PRESSURE VESSELS AND PIPING SYSTEMS: RELIABILITY, RISK AND SAFETY ASSESSMENT

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Summary

Pressure vessels and piping systems are designed, fabricated, and operated to ensure very high levels of structural integrity, because the consequences of structural failures can be severe. Catastrophic ruptures can produce high-energy missiles, and cause damage to adjacent equipment and structures along with injuries and fatalities to workers and the public. Failure modes of a less catastrophic nature, such as leaks, can release hazardous and flammable materials that can also present significant hazards. While service experience over the last century shows an excellent record of reliability, efforts continue to improve and maintain the reliability of vessels and piping systems. This chapter describes methods to predict probabilities of failure and to quantify the consequences of such failures. These methods can be applied to vessels or piping systems taking into consideration component-specific design features, materials of construction, fabrication practices, operating stresses and temperatures, environmental factors, operating and maintenance practices, and in-service inspection programs. Topics covered include: 1) probabilistic structural mechanics and fracture mechanics, 2)

the role of probabilistic risk assessment evaluations, 3) application of failure event data from operating experience, 4) risk-informed in-service inspection, and 5) probabilistic design methods.

1. Introduction

The safety and reliability of pressure vessels and piping has been a public concern since the beginning of the industrial age. Failures of early steam boilers became widely reported as boiler explosions killed thousands of people per year and inflicted great damage to property. As a result, engineering organizations and government agencies developed and imposed legal requirements for engineering codes that applied to the design, construction, and operation of boilers and other high pressure vessels. In the 50 years after the American Society of Mechanical Engineering (ASME) was adopted, the number of deaths caused by explosions of properly operated boilers and pressure vessels was significantly reduced. Nevertheless, catastrophic failures still occur on rare occasions and other failures of a less significant nature (cracks and leaks) are more commonly reported. This chapter describes methods that can be used to estimate failure rates for vessels and piping systems. Also described, how such failure rates are used today in combination with evaluations of failure consequences using probabilistic risk assessment methods. Based on the author’s experience, the examples will focus on nuclear power plant applications. However, the same approaches also apply to other industries such as petro-chemical, gas transmission pipelines, and to more common items such as heating boilers and water heaters.

Pressure vessels and piping systems are designed, fabricated, and operated to ensure a very high level of structural integrity because the consequences of structural failures can be severe. Even less catastrophic failures (such as leaks) can release hazardous and flammable materials that present significant hazards. Despite excellent safety records ongoing efforts are needed to ensure that the reliability of vessels and piping systems are maintained. This chapter describes methods developed over recent decades to predict frequencies of failure and to quantify the consequences of failures. Such methods can take into account vessel-specific design features, materials, fabrication practices, operating stresses, operating temperatures, environmental factors, operating practices, and in-service inspection programs. Topics include: 1) probabilistic structural mechanics and fracture mechanics, 2) the role of probabilistic risk assessment, 3) application of failure event data from plant operating experience, 4) risk-informed in-service inspection, and 5) probabilistic design methods.

2. Failure Mechanisms and Failure Modes

Before the reliability of a vessel or piping system is evaluated, it is first necessary to identify the potential failure mechanisms and failure modes of concern. One must also relate different failure modes to possible safety and/or economic consequences. Judgment is needed to focus evaluations on those failure scenarios having highest likelihoods of occurrence.

2.1 Failure Modes

There are many possible definitions (or degrees) of failure that may be of concern. Table 1 lists modes of failure that can be considered. These modes are presented in an increasing order of severity of consequence. The less severe modes (small cracks) are most likely to occur than the more severe modes (rupture). In addition, degradation if not detected and repaired will generally progress over time from a less severe mode (small crack) to more significant modes (leaking through-wall crack) and ultimately even to catastrophic failure.

Small crack
Local corrosion/wall thinning
Excessive distortion
Leaking Through-Wall Crack
Through-wall corrosion/wall thinning
Excessive Leakage
Fracture/catastrophic rupture

Table 1. Example Failure Modes

In some cases, concerns may be limited to catastrophic ruptures that would present the greatest threat to workers or to the general public. In other cases, evaluations may have a broader objective that considers unexpected degradation (corrosion, cracking, etc.) that would require repairs or replacements of components and thereby have an economic impact associated with repair costs and/or the loss of the productive use of the component. The consequences of small leaks can be very different depending on the situation. For a water storage vessel, the loss of a small volume of water could be of little concern; whereas, small leaks in vessels containing toxic or flammable materials could result in a large number of fatalities.

Table 1 lists failure modes in order of increasing consequences as follows:

- Small Crack – Degradation is sometimes detected in the form of a crack that does not fully penetrate the wall of the vessel or piping component. While such structural degradation by itself may pose no immediate safety consequences, it is prudent to take corrective actions to prevent future consequences. The need for repairs to the degraded component should be determined and implications for other similar components should be evaluated. Corrective actions could include an aggressive inspection program. In some cases, complete replacement of piping and vessels may be needed if the original designs and the selected materials are determined to be unsuitable for the operating conditions at the facility.
- Local Corrosion and Wall Thinning – While design methods usually specify a wall thickness that includes some allowance for corrosion over the life of the vessel and piping, the actual operating conditions may produce local rates of corrosion that exceed the expected rates. Inspections can and should detect corrosion before it fully penetrates the wall thickness and before any safety impacts result. As in the case of cracking, corrective measures in the form of repairs and additional inspections should be implemented to ensure safe and economical operation.

- Excessive Distortion – A failure mode of concern may not involve penetration of the component wall, but may rather degrade the function of the component because of excessive deflection or distortion. For example, seating surfaces may become sufficiently misaligned to the degree that gasket leakage results.
- Leaking Through-Wall Crack – In some cases, even a small amount of leakage can have significant safety consequences, especially if the leaking fluid is highly toxic or flammable. In other cases, the release of otherwise non-hazardous fluids could impact the operation of nearby critical equipment by causing corrosion or electrical malfunctions.
- Through-Wall Corrosion/Wall Thinning – As for cracking, leakage even at relatively small rates can present significant safety or economic consequences.
- Excessive Leakage – Leakage rates can over time increase to levels that impact the function of a system or component. For example, a leak could eventually depressurize a critical system to the extent that it could no longer perform its intended function. In other cases, the leakage could create a water spray that could cause damage in the area adjacent to the leak.
- Fracture/Catastrophic Rupture – This most severe of consequences comes from sudden fracture or ruptures, which can occur without any prior leakage to give any warning of impending failure. The consequences of concern can be related to loss of function of the rupture component itself (e.g., loss of cooling water to process equipment) or can come from the extreme energy of the rupture event (e.g., high velocity missiles, blast waves, release of hot fluids, etc.).

Figure 1. Pipe that ruptured at nuclear power plant after severe wall thinning at inner surface caused by flow-assisted corrosion.

Figures 1–3 show some examples of ruptured piping. In each case, the failure involved the release of large amounts of energy along with significant economic impacts in terms of repair costs and shutdowns of important industrial facilities for extended periods of time. Figure 1 illustrates a failure associated with severe thinning of the pipe wall that caused a pipe rupture and fatalities to workers at a nuclear power plant. Figure 2 shows a ruptured pipe that had been in service for a large number of years. In this case, the corrosion damage to the older pipe was relatively small with the primary cause of failure being a sudden over-pressure from a water hammer event. Figure 3 shows another ruptured pipe that failed at a coal-fired power plant. In this case, the degradation was not wall thinning but cracking by the mechanism of creep damage to an axial weld in the pipe that operated at a relatively high temperature. The catastrophic nature of the failures shown by Figures 1–3 serve to emphasize hazards associated with operation of pressure vessels and piping and the need to reduce failure frequencies to the lowest possible levels.

Figure 2. Steam pipe at municipal heating system that ruptured because of severe load imposed by water hammer event.

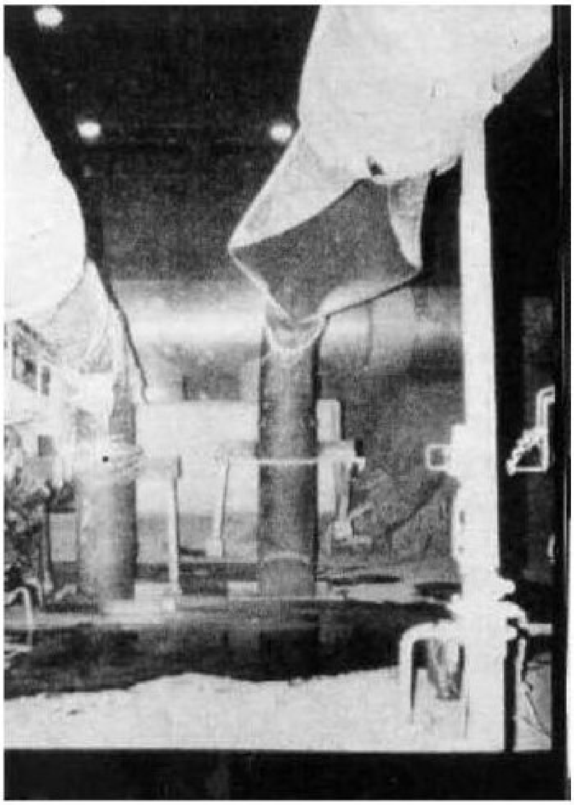

Figure 3. Pipe at coal-fired power plant that ruptured along axial weld because of high temperature creep damage to weld.

2.1. Failure Mechanisms

Table 2 lists a number of failure mechanisms and other causes that are known to result in failures of pressure vessels and piping systems. This list is intended only to show examples and will not be discussed in detail. Many failures come from gradual material degradation (e.g., corrosion, fatigue cracking, wear, etc.) that occurs over time spans of many years before it advances to a stage sufficient to cause a structural failure (leak or rupture event). Metal fatigue is one common failure mechanism. Small-diameter piping is often subject to vibrational stresses that cause cracking. Fatigue failures of larger sizes of vessels and piping are more likely to come from cyclic thermal stresses such as at locations exposed to cyclic exposures to hot and cold fluids. Corrosion mechanisms are a particularly common cause of failures both in the form of widespread loss material (wall thinning) or as local attack such as pitting or cracking.

In other cases, a single short-term event (e.g., overpressure, extreme overheating, water hammer, etc.) can cause a sudden failure. Some loading events are natural occurrences such as earthquake loadings; whereas, other events come from human errors in operating and maintaining the facility such as from improper repairs and operation at pressures or temperatures over design limits. Pressurized systems are usually protected from excess pressures and temperatures by safety devices, but these devices can fail to function due to time-related degradation or improper installation or maintenance.

Operation at loads and/or pressures exceeding design limits
Operation at temperatures over design limits
Operation at temperatures below brittle fracture limits
Improper design and fabrication
Improper repairs and alterations
Structural damage from maintenance
Improper or degraded supports for components
Structural damage from external events (impact, crushing, etc.)
Excessive vibration
Improper or degraded overpressure protection
Material or welding defects
General corrosion
Flow-assisted corrosion
Wear (excessive maintenance)
Thermal fatigue cracking
Vibration fatigue cracking
Stress corrosion cracking
High-temperature creep
Long-term embrittlement
Loose or missing fasteners

Table 2. Example Failure Causes

3. Reliability and Risk

Terms related to reliability and risk must be clearly defined and understood within the context of vessel and piping integrity. Risk combines the concepts of probability of failure and consequences of failure using the definition

$$Risk \ = \ \mathrm{Pr}obability \ of \ Failure \times Consequences \ of \ Failure$$

Probability is usually quantified as a failure frequency, which expresses the number of failure events that occur over a given time span. It is important to define the event of concern along with the time span of interest. An example definition would be rupture events per vessel per year of operation. Another example related to piping systems would be leaks per weld per year or leaks per meter of pipe per year. In other cases, it may be of interest to address reliability in a larger context such as failures per plant or failures per system.

The concept of failure frequency is applied to systems that operate on a continuing basis, as for example at electric power plants. However, other systems remain in a standby mode during normal operation and are needed only rarely to perform critical functions in times of emergencies. An example would be piping in a fire protection system. For such systems, risk evaluations express reliability in terms of probability of failure per demand rather than as failures per year.

Different failure events can have wide ranging consequences. Consequences can only be of an economic nature expressed in terms of dollars associated with loss of production plus the labor and materials for repairs. There can also be safety consequences from injuries to workers and/or the general public. For example, a small leak at a power plant would have no safety consequences and only minor economic consequences if the repair of the leak can be accomplished without interrupting the operation of the plant. On the other hand, the rupture of a pressure vessel or a large pipe could cause a large energy release, an explosion, or a fire with human deaths and injuries. In addition to severe safety consequences, ruptures can have major economic consequences totaling millions of dollars both from an extended shut down of a large production facility and major costs to replace the ruptured component along with repairs to damage inflicted on adjacent components and structures.

4. Failure Frequency Estimation

Failure frequencies for pressure boundary components must often be estimated to support Probabilistic Risk Assessments (PRAs) and other decision making purposes. Estimates are most often based on reported failures from past service experience and have focused on a system level rather than on the component level. Such estimates have limitations for predicting future performance and in identifying priorities for managing the integrity of specific components. Estimates based on service experience are better for evaluations of more common failure modes consisting of small leaks. Estimates for the frequencies of larger leaks and rupture events are, however, subject to larger uncertainties if based soley on service experience.

Risk evaluations require realistic estimates of failure frequencies that apply to the specific combinations of materials, degradation mechanisms, and operating conditions. There are four basic approaches discussed below for estimating piping and vessel reliability:
(1) Statistical estimation using service data,
(2) Structural reliability analysis (SRA) based on probabilistic fracture mechanics,
(3) Expert judgment/expert elicitation, and
(4) Any combination of (1) through (3).

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Biographical Sketch

Fredric Simonen, a mechanical engineer, graduated in 1966 with a Ph.D. degree in Engineering Mechanics from Stanford University located at Stanford, California, USA. He is presently a Laboratory Fellow (retired) in the Computational Mechanics Group at Pacific Northwest National Laboratory in Richland, Washington, USA. Since joining the Pacific Northwest National Laboratory in 1976, and before that at the Battelle Columbus Division beginning in 1966, Dr. Simonen has worked in the areas of fracture mechanics and structural integrity. His research has addressed the safety and reliability of nuclear pressure vessels and piping as well as other industrial and aerospace structures and components. Since the early 1980s, he has lead several studies for the U.S. Nuclear Regulatory Commission of the effects of pressurized thermal shock on the failure probability of reactor pressure vessels. This work has advanced the technology of probabilistic fracture mechanics and methods for estimating the number and sizes of flaws in vessel welds. During the 1990s, Dr. Simonen was a leader on the behalf of NRC and the American Society of Mechanical Engineers in the implementation of risk-informed methods for the inspection of nuclear piping systems. He has published over 200 papers, articles, and reports in the open literature. Dr. Simonen is a member of the American Society of Mechanical Engineers and has served on numerous ASME committees and codes and standards bodies.