Pressure Vessel Safety

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1. HISTORY AND BACKGROUND

As engineers, we often deal with pressure vessels. Occupational Safety and Health Administration (OSHA) has safety standards and the American Society of Mechanical Engineers (ASME) has an entire section of codes devoted to pressure vessels. A plant's safety program must take these as well as other standards into account. Pressure vessels are designed to store their contents under pressure and have inherent risks. Codes are usually written in response to a catastrophic incident. One of the earliest pressure vessels designed was by Leonardo da Vinci in 1495.

The first edition of the ASME Boiler and Pressure Vessel Code was started in 1911 and was released in 1915. One of the failures leading up to the proving that there was a need for boiler design codes was in 1905. The Grover Shoes Factory in Brockton, Massachusetts had a boiler explosion on March 10, 1905. The explosion killed 58 and injured 117, while leveling the factory.

On July 23, 1984, a refinery in Romeoville, Illinois, owned by Union Oil Company of California, experienced a disastrous explosion and fire. An amine absorber pressure vessel rupture released large quantities of flammable gases and vapors. Seventeen people died, seventeen people were hospitalized, and there was more than $100 million in damages.

To give a perspective on the numbers involved in more recent pressure vessel failures, examination of the numbers was conducted by OSHA. In the 1980's OSHA made an examination of some of the numbers involved in pressure vessel accidents. In 1984, 73 deaths and 437 injuries were attributed to pressure vessel failures. The next year, there were 269 injuries and 78 deaths. In 1986, the number of injuries was 99 and 44 deaths. The last year examined in study was 1987, which had 44 injuries and 5 deaths. Reporting was voluntary, so the actual number were likely much higher and incidents that did not involve injuries may not have been reported.

2. INTRODUCTION

Pressure Vessels are manufactured in a variety of shapes and sizes and mostly in carbon or low-alloy steel. They can range from small simple air compressor tanks to large and complex nuclear reactor pressure vessels. The scope of OSHA PUB 8-1.5 would be in the middle range of these, constructed of carbon and low-alloy steels at temperatures between -100 ºF to 600 ºF. These vessels would typically be covered under the ASME Section VIII Division 1 design code.

Inspection and testing programs conducted by the National Association of Corrosion Engineers (NACE) on older pressure vessels and storage tanks have revealed problems. Cracking was revealed to have occurred in a variety of service environments, to include amine, wet hydrogen sulfide, anhydrous ammonia, deaerated water, and hydrogen fluoride. Issues have been found in a considerable number of the vessels that have been inspected. Cracking and damage in a pressure vessel can cause leakage or a rupture that can be a safety hazard for nearby personnel. NACE standards are typically written for dealing with the problem of Stress Corrosion Cracking (SCC) in the oil and gas industry. Examples of these are MR0175 and MR0103.

A complete rupture of a pressure vessel can lead to two possible outcomes. The first is that a blast effect (pressure wave) can occur due to the sudden expansion of pressurized fluid. The second is that there can also be injury from fragments when a fragmentation type rupture occurs.

A leakage failure can have varying effects that depend on the fluid. These can range from no effect to serious injury or death. These effects can be suffocation or poisoning (depending on the liquid) can occur if the leak occurs in a closed space. A fire or explosion (physical hazard) can occur if the fluid is flammable. Process fluids can also cause chemical or thermal burns.

3. PRESSURE VESSEL DESIGN

There are two main codes for the design of pressure vessels. The first is Section VIII of the ASME Boiler and Pressure Vessel Code. The second is the American Petroleum Institute (API) Standard 620. ASME Section VIII contains the rules for the design, fabrication, inspection, and testing of pressure vessels. It covers the following:

a) Acceptable materials of construction
b) Allowable design stresses for the listed materials
c) Design Rules and the acceptable design details
d) Acceptable fabrication methods
e) Bolting materials and design
f) Inspection and testing
g) Pressure relief devices and their requirements

Pressure vessels designed and constructed between the years of 1934 and 1956 may have used the API-ASME Code for Unfired Pressure Vessels for Petroleum Liquids and Gases. The use of this code was discontinued in 1956.

The OSHA technical manual covers pressure vessels and low-pressure storage tanks used in the process, pulp and paper, petroleum refining, and petrochemical industries and for water treatment systems of boilers and steam generation equipment. It does not cover connecting piping and valves. The types of pressure vessels and their applications that are included and excluded are summarized in the table below:

Vessels included:	**Vessel types specifically excluded:**
Stationary and unfired	Vessels used as fired boilers
Used for pressure containment of gases and liquids	Vessels used in high-temperature processes (above 315 °C, 600 °F) or at very low and cryogenic temperatures
Constructed of carbon steel or low alloy steel	Vessels and containers used in transportable systems

Operated at temperatures between -75° C and 315° C (-100° F and 600° F)	Storage tanks that operate at nominally atmospheric pressure Piping and pipelines Safety and pressure-relief valves Special-purpose vessels, such as those for human occupancy

Figure 1 Types of pressure vessels and their applications

The major parts of a pressure vessel are shown in the illustration below:

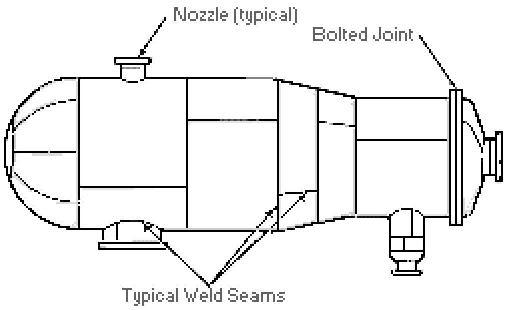

Figure 2 Major parts of a pressure vessel

4. CRACKING IN PRESSURE VESSELS

Recent experience with pressure vessels has shown cracking in several types of services. These service environments include deaerator service, amine service, wet hydrogen sulfide (H_2S) service, ammonia (NH_3) service, and pulp digester service. The chemical environment has a strong influence on the occurrence of cracking. Most design codes do not take the chemical environment into account, so in-service inspection and testing is often necessary to assess the safety of a vessel in a particular service. Inspection and testing should be conducted on the following vessels and/or parts of vessels:

a) Vessels in deaerator, amine, wet H_2S, ammonia and pulp digesting service
b) Welds and adjacent regions
c) Vessels that have not been thermally stress relieved (no PWHT of fabrication welds)
d) Repaired vessels, especially those without Post-Weld Heat Treat (PWHT) after repair

4.1. Deaerator Service

Deaeration refers to the removal of non-condensable gases, primarily oxygen, from the water used in a steam generation system. Deaerators are used in many industrial applications including power generation, pulp and paper, chemical, and petroleum refining and in many public facilities such as hospitals and schools where steam generation is required. In practice, the deaerator vessel can be separate from the storage vessel or combined with a storage vessel into a single unit.

The typical operational conditions for deaerator vessels can range up to approximately 300 psi of pressure and up to about 300° F in temperature. Most vessels are designed to ASME Code, resulting in vessel wall thicknesses up to but generally less than 1 inch. The vessel material is usually carbon steel.

Analysis of the reported incident survey data and other investigations has determined the following features about the deaerator vessel cracking:

a) Water hammer or pressure surge is the only design or operational factor that has a correlation to cracking
b) Cracking is generally limited to weld regions of vessels with no PWHT (typically stress relieve)
c) Corrosion fatigue appears to be the predominant mechanism of crack formation and growth

Due to the results of the incident survey data, several organizations such as NACE, have prepared recommendations for operation, inspection, and repair of these pressure vessels. These recommendations suggest the following:

a) Special attention to the internal surface of all welds and heat-affected zones (HAZ)
b) Use of the wet fluorescent magnetic particle method (also known as the wet mag or MT) for inspection.
c) Inspection by personnel certified to American Society for Nondestructive Testing's (ASNT) SNT-TC-1A minimum Level I and interpretation of the results by minimum Level II.
d) Reinspection of repaired vessels within one year, 1-2 years for vessels with discontinuities but not repaired, and 3-5 years for vessels found free of discontinuities.

4.2. Amine Service

The amine process is used to remove hydrogen sulfide (H_2S) from petroleum gases, such as propane and butane. It is also used for removing carbon dioxide (CO_2) in some processes. Amine is a generic term and includes monoethanolamine (MEA), diethanolamine (DEA) and others in the amine group. These units are used in petroleum refineries, gas treatment plants, and chemical plants.

The operating temperature of the amine process is generally in the 100° F to 200° F range and therefore the plant equipment is usually constructed from one of the carbon steel grades. The wall thickness of the pressure vessels in amine plants is typically about 1 inch.

The survey found an approximately 40% cracking incidence rate in a total of 294 plants. Cracking had occurred in the absorber/contactor, the regenerator and the heat exchanger vessels, and in the piping and other auxiliary equipment. Some of the significant findings of the survey were:

a) All cracks were in or near welds
b) Cracking occurred predominantly in stressed or unrelieved (not PWHT) welds
c) Cracking occurred in all amine vessel processes but was most prevalent in MEA units
d) MT and UT (ultrasonic test) were the predominant detection methods for cracks; internal examination by MT was the preferred method

Laboratory studies indicate that pure amine itself does not cause cracking of carbon steels, but amine with carbon dioxide in the gas phase causes severe cracking. The presence or absence of chlorides, cyanides, or hydrogen sulfide may also be factors. Their role in the cracking mechanism is not completely understood at present.

4.3. Wet Hydrogen Sulfide

Wet Hydrogen Sulfide refers to any fluid containing water and hydrogen sulfide (H_2S). Hydrogen is generated when steel is exposed to this mixture and the hydrogen can enter into the steel. The dissolved hydrogen can cause cracking, blistering, and embrittlement.

The harmful effects of hydrogen generating environments on steel have been known and recognized for a long time in the petroleum and petrochemical industries. In particular, sensitivity to damage by hydrogen increases with the hardness and strength of the steel; and damage and cracking are more apt to occur in high strength steels, as follows:

a) Significant cracks can start from very small hard zones associated with welds; these hard zones are not detected by conventional hardness tests.
b) Initially small cracks can grow by a stepwise form of hydrogen blistering to form through thickness cracks.
c) NACE/API limits on weld hardness may not be completely effective in preventing cracking.
d) Thermal stress relief (post-weld heat treatment, PWHT) appears to reduce the sensitivity to and the severity of cracking.

Wet hydrogen sulfide has also been found to cause cracking in liquefied petroleum gas (LPG) storage vessels. The cracking in the LPG vessels occurs predominantly in the weld heat affected zone (HAZ). The vessels are usually spherical with wall thickness in the 0.8 inch to 3 inch range.

Recommendations for wet hydrogen-sulfide pressure vessels to minimize the risk of a major failure include:

a) Use lower-strength steels for new vessels
b) Schedule an early inspection for vessels more than five years in service

c) Improve monitoring to minimize breakthrough of hydrogen sulfide
d) Replace unsafe vessels or downgrade to less severe, usually lower-pressure, service

4.4. Ammonia Service

Commercial refrigeration systems, certain chemical processes, and formulators of agricultural chemicals will be sites of ammonia service tanks. Careful inspection of vessels used for storage of ammonia (in either vapor or liquid form) in recent years has produced evidence of serious stress corrosion cracking problems. The vessels for this service are usually constructed as spheres from carbon steel, and they operate in the ambient temperature range.

The water and oxygen content in the ammonia has a strong influence on the tendency of carbon steels to crack in this environment. Cracks are likely to be found to be in or near the welds in as-welded vessels. Cracks occur both transverse and parallel to the weld direction. Thermal stress relieving seems to be a mitigating procedure for new vessels, but its efficacy for older vessels after a period of operation is dubious partly because small, undetected cracks may be present.

4.5. Pulp Digester Service

The kraft pulping process has been used in the pulp and paper industry to digest the pulp in the papermaking process since the early 1950's. The operation is done in a relatively weak (a few percent) water solution of sodium hydroxide and sodium sulfide typically in the 230° to 285° F temperature range. Nearly all of the vessels are ASME Code vessels made using carbon steel with typical design conditions of 350° to 360° F and 150 psi.

These vessels had a very good service record with only isolated reports of cracking problems until the occurrence of a sudden rupture failure in 1980. The inspection survey has revealed that about 65% of the properly inspected vessels had some cracking. Some of the cracks were fabrication flaws revealed by the use of more sensitive inspection techniques but most of the cracking was service-induced. The inspection survey and analysis indicates the following features about the cracking.

a) All cracking was associated with welds
b) Wet fluorescent magnetic particle (WFMT) testing with proper surface preparation was the most effective method of detecting the cracking
c) Fully stress-relieved vessels were less susceptible
d) No clear correlation of cracking and non-cracking could be found with vessel age and manufacture or with process variables and practices

Analysis and research indicate that the cracking is due to a caustic stress corrosion cracking mechanism although its occurrence at the relatively low caustic concentrations of the digester process was unexpected

Currently, preventive measures such as weld hard facing, spray coatings, and anodic protection are being studied, and considerable information has been obtained. In the meantime, the recommended guideline is to perform an annual examination.

5. NONDESTRUCTIVE TESTING

Of the various conventional and advanced nondestructive examination (NDE or NDT) methods, five are widely used for the examination of pressure vessels and tanks by certified pressure vessel inspectors. The names and acronyms of these common methods are:

a) Visual Examination (VT)
b) Liquid Penetrant Test (PT)
c) Magnetic Particle Test (MT)
d) Gamma and X-ray Radiography Test (RT)
e) Ultrasonic Test (UT)

Each of the NDE testing methods has its strengths and weaknesses. For example, VT, PT, and MT are surface tests. That means they can detect only those discontinuities and defects that are open to the surface or are very near the surface. In contrast, RT and UT can detect conditions that are located within the part. For these reasons, the first three are often referred to as "surface" examination methods and the last two as “volumetric” examinations. Even volumetric examinations have limitations.

5.1. Visual Examination

Visual Examination (VT) is easy to conduct and can cover a large area in a short time. It is very useful for assessing the general condition of the equipment and for detecting some specific problems such as severe instances of corrosion, erosion, and hydrogen blistering. The obvious requirements for a meaningful visual examination are a clean surface and proper lighting.

5.2. Liquid Penetrant Test

Liquid Penetrant Test (PT or LP) depends on allowing a specially formulated liquid (penetrant) to seep into an open discontinuity and then detecting the entrapped liquid by a developing agent. When the penetrant is removed from the surface, some of it remains entrapped in the discontinuities. Application of a developer draws out the entrapped penetrant and magnifies the discontinuity. Chemicals which fluoresce under black (ultraviolet) light can be added to the penetrant to aid the detectability and visibility of the developed indications. The essential feature of PT is that the discontinuity must be "open," which means a clean, undisturbed surface.

The PT method is independent of the type and composition of the metal alloy so it can be used for the examination of austenitic stainless steels and nonferrous alloys where the magnetic particle test is not applicable.

5.3. Magnetic Particle Test

Magnetic Particle Test (MT) depends on the fact that discontinuities in or near the surface perturb magnetic flux lines induced into a ferromagnetic material. For a component such as a pressure vessel where access is generally limited to one surface at a time, the "prod" technique is widely used. The magnetic field is produced in the region around and between the prods (contact probes) by an electric current (either AC or DC) flowing between the prods. The ferromagnetic material requirement basically limits the applicability of MT to carbon and low-alloy steels. Typically materials such as carbon or low-alloy steels can me MT tested because they are magnetic. Stainless steels typically cannot, because they are not typically magnetic. If a magnet sticks to the material, you should be able to MT test it.

The perturbations of the magnetic lines are revealed by applying fine particles of a ferromagnetic material to the surface. The particles can be either a dry powder or a wet suspension in a liquid. The particles can also be treated to fluoresce under black light. These options lead to variations such as the "wet fluorescent magnetic particle test" (WFMT). MT has some capability for detecting subsurface defects. However, there is no easy way to determine the limiting depth of sensitivity since it is highly dependent on magnetizing current, material and geometry and size of the defect. A very crude approximation would be a depth no more than 1.5 mm to 3 mm (1/16 in. to 1/8 in.).

A very important precaution in performing MT is that corners and surface irregularities also perturb the magnetic field. Therefore, examining for defects in corners and near or in welds must be performed with extra care. Another precaution is that MT is most sensitive to discontinuities which are oriented transverse to the magnetic flux lines and this characteristic needs to be taken into account in determining the procedure for inducing the magnetic field.

5.4. Gamma and X-ray Radiography Test

Radiography (RT) is a volumetric examination that operates on the principle that radiographic examination of metallic objects is the same as in any other form of radiography such as medical radiography. Holes, voids, and discontinuities decrease the attenuation of the X-ray and produce greater exposure on the film (darker areas on the negative film).

Because RT depends on density differences, cracks with tightly closed surfaces are much more difficult to detect than open voids. Also, defects located in an area of an abrupt dimensional change are difficult to detect due to the superimposed density difference. RT is effective in showing defect dimensions on a plane normal to the beam direction but determination of the depth dimension and location requires specialized techniques. Since ionizing radiation is involved, field application of RT requires careful implementation to prevent health hazards.

5.5. Ultrasonic Test

Ultrasonic Testing (UT) the fundamental principles of ultrasonic testing of metallic materials are similar to radar and related methods of using electromagnetic and acoustic waves for detection of foreign objects for a volumetric examination. The distinctive aspect of UT for the inspection of metallic parts is that the waves are mechanical, so the test equipment requires three basic components:

a) Electronic system for generating electrical signal
b) Transducer system to convert the electrical signal into mechanical vibrations and vice versa and to inject the vibrations into and extract them from the material

c) Electronic system for amplifying, processing, and displaying the return signal

Very short signal pulses are induced into the material and waves reflected back from discontinuities are detected during the "receive" mode. The transmitting and detection can be done with one transducer or with two separate transducers (the tandem technique).

Unlike radiography, ultrasonic testing in its basic form does not produce a permanent record of the examination. However, more recent versions of UT equipment include automated operation and electronic recording of the signals.

Ultrasonic techniques can also be used for the detection and measurement of general material loss such as by corrosion and erosion. Since wave velocity is constant for a specific material, the transit time between the initial pulse and the back reflection is a measure of the travel distance and the thickness.

The implementation of NDE (nondestructive examination) results for structural integrity and safety assessment involves a detailed consideration of two separate but interrelated factors.

a) Detecting the discontinuity
b) Identifying the nature of the discontinuity and determining its size

Much of the available information on detection and sizing capabilities has been developed for aircraft and nuclear power applications. This kind of information is very specific to the nature of the flaw, the material, and the details of the test technique, and direct transference to other situations is not always justified.

The overall reliability of NDE is obviously an important factor in a safety and hazard assessment. Failing to detect or under sizing existing discontinuities reduces the safety margin while oversizing errors can result in unnecessary and expensive outages. High reliability is achieved through a combination of factors, as follows:

a) Validated procedures, equipment and test personnel.
b) Utilization of diverse methods and techniques.
c) Application of redundancy by repetitive and independent tests.

It is useful to note that safety assessment depends on evaluating the ‘largest flaw that may be missed, not the smallest one that can be found’.

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