UCRL-JC-133290
PREPRINT

Pressure Vessels and Piping Systems: General Requirements for Documentation and Testing

B. Blyukher
C. Borzileri
Y. Brailovsky
A. Tsicalo

This paper was prepared for submittal to the
1999 American Society of Mechanical Engineers
Pressure Vessels and Piping Conference
Boston, MA
July 21-26, 1999

February 25, 1999

Lawrence Livermore National Laboratory

PRESSURE VESSELS AND PIPING SYSTEMS: GENERAL REQUIREMENTS FOR DOCUMENTATION AND TESTING

Boris Blyukher
Health and Safety Department
Indiana State University
Terre Haute, IN

Chuck Borzileri
Lawrence Livermore National Laboratory
Livermore, CA

Yakov Brailovsky
Kislorodmach Co.
Odessa, Ukraine

Alfred Tsicalo
Refrigeration Academy
Odessa, Ukraine

ABSTRACT

Pressure vessel and piping systems are widely used throughout industry and research laboratories and contain a very large concentration of energy, and yet, despite the fact that their design and installation comply with federal, state and local regulations and recognized industrial standards, there continue to be serious pressure equipment failures.

There are many reasons for pressure equipment failure: degradation and thinning of materials with usage, aging, hidden flaws during fabrication, etc. Fortunately, periodic testing and internal and external inspections significantly improve the safety of a pressure vessel or facility. A good testing and inspection program is based on development of procedures for specific industries or types of vessels.

This paper describes the elements that should be a part of a pressure testing safety program and the requirements that it should address. The program should comply with pressure safety standards and include the requirements for inspecting pressure vessels, establishing and implementing a written pressure system test work permit, maintaining safety in the testing area, developing in-place pressure testing procedures, keeping records for pressure test calculations and results, and evaluating the system's internal and external integrity.

INTRODUCTION

A number of recent accidents at cryogenic and compressed gas plants, research and development, and test facilities has served to focus attention on the hazards and risks associated with storage, handling, and transfer of fluids under pressure. More injuries and fatalities are associated with pressure vessel accidents than from boiler accidents (Kohan 1987; Cheremisinoff 1998). When pressure vessels do fail, it is typically the result of shell failure resulting from corrosion and erosion (57 percent of total shell failures).

All pressure vessels have their own peculiar hazards, including great stored potential force, points of wear and corrosion, and possible failure of overpressure and temperature control safety devices.

In developing requirements for a pressure testing safety program, we consulted OSHA, ASME, ANSI, and industry standards and regulations (see the Bibliography). The resulting recommendations are believed to represent a summation of the best experience available. The paper also draws on international experience gained from development of pressure testing and inspection programs at Lawrence Livermore National Laboratory in Livermore, California, the Superconducting Super Collider Laboratory in Dallas, Texas, and several cryogenic industrial and R&D facilities in the Ukraine.

Government and industry have responded to the need for improved pressure systems testing by producing standards and regulations specifying general pressure safety requirements (e.g., 49 CFR 100179 [Transportation]; 29 CFR 1910 [General Industry]; ASME Boiler and Pressure Vessel Code, Sections I through XI; DOE Pressure Safety Guidelines, M-089; and others). These regulations outline requirements for implementation of the pressure testing safety program. It is critical that design and operating personnel use these standards as benchmark criteria for writing and implementing a pressure testing safety program.

This paper outlines the requirements for the safe testing of pressure systems, with the exception of:

- Refrigeration systems that comply with the ASME Unfired Pressure Vessel Code and applicable Air-Conditioning and Refrigeration Institute (ARI) standards.
- Building service systems for plumbing and heating, fire protection piping, air-conditioning equipment, and boilers that are covered under other codes and standards.
- Systems that operate at a Maximum Allowable Working Pressure (MAWP) less than atmospheric pressure. (Design guidance for these systems is given in the ASME Code, Section VIII, Division 1, Appendix V).
- Vessels having an inside diameter not exceeding six inches and containing a maximum stored energy of 2000 joules.

An extensive list of relevant standards and useful references is presented in the Bibliography.

PRESSURE TESTING PROGRAM ELEMENTS

A good pressure testing safety program should detect fabrication defects and deterioration from aging, cracking, corrosion and other factors before they cause vessel failure and to determine (1) if the vessel can continue to be operated at the same pressure, (2) what measures of control and repair may be needed so that the pressure system can be operated at the original pressure, and (3) whether pressure must be reduced in order to operate the system safely.

The pressure testing safety program is designed to assure a safe pressure system environment during operational and storage stages. It conforms to the pressure safety standards of OSHA, DOT, ASME, local, state, and other federal codes and standards related to general safety and industrial hygiene. The program documentation includes definition of the responsibilities of engineering, management, and safety personnel; the general requirements for equipment and materials; procedures for hydrostatic and pneumatic testing to verify the integrity of a system and its components; and guidelines for a pressure testing plan, emergency procedures, documentation, and hazard control measures. These measures include pressure release control, protection against the effects of noise exposure, environmental and personal monitoring, and protection from the presence of toxic or flammable gases and high pressures.

Pressure Testing Procedure

Definitions (49 CFR 100179 [Transportation]; 29 CFR 1910 [General Industry]; ASME Boiler and Pressure Vessel Code, Sections I through XI; DOE Pressure Safety Guidelines, M-089)

Corrosion Allowance—The extra thickness of material added by design to allow for material loss from corrosive or erosive attack.

Corrosive Service—Any pressure system service that, because of chemical or other interaction with the container's materials of construction, contents, or external environment, causes the pressure container to crack, to become embrittled, to lose more than 0.01 in. of thickness per year of operation, or to deteriorate in any way.

Engineering Safety Note (ESN)—A management-approved document describing the anticipated hazards associated with equipment and the design parameters that will be used.

High Pressure—Gas Pressure greater than 20 MPa gauge (3000 psig) and liquid pressure greater than 35 MPa gauge (5000).

Intermediate Pressure—Gas Pressure from 1 to 20 MPa gauge (150 to 3000 psig) and liquid pressure from 10 to 35 MPa gauge (1500 to 5000 psig).

Leak Test or Check—A pressure or vacuum test to determine the existence, rate, and/or location of a leak.

Low Pressure—Gas Pressure less than 1 MPa gauge (150 psig) or liquid pressure less than 10 MPa (1500 psig).

Manned-area operation—A pressure operation, that may be conducted (within specified limits) with personnel present.

Maximum Allowable Working Pressure (MAWP)—The highest pressure at which a system is safe to operate. This is the maximum setting for the primary pressure relief device.

Maximum Operating Pressure (MOP)—The highest pressure expected during operation. This is usually 10-20% below the MAWP.

Mpa—Absolute pressure in SI units. 1 atmosphere (14.7 psig) is equal to 0.1 MPa.

Operational Safety Procedure (OSP)—The Document used to describe the controls necessary to ensure that the risks associated with a potentially hazardous research project or unique activity are at an acceptable level.

Pressure Equipment—Any equipment, e.g., vessels, manifolds, piping, or other components, that operates above or below (in the case of vacuum equipment) atmospheric pressure.

Pressure Vessel—A relatively high-volume pressure component (such as a spherical or cylindrical container) with a cross section larger than the associated piping.

Proof Test—A test in which equipment prototypes are pressurized to determine the actual yield or failure (burst) pressure (used to calculate the MAWP).

Remote Operation—A pressure operation, that may not be conducted with personnel present. The equipment must be installed in test cells, behind certified barricades, or be operated from a safe location.

Safety Factor (SF)—The ratio of the ultimate (i.e., burst or failure) pressure (measured or calculated) to the MAWP. A Safety Factor related to something other than the failure pressure should be identified with an appropriate subscript.

General Information

- Pressure tests can be hydrostatic (the preferred method, using a liquid such as water or oil) or pneumatic (using a dry gas such as air or nitrogen). In a typical pressure test, the liquid or gas is placed in the system at sufficient pressure to determine the integrity of the container and related components. The test pressure should not exceed calculated and recommended limits of applicable national codes and national consensus standards. Before conducting any pressure tests, the need for a written standard operating procedure or special work permit should be considered (Fig. 1).
- All pressure systems should be pressure-tested before initial operation or use and after any modifications, changes, or repairs to the system or components.
- All pressure tests must be conducted remotely and be observed (or conducted) and certified by a Pressure Inspector.
- In a hydrostatic test, all air or gas is displaced from the system. Hydropneumatic tests are performed on systems from which essentially all the air or gas cannot be displaced by a test liquid. Hydropneumatic tests require the same safety precautions as those needed for pneumatic tests. Sometimes fillers can be inserted to reduce the volume of fluid.
- Hydrostatic tests require fewer precautions than pneumatic tests. The initial hydrostatic test of a new pressure vessel should be performed at 1.5 times the calculated MAWP, including any corrosion allowance. This test does not increase the design MAWP of the pressure system but it does test all system components at the highest realistic test pressure. Hydrostatic tests on some pressure system materials, such as stainless steel, should only be performed with sediment-free water. Hydrostatic tests on many cast iron systems should only be performed with water at temperatures greater than 70F.
- After a pressure system has been modified or repaired or its configuration has been changed, the system should be hydrostatically pressure-tested at 1.5 times the MAWP (recalculated for the modified system). To derate the MAWP, an allowance for corrosion should be maintained in the calculation. This derated MAWP is the maximum pressure rating for the modified system.

Special Responsibilities

The engineer responsible for the design, procurement or operation of the vessel shall:

- Perform the pressure test.
- Write the Engineering Note (when required).
- Prepare a report on the pressure vessel test.
- Prepare approved Pressure Test plan.
- Obtain a signed Pressure Testing Permit prior to conducting the test.

- Submit a completed report for the ES&H Section Pressure Vessel master File to be attached to the appropriate Engineering Note.

The division/section safety officer or designee shall be responsible for:

- Reviewing the system to assure all appropriate safety precautions have been taken prior to commencement of the test.
- Observing the test.
- Maintaining a file with a copy of the competed report.

The Pressure Safety Review Subcommittee is available to advise and assist division/section personnel with the testing.

Testing Area

In both hydrostatic and pneumatic tests, the test area should be restricted and barricaded. The vessel being pressure-tested should be oriented so that bolts, flanges, and other possible missiles point away from people and other equipment. In all cases, specialized pressure systems should be pressure-tested.

In-Place Pressure Testing

If it is impractical to pressure-test a vessel or system at the Mechanical Shop or some other approved location, pressure test may be performed in-place. In this case, the Responsible User must ensure that in-place *retesting* of pressure equipment is performed. Although other individuals may be designated to observe and direct testing or retesting, responsibility for safe conduct of the test and safe functioning of tested pressure equipment cannot be delegated.

The Responsible Engineer must prepare the required test procedure, direct the test personnel, and witness in-place pressure testing.

Test Procedures

- A written test procedure must be prepared for every pressure test. When testing will be conducted in place, the test procedure must be included in (or appended to) the OSP (if applicable).
- Standard procedures that may be used for conducting pressure system tests are outlined in (Blyukher, B., 1993; DOE Pressure Safety Guidelines, M-089, and Pressure Safety Manual, 1993).
- Procedures for in-place testing must be reviewed by the Safety Group and Quality Assurance Group (QA) and approved by Department Head.
- The supervisor of the area where the test will be performed must be advised of pressure tests planned to occur.
- The tests shall be witnessed by safety and QA representatives.

Testing Records

Records of all pressure test calculations and the results shall be maintained by the group responsible for each pressure system. The following information should be recorded for each pressure test conducted (See form shown in Fig.2):

- Identification of vessel(s) or system.
- Location of vessel(s) or system.
- MAWP of vessel(s) or system.
- Planned test pressure.
- Supporting calculations.
- Date and time that test started.
- Date and time that test was completed or failed.
- Maximum pressure attained.
- Chart of test-pressure sequence (optional).
- Test liquid or gas.
- External temperature of system.
- Temperature of test liquid of gas.
- Organization conducting test.
- People witnessing the test and their organization.
- Maximum deformation or strain.

Compressed Gas Systems

Pressure tests on compressed gas cylinders must comply with the requirements of the DOT, 49 CFR, Parts 100-199.

Pressure tests on systems that contain reactive gases must be carefully planned to avoid contamination and corrosion (Blyukher, B., 1993; DOE Pressure Safety Guidelines, M-089).

Pressure Piping Systems

To safely pressure-test a pressure piping system, isolate the system from equipment that is not being tested. Because simply closing valves is not sufficient isolation, the following procedures should be considered:

- Use full-pressure pancake between interconnecting flanges.
- Use blanks in unions.
- Close two valves in series and open an intervening drain, or
- Close a valve and remove the pipe section that is immediately downstream.
- Before hydrostatically testing pressure piping systems, carefully assess whether additional high-point vents or low-point drains are needed. High-point vents ensure that filling the system fully displaces all air. Low-point drains ensure that all liquid can be removed after the test is complete. The test liquid should be flowing from the high-point vents before they are closed to ensure a true hydrostatic test, and the order in which vents are closed may be important. Occasionally, it may be necessary to remove the test liquid by flushing the piping system with dry air or nitrogen.

Pressure Vessels

- Pressure vessels should be pressure-tested with all accessories in place that are not typically isolated from the vessel by a valve. This may include instrument connections, sight and level glasses, liquid level gauges, and view windows. All other vessel nozzles and connections must be closed off with test blinds or plugs.
- Test pressure vessels using an inert fluid. Initially test manned-area vessels at 150% of their MAWP or at the test pressure specified in the ESN.
- Take appropriate diameter measurements, accurate to within 0.001in.(0.025mm), both before and after testing to show that detectable plastic yielding has not occurred during pressurization.
- Remote-operation vessels should be tested at a pressure that is consistent with the functional reliability required (usually 125% of the MAWP). Inspect the vessel ultrasonically. In addition, check the vessel for surface cracks by the magnetic particle test or the fluorescent penetrant test (for non-magnetic vessels).

Pressure Systems

- Test non-hazardous liquid, inert gas, and compressed air systems at 125% of their MAWP using an inert fluid.
- Test toxic, oxygen, radioactive, and flammable fluid systems at 150% or their MAWP using an inert fluid.

Pressure Relief Systems

- All pressure-relief devices are tested and calibrated by a certified testing facility before installation. After installation, pressure calibration tests should be scheduled for all pressure relief devices, excluding rupture (or frangible) disks.
- Pressure-relief devices in corrosive service should be pressure-calibration-tested annually.
- Pressure-relief devices in benign service should be pressure-calibration-tested at least every 3 years.
- A maintenance schedule should be established when the system is installed.
- Pressure-relief devices must be removed from the pressure system before pressure calibration tests. Pressure-relief systems may be pressure-tested up to the point where the pressure-relief device is connected.
- Pressure-relief devices, no matter how massive they may appear, are delicate instruments and should be treated as such. Safety and relief valves that are dropped or bumped should be sent back for recalibration. Rupture disks should be handled in their original shipping boxes until they can be installed (CGA S-1.1).

Proof Tests

A proof test is occasionally necessary for pressure system configurations that cannot be verified by traditional design calculations or other design algorithms. A proof test is a pressure test to verify that a pressure system can operate at a specific maximum pressure. The purpose of proof tests is to reach the maximum pressure without excessive deformation of the vessel, as indicated by strain gauges or brittle coatings. If a vessel is deformed during proof tests, it cannot be used for any service without approval of the Pressure Safety Committee.

Proof tests are potentially very dangerous unless properly controlled and unless personnel are protected. A written standard operating procedure or special work permit (See Fig. 1) is required for all proof tests.

Leak Tests

Leak tests determine the integrity of all types of connections (including flanged, threaded, compression, flared, expanded, and welded connections) within a pressure system. The purpose of leak tests is to find leaks that may permit pressurized material to escape or air or other contaminants to enter the pressure/vacuum envelope. Gross leakage can be detected by observing the drop in pressure on the test gauge during pressure testing, and can be pinpointed with leak-detection fluid. Small leaks can be located with commercial leak detectors. Soap solutions or helium sensors are often used for leak tests and detection.

Leak tests should be done in stages, beginning with relatively low pressures. For example, the following leak test could be used for a 100 psig MAWP system:

1. Seal system.
2. Pressurize at 1 or 2 psig; check for leaks.
3. Increase pressure to 5 psig; check for leaks.
4. Increase pressure to 10 psig; check for leaks.
5. Increase pressure to 25 psig; check for leaks.
6. Increase pressure to 50 psig; check for leaks.
7. Increase pressure to 100 psig; check for leaks.

Leak test should be performed remotely. Manned-area leak checking of successfully pressure-tested, remote-operation vessels and systems is limited to a maximum of 20% of the test pressure. An open flame for leak checking shall not be used.

If a leak is found during pressure testing of a documented (ESN, ASME, DOT, or unmodified commercial hardware) manned-area vessel or system, the following actions shall be performed:

1. Mark the location exactly.
2. Slowly depressurize the system.
3. Make any appropriate repairs. *Never, under any circumstances, work on a pressure system repair while it is under pressure.*
4. Begin the leak test again at the lowest pressure (1 or 2 psig in the example). No undocumented vessels or systems may be leak checked in a manned-area mode at pressures higher than 20% of the test pressure.

SUMMARY

1. This paper demonstrates how to establish and implement a pressure testing safety program by using the basic pressure safety principles used by OSHA and industry standards.
2. The primary potential hazards common to operation of pressure systems operations and facilities are mechanical hazards, noise, the remote possibility of compressed gas release or leak, oxygen deficiency hazard, and possibility of fire. The safety requirements and management program components discussed can be applied to all types of pressure equipment (e.g., vessels, gas cylinders and containers, and piping) that are an integral part of R&D, manufacturing, production, and testing facilities for the petroleum, petrochemical, chemical, air separation, and gas production industries.
3. Prior to testing a pressure system, users must become familiar with, and comply with all applicable OSHA, ASME, ANSI, and industry regulations, as well as other applicable federal, state and local codes and standards. These include regulations for personal protective equipment (e.g., eye and face protective equipment, respiratory protective equipment, protective clothing, protective shields, and barriers) and administrative and/or engineering controls for noise exposure.
4. Pressure safety testing programs should be incorporated into occupational safety and health programs and emergency preparedness plans.
5. By establishing and implementing of a pressure testing safety program, risk to the workforce and the workplace from the pressure vessel failure release compressed gases can be greatly reduced.

BIBLIOGRAPHY

ASME BOILER AND PRESSURE VESSEL CODE, Sections I through XI (American Society of Mechanical Engineers, 1992.

Blyukher, B., 1993, *"Pressure System Safety", Practice Guide*, AQA-1010110, Superconducting Super Collider Laboratory, Dallas, Texas.

CGA S-1.1, *Pressure Relief Device Standards—Part 1, Cylinders for Compressed Gases*, Compressed Gas Association.

Cheremisinoff, Nicholas P., 1998. *Pressure Safety Design Practices for Refinery and Chemical Operations.* Westwood, NJ: Noyes Publications.

Code of Federal Regulations, 29 CFR 1910 [General Industry], U.S. Department of Labor.

Code of Federal Regulation, 49 CFR 100179 [Transportation], U.S. Department of Transportation.

DOE Pressure Safety Guidelines, M-089.

Handbook of Compressed Gases, Compressed Gas Association, 1990.

Kohan, Anthony Lawrence, 1987. *Pressure Vessel Systems. A User's Guide to Safe Operations and Maintenance*. McGraw-Hill Book Company. NY.

National Board Inspection Code—A Manual for Boiler and Pressure Vessel Inspectors, National Board or Boiler and Pressure Vessel Inspectors.

NBIC, National Board Inspection Code, ANSI/NB-23.

Pressure Safety Manual, 1993, MN 471000, Sandia National Laboratories.

Pressure Vessel Inspection Code, ANSI/API 510, American Petroleum Institute, most recent edition.

Standards for Low Pressure and Atmospheric Pressure Storage Tanks, American Petroleum Institute, most recent edition.

Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.