (internal pressure equal to external pressure interlock).
For manually operated locking mechanisms designed to release the vessel pressure before the mechanism has been fully disengaged	Provide an audible or visible warning device to alarm when an attempt is made to pressurize with an incompletely engaged mechanism, or to alarm when an attempt is made to disengage a mechanism when the vessel is pressurized.
For all quick-actuating closure equipped vessels	- Provide a pressure-indicating device, and ensure it is visible from the operating area. - Provide at least one safety device to prevent release of the locking mechanism until the vessel pressure is verified equal to ambient pressure. (Not applicable to multi-bolted closures.)
INSPECTION AND TESTING	
ITEM	**ACTION**
Bearing surfaces	Examine for evidence of excessive wear. If found, discontinue use of vessel until corrective action is completed.
Gaskets	Examine for wear, damage, and leakage. Replace gaskets in accordance with manufacturer's specifications, with no deviations.
Closure hinge mechanisms	- Check for proper alignment - Ensure adjustment screws and locking nuts are properly secured.
Closure-ring and locking-ring lugs	- Examine for evidence of undue stress and for cracks at the junction of the lug and closure or locking ring. - Check locking ring and closure wedges to verify full engagement when closed, proper bearing surface contact, wear patterns, and condition. - Consult the closure manufacturer for replacement of missing wedges or securement of loose wedges.
Closure with contracting-ring locking device	Check the ring for loss of flexibility, cracks at the points of attachment of the operating lugs, evidence of undue wear on the ring, and shear on the pins in the lugs and on the operating mechanism.
Clamp-type closures	- Check the surfaces of the clamps for wear and examine the clamps for distortion at the portions overlapping the shell ring and closure ring. - Check hinge pins and locking-device parts for wear and evidence of shear.
Bar-type closures	- Inspect all bearing surfaces for undue wear and check the various parts for indications of undue stress as well as for distortion. - Check arm-pivot pins to be sure they are securely held in place and are not bent. - Check pivot-pin mounting brackets for cracks at the point of attachment to the head and evidence of undue stress in line with the pin holes. - Check threads of the operating screw for wear and fit in the nut or hand wheel hub.
Swing-bolt type closures	- Check for missing bolts. If any are missing, replace at once. - Check bolts for soundness, particularly at the eye, and check the threads for evidence of stripping or excessive wear. The bolt washers should be flat. Washers that are distorted to a dish shape tend to allow bolt movement out of the slot when the nuts are improperly torqued. - Also inspect the closure when closed to be sure the nuts are fully engaged. Examine the pins for distortion and for secure fit.

Table 1. Design, Inspection, and Testing, and Procedural Details for Vessels Equipped with Quick-Actuating Closures (continued)

INSPECTION AND TESTING	
ITEM	**ACTION**
Closure safety-locking appliances	At each inspection of the vessel, check the closure safety-locking appliances are tested to be sure that they are operating properly and are in good repair.
Closure and locking mechanisms	- Check both in a closed and in an open position. - Observe the position of the locking ring, the amount of overlap, and any shift in the ring position. - Anytime a locking ring binds or catches at some point during its movement, the point becomes a fulcrum and the entire ring tries to rotate around it. This may result in shifting of the ring position and cause unequal overlap on the lugs. Therefore, it is important that any safety device that determines the positioning of the ring, such as micro switches, manually operated pins with two-way valves connected to steam signals, or any other type of device, be located at four equal quadrants of the ring. One safety device at one point is not sufficient to properly indicate the position of the ring. Test these four devices.
Vessel opening	Check for out-of-roundness at the outer edge. This is the difference between the maximum and minimum inside diameter at any cross section. Under no circumstances should it exceed 1% of the nominal diameter of the cross section under consideration. Preferably, it should be zero.
TRAINING/OPERATING PROCEDURES	
Provide the following training and operating procedures for vessels having quick-actuating closures. An operator who has not yet acquired sufficient knowledge and experience with quick-actuating closures should be closely supervised by a trained and experienced person:	
Train operators in the proper operation of quick-actuating closures. Instruct operators about the potential for accidents involving the vessel and of the tremendous forces acting on the closure. Ensure operators are aware of and understand the importance of the following: - Ensuring the vessel is completely vented before attempting to open the closure - The function of all operating controls and closure interlocking devices - The danger of interfering with or bypassing any safety device	
Develop and implement safe and proper operating procedures. Incorporate the closure manufacturer’s operating instructions. Implement a system to ensure procedures are kept current and operators continue to follow the procedures. These procedures should ensure the following: - The closure, the closure gasket, and the gasket bearing surfaces will not be damaged during loading and unloading operations. - Only trained operators engage or disengage the quick-actuating closure. - Gasket and gasket bearing surfaces are examined for, and cleaned of foreign matter, prior to engaging the closure. - Any difficulty encountered in actuating the closure is investigated and corrected immediately, before the closure cycle is completed. - No attempt is made to open the closure until the operator has determined all pressure has been relieved.	