LA-UR-16-21269

Title: Pressure Safety: Advanced Self-Study 30120

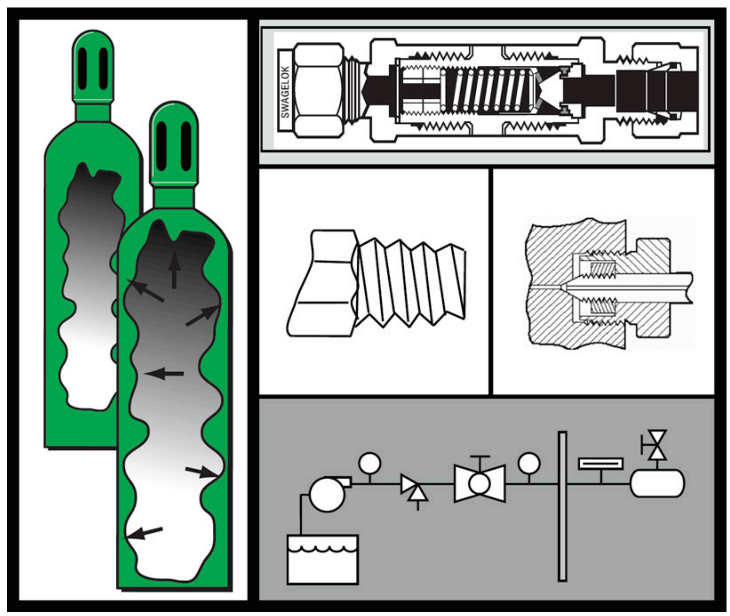
Author(s): Glass, George

Intended for: Training Manual

Issued: 2016-02-29

Pressure Safety: Advanced

Self-Study 30120



February 2016

Los Alamos NATIONAL LABORATORY
EST. 1943

Operated by Los Alamos National Security, LLC for the NNSA

Institutional Training Services Group Leader
Cindy Dutro

Instructional Designers
George Glass and Phill Grogin

Technical Advisor
George Hrbek

Editor/Compositor
Lisa Rothrock

Course Number: 30120
February 2016
LA-UR-16-
Controlled Document Number: Press_Saf_Adv_30120_SS,R0.1

Contents

Introduction 1
Course Overview 1
Course Objectives 1
Program Owner 1
Target Audience 2
About This Course 2
Course Limitations 2
Module 1: Pressure System Hazards 4
Module Objectives 4
Lessons Learned 4
Pressure System Hazards 6
Causes of Pressure System Failure 7
Module 2: LANL Pressure Safety Program 10
Module Objectives 10
LANL Pressure Safety Program 10
Pressure Safety Program Documents 10
Pressure Safety Program Assistance 12
Module 3: Physics of Pressure Systems 14
Module Objectives 14
Units for Pressure and Their Conversions 14
Pressure Readings 16
Pressure Gauges 16
Temperature Scales 17
Temperature Conversions 17
Pressure, Area, and Force 18
Pressure, Volume, and Temperature 23
Stored Energy 28
Lessons Learned 31
Module 4: Pressure Fittings and Equipment 33
Module Objectives 33
Pressure System Categories at LANL 33
Maximum Allowable Working Pressure 34
Pressure System Components 35

Pressure System Component Configurations........................ 52
Module 5: Pressure Safety Practices.. 53
Module Overview.. 53
Module Objectives.. 53
System Design 53
Pressure Testing 55
Inspection... 58
Working Safely with Pressure Systems.................................. 59
Warning Signs and Signals 60
Acronyms and Abbreviations............. Error! Bookmark not defined.
Glossary 61
References 65

Introduction

Course Overview

Many Los Alamos National Laboratory (LANL) operations use pressure equipment and systems. Failure to follow proper procedures when designing or operating pressure systems can result in injuries to personnel and damage to equipment and/or the environment. This manual presents an overview of the requirements and recommendations that address the safe design and operation of pressure systems at LANL.

Course Objectives

When you have completed this course, you will be able to

- recognize hazards associated with pressure systems and causes of pressure system failure;
- identify standards and requirements that govern the design and use of pressure systems at LANL;
- recognize basic physics associated with pressure systems;
- identify considerations that affect the selection and use of pressure system components; and
- recognize factors that affect design and operation of pressure systems, including testing and inspection, requirements, safe work practices, and danger signals.

Program Owner

This course was developed under the direction and technical oversight of Occupational Safety and Health (OSH), the functional program owner for this training.

Target Audience

Successful completion of this course (or a recognized equivalent course) is ***required*** by LANL Procedure (P) 101-34, *Pressure Safety,* for workers who design, fabricate, install, operate, inspect, and/or test pressure-components systems, and/or maintain pressure systems. This course is ***recommended*** for LANL workers who will work with intermediate- and/or high-pressure equipment or systems (see Pressure System Categories in Module 4) and for supervisors of those working with such systems.

About This Course

Pressure Safety Advance Self-Study (Course 30120) consists of an introduction, five modules, and a quiz. To receive credit in UTrain for completing this course, you must score 80% or better on the 15-question quiz (check UTrain). Directions for initiating the quiz are appended to the end of this training manual.

This course contains several links to LANL websites. UTrain might not support active links, so please copy links into the address line in your browser.

Course Limitations

This course is NOT considered site-specific training and does NOT cover every conceivable hazard and control that may be encountered during pressurized system work. This course does NOT address qualification requirements for pressure system designers, pressure safety officers, and inspectors, which are defined in the *LANL Engineering Standards Manual,* Chapter 17, Pressure Safety.

This course builds on introductory information presented in *Pressure Safety Orientation* (#769) and *Gas Cylinder Safety* (#9518), which ***are recommended prerequisites for this course***.

Additional LANL training that supports working safely with intermediate- and high-pressure systems includes *Cryogen Safety* (#8876) and *Compression Fittings Assembly* (#30831).

Acronyms

ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
atm	atmospheres
CGA	Compressed Gas Association

Acronyms—continued

DOE	Department of Energy
ESM	Engineering Standards Manual
HAZOP	hazard and operability
HCl	hydrogen chloride
HIP	hot isostatic press
ID	inside diameter
IPS	iron pipe size
ISO	International Organization for Standardization
IWD	integrated work document
J	joule
LANL	Los Alamos National Laboratory
MAWP	maximum allowable working pressure
MOP	maximum operating pressure
N	Newton
NBIC	National Boiler Inspection Code
NFPA	National Fire Protection Association
NFV	needle flow valve
NH_3	Ammonia
NPS	national pipe straight (thread)
NPT	national pipe tapered (thread)
OD	outside diameter
OSH	Occupational Safety and Health Division
OSHA	Occupational Safety and Health Administration
P	procedure
Pa	Pascal
PRD	pressure-relief device
psi	pounds per square inch
psia	pounds per square inch absolute
psig	pounds per square inch gauge
PSC	Pressure Safety Committee
SCF	standard cubic foot
VCO	vacuum coupling O-ring
VCR	vacuum coupling rad lab

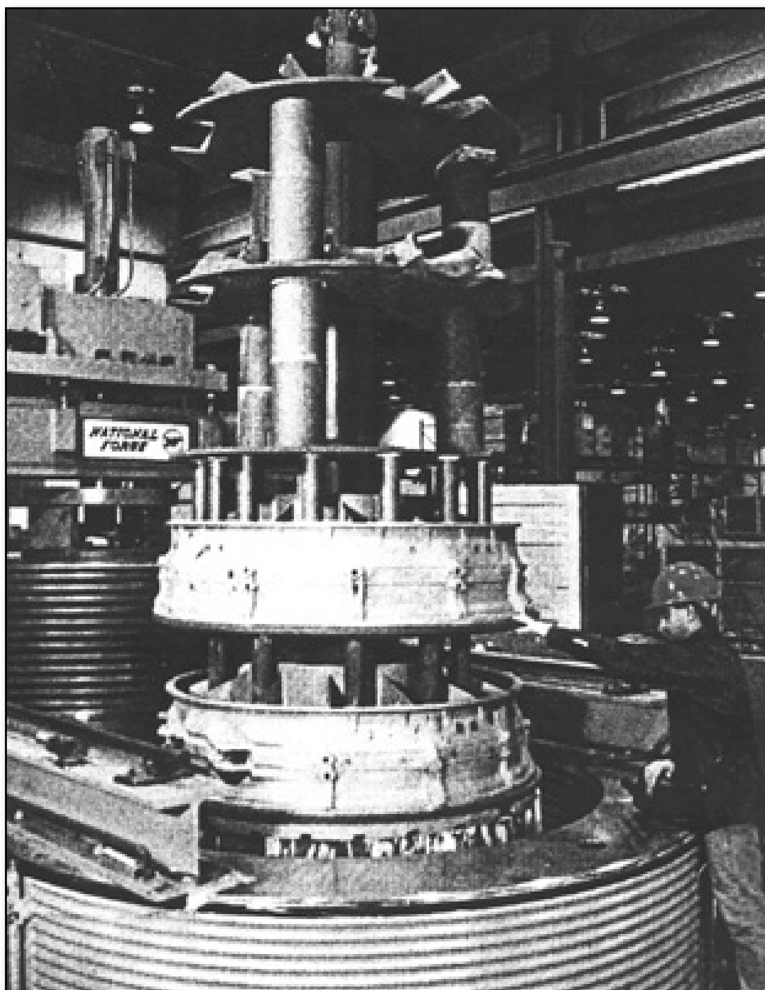
Module 1: Pressure System Hazards

Module Objectives

When you have completed this module, you will be able to

- identify general hazards associated with pressure systems and
- identify causes of pressure system failure and factors that affect the severity of pressure system hazards.

Lessons Learned



A hot isostatic press (HIP) is used to compress powdered materials at very high pressure. The failure of the outer cylinder on what was the largest HIP in the world led to the complete destruction of a factory.

Lessons Learned—continued

65,000-ft^2 factory with HIP before incident.

Factory after the HIP rupture. The energy released was estimated to be equivalent to a ton of TNT.

Pressure System Hazards

Pressure system hazards stem from the amount of energy stored in the system, the rate at which the energy is released, and the properties of the system contents. The uncontrolled release of the stored energy from a pressure system can injure personnel and damage equipment and/or the environment. In general, hazards of pressure systems include

- rapid release of mechanical, thermal, chemical, or cryogenic stored energy (see table below);
- fire or explosion following the release of contents that ignite or react with other materials;
- release of corrosive, toxic, or flammable contents;
- generation of corrosives or hazardous gases following release of contents that react chemically with the atmosphere or other materials; and
- displacement or depletion of breathable oxygen.

The failure of gaseous systems creates a much greater fragmentation hazard than a liquid system of the same initial pressure; the gas behind the fragments provides a longer pressure pulse than from a liquid system, allowing fragments to develop greater velocity.

Potential Effects from the Rapid Release of Stored Energy	
Pressure Wave	**Typical Effect**
0.2 psi	Breaks windows
0.5–1.0	Shatters windows
1.0 psi	Partial demolition of houses
1–8 psi	Laceration injuries from projectiles
3 psi	Distorts steel frame buildings
5 psi	Ruptures eardrums
10 psi	Damages lungs
11–15 psi	Fatal injuries (ruptured internal organs)

Effects on piping from external corrosion *(above left)* and internal corrosion *(above right).*

Causes of Pressure System Failure

Most pressure systems failures are initiated at three different stages of a system's life cycle:

- the engineering/construction stage,
- the administrative stage, or
- the technician/user stage.

Engineering/Construction Stage

Errors made in the engineering/construction stage that can result in accidents, even during normal system operation, include

- selection of materials incompatible with other system components or contents,
- underestimating necessary material strengths,
- selection of inappropriate controls or safety devices,
- faulty component or system manufacturing,
- use of components that do not meet system requirements, and
- faulty installation and lack of adequate testing.

Administrative Stage

Occurrence reports often conclude that the root cause of an incident is lack of management oversight. For example,

- workers are not qualified to perform assigned tasks,
- workers are not trained to perform assigned tasks, and/or
- procedures are approved without sufficient review.

Technician/User Stage

During the technician/user stage, pressure-related accidents typically result from

- component failure,
- whipping lines,
- body contact with system contents, and
- undesired mixing of substances.

Causes of Pressure System Failure—continued

Technician-User Stage—continued

Mistakes at the technician/user stage that can lead to pressure system failures include

- use of equipment that is not suitable because of age, condition, or design;
- faulty assembly or reassembly;
- poor maintenance, including inadequate repairs or modifications; and
- poor operating practices, including
  - failure to follow proper procedures, including integrated work documents (IWDs);
  - improvised equipment uses;
  - use of the wrong tools or materials to maintain or repair systems; and/or
  - misuse of systems.

Gas Cylinder Gasket Reacts with Anhydrous Hydrogen Chloride

A scientist had a stainless steel regulator reconfigured for an experiment by changing out a 350-Compressed Gas Association (CGA) fitting with a 330-CGA fitting for anhydrous hydrogen chloride (HCl) use. The lab's regulator shop performed the changeout and supplied a "white plastic" gasket to seal the high-pressure fitting. The researcher used the regulator to fill a small chamber with some HCl. The regulator and the filling system were then evacuated.

When the HCl lecture bottle was taken offline, it was noted that the "white plastic" gasket had reacted with the anhydrous HCl and melted. Apparently, the white plastic gasket was not made out of an inert material such as Teflon, but made out of a plastic that de-polymerized when in contact with HCl.

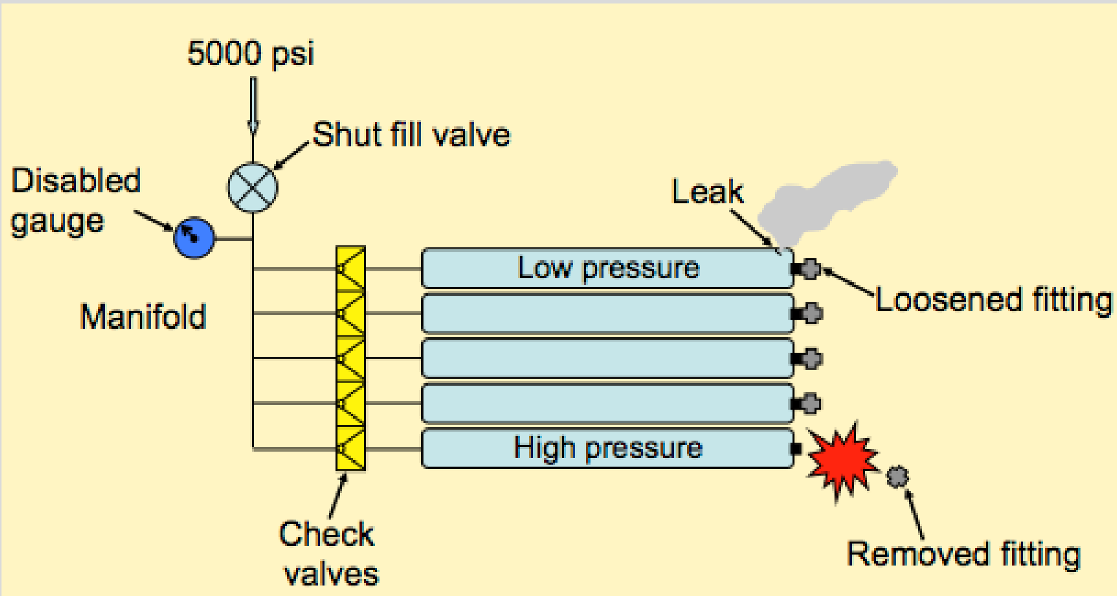
Lessons Learned

All construction materials that can come in contact with toxic or reactive materials must be compatible. This applies not only to gasket material, check valves, and seals, but also to tubing and reaction vessels.

-paraphrased from Lesson ID: LBNL-LL11-0020

Scenario

In April 1996, pipe fitters at the Hanford Nuclear Facility were hydrostatically pressure-testing a tubing bundle at 5000 lb per sq in. gauge (psig) when they found they were unable to maintain pressure. The fitters located a leak near one of several capped fittings on a tube. Because there was no vent valve to relieve the pressure, they decided to depressurize the system by loosening a fitting on the tube downstream from the pressure gauge.



The resulting drop in pressure jarred the gauge, disabling it. Believing all the tubes were depressurized, the pipe fitters then removed a cap from a different fitting at the end of the run, not realizing that it was isolated from the manifold by a check valve and still pressurized. The cap, fitting, and ferrules blew off the tube and became airborne. No one was standing in front of the fitting, and there were no injuries.

Causes

Investigators determined that the hydrotesting procedure yielded inadequate information to support testing at or above 200 psig. In addition, the procedure required a vent valve on the tubing run.

The investigation also determined that the pipe fitters should have recognized that the tubing run was pressurized between the check valves and the end caps. This incident underscores the importance of attention to detail when working with high-pressure systems.

Corrective Actions

The testing procedure was revised to include requirements for system setup to safely relieve pressure. New procedures also require quality-control inspectors to verify the setup before pressure testing is performed.

Training programs for pressure testing were reviewed, and appropriate training was required. Safety analysis and pre-job briefings were initiated for activities not part of daily operations.

Module 2: LANL Pressure Safety Program

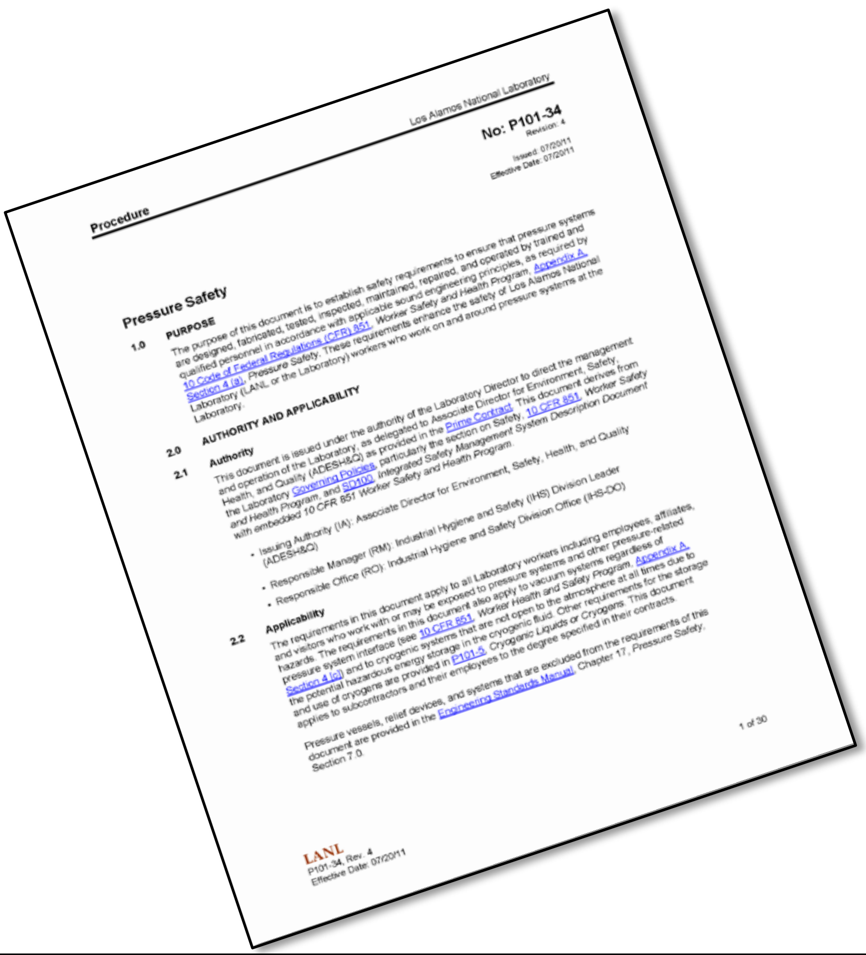
Module Objectives

When you have completed this module, you will be able to

- identify documents that specify pressure-safety requirements used in the LANL Pressure Safety Program and
- recognize groups and organizations at LANL that provide pressure safety assistance.

LANL Pressure Safety Program

The LANL Pressure Safety Program is an effort to ensure the safety of Laboratory workers in the field of pressurized safety systems. The program is composed of requirements, which include training, and resources and is set forth in P101-34, *Pressure Safety*.


Los Alamos National Laboratory

Procedure

No: P101-34
Revision: 4
Issued: 07/20/11
Effective Date: 07/20/11

Pressure Safety

1.0 PURPOSE

The purpose of this document is to establish safety requirements to ensure that pressure systems are designed, fabricated, tested, inspected, maintained, repaired, and operated by trained and qualified personnel in accordance with applicable sound engineering principles, as required by 10 Code of Federal Regulations (CFR) 851, *Worker Safety and Health Program*, Appendix A, Section 4 (a), Pressure Safety. These requirements enhance the safety of Los Alamos National Laboratory (LANL or the Laboratory) workers who work on and around pressure systems at the Laboratory.

2.0 AUTHORITY AND APPLICABILITY

2.1 Authority

This document is issued under the authority of the Laboratory Director to direct the management and operation of the Laboratory, as delegated to Associate Director for Environment, Safety, Health, and Quality (ADESH&Q) as provided in the Prime Contract. This document derives from the Laboratory Governing Policies, particularly the section on Safety, 10 CFR 851, *Worker Safety and Health Program*, and SD100, *Integrated Safety Management System Description Document with embedded 10 CFR 851 Worker Safety and Health Program*.

- Issuing Authority (IA): Associate Director for Environment, Safety, Health, and Quality (ADESH&Q)
- Responsible Manager (RM): Industrial Hygiene and Safety (IHS) Division Leader
- Responsible Office (RO): Industrial Hygiene and Safety Division Office (IHS-DO)

2.2 Applicability

The requirements in this document apply to all Laboratory workers including employees, affiliates, and visitors who work with or may be exposed to pressure systems and other pressure-related hazards. The requirements in this document also apply to vacuum systems regardless of pressure system interface (see 10 CFR 851, *Worker Health and Safety Program*, Appendix A, Section 4 (c)) and to cryogenic systems that are not open to the atmosphere at all times due to the potential hazardous energy storage in the cryogenic fluid. Other requirements for the storage and use of cryogens are provided in P101-5, *Cryogenic Liquids or Cryogens*. This document applies to subcontractors and their employees to the degree specified in their contracts.

Pressure vessels, relief devices, and systems that are excluded from the requirements of this document are provided in the Engineering Standards Manual, Chapter 17, *Pressure Safety*, Section 7.0.

1 of 30

LANL
P101-34, Rev. 4
Effective Date: 07/20/11

Pressure Safety Program Documents

The table below lists documents that affect the LANL Pressure Safety Program; these are accessible from the LANL homepage.

Document	Contents
10 CFR 851, *Worker Safety and Health Program*	• Contractor worker safety and health program must address pressure safety. • Contractors must establish policies and procedures to ensure that pressure systems are designed, fabricated, tested, inspected, maintained, repaired, and operated by trained and qualified personnel. • When national codes are not applicable (because of pressure range, vessel geometry, use of special materials, etc.), contractors must implement measures to provide equal or greater protection as follows: o Design drawings, sketches, and calculations must be reviewed and approved by a qualified independent design professional. Documented, organizational peer review is acceptable. o Qualified personnel must be used to perform examinations and inspections of materials, in-process fabrications, nondestructive tests, and acceptance tests. o Documentation, traceability, and accountability must be maintained for each unique pressure vessel or system, including descriptions of design, pressure conditions, testing, inspection, operation, repair, and maintenance.
P101-34, *Pressure Safety*	• Requirements for training and the design, installation, testing, inspection, and operation of pressure systems. • Refers to national codes and standards, including: o *Boiler and Pressure Vessel Code,* the American Society of Mechanical Engineers (ASME); o *Pressure Piping Code,* the American National Standards Institute (ANSI/ASME); o *Handbook of Compressed Gases*, the CGA; o *Matheson Gas Data Book*; and o *National Fire Codes and Standards*, the National Fire Protection Association (NFPA).
P101-14, *Chemical Management*	Requirements for handling toxic, corrosive, flammable, and oxidizing gases.
P101-5, *Cryogens*	Requirements for handling cryogenic fluids.
P342, *Engineering Standards Manual*, Chapter 17, *Pressure Safety*	Directs actions necessary to ensure safety, reliability, and contractual compliance of LANL pressure systems. Provides specific information, such as the following: • Exclusions from program • Occupational Safety and Health Administration (OSHA) requirements for pressure systems • Code and regulation application • Category M fluids • Designer-approved alternative hose restraints • Swagelok flex hoses • Copper tubing alternative • Unlisted, specialty, or unique components

Pressure Safety Program Assistance

All specialized pressure systems must be reviewed and approved by the PSC.

All pressure systems, including small, one-of-a-kind experimental devices and systems, must be designed, fabricated, installed, tested, inspected, and operated in compliance with national codes and consensus standards. The ASME stamp on pressure vessels represents one such recognized standard. Any pressure system falling outside the scope of these codes and standards is a specialized pressure system. ***All specialized pressure systems must be reviewed and approved of by the Pressure Safety Committee (PSC) upon completion of design and again before initial operation.***

System evaluation by the PSC requires knowledge of:

- the function of the system,
- how the system operates,
- whether the hazards of the system have been mitigated,
- the inspection and maintenance schedule of the system,
- how to examine system parts that are subject to deterioration, and
- training requirements for safe operation of the system.

The PSC also provides the following services for LANL pressure systems.

Pressure Safety Committee (PSC) Services
• Prescribes LANL-wide safeguards • Distributes pressure-related information • Reviews pressure safety program documents • Assists with hazard assessments and IWDs • Reviews and assists with system design • Reviews noncode designs • Performs walk-arounds of pressure systems • Reviews operations, systems, vacuum vessels, and the safety of cryogenic Dewars • Maintains a website at http://int.lanl.gov/safety/pressure

Pressure Safety Program Assistance—continued

Additional groups at LANL that can assist with the safe evaluation and performance of pressurized work are shown below.

Pressure Safety Issue	Group or Organization	Phone Number
General hazards and controls	Occupational Safety and Health	6-0295
Building/facility interface	Maintenance and Site Services	5-3065
Operation, maintenance, and testing	Engineering Services	7-5754
Fire-protection standards	Emergency Operations - Fire Protection	7-9045
Pressure-device calibration	Quality-Standards and Calibration	5-5437
Compressed gas procurement	Compressed Gas Facility (“Gas Plant”)	7-4406
Institutional ESH training	Institutional Training Services	7-0059

Module 3: Physics of Pressure Systems

Module Objectives

When you have completed this module, you will be able to

- convert different temperature and pressure units;
- recognize how pressure, area, and force are related;
- recognize how pressure, volume, and temperature are related; and
- recognize the stored-energy considerations for pressure systems.

Units for Pressure and Their Conversions

Many different units are used to measure pressure. Some are derived from direct measurements of pressure; others are derived from the units for force and area used in the different measurement systems. The following table lists some of the more commonplace units for pressure measurement.

The abbreviation . . .	represents . . .
atm	atmospheres
in. of Hg	inches of mercury
in. of H_2O	inches of water
ksi	1000 pounds per square inch
kPa	kilopascals (1000 Pa)
MPa	megapascals (1,000,000 Pa).
Pa	pascals (newtons per square meter)
psi	pounds per square inch
psia	pounds per square inch absolute
psig	pounds per square inch gauge
Torr	millimeters of mercury

Units for Pressure and Their Conversions—continued

The table below, adapted from the *Department of Energy Pressure Safety Manual,* shows conversions from one unit measure to another.

To convert a pressure given in units in the top row to units in the left-hand column, multiply the pressure value by the number at the intersection of the original column and the final unit row.

Example: To convert 20.0 psi to __ pascals,
20.0 psi × 6894.8 = 137896.0 pascals

Pressure Unit Conversion Table*

MULTIPLY → / TO GET ↓ BY	atm	bar	lb/in^2 (psi)	Newton/m^2 (pascal)	in. H_2O (4^{o}C)	ft H_2O	mm Hg (Torr)
atm	1	0.9869	0.0680	9.8692E-6	2.458E-3	0.02949	1.316E-3
bar	1.013	1	0.0689	1.0000E-5	2.491E-3	0.02987	1.333E-3
lb/in^2 (psi)	14.696	14.50	1	1.450E-4	0.03613	0.4333	0.01934
Newton/m^2 (pascal)	101325	100000	6894.8	1	24.91	2986.9	133.322
in. H_2O (4^{o}C)	406.8	401.4	27.68	0.004014	1	12.000	0.5353
ft H_2O	33.9	33.456	2.3076	3.348E-4	0.08333	1	0.04461
mm Hg (Torr)	760	750.06	51.715	7.5006E-3	1.868	22.42	1

***** *Some numbers are taken from the CRC Handbook of Chemistry and Physics*, *1997-1998.*

Exponential notation, e.g., 5.0E-3 = 5.0 x 10^{-3}

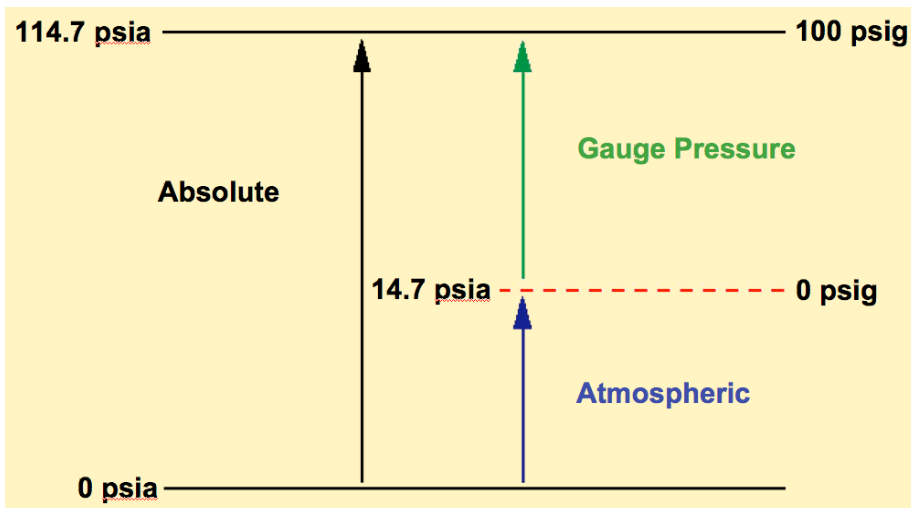
Pressure Readings

Atmospheric pressure is 14.7 psi at sea level and ~11.3 psi at Los Alamos (~7300 feet elevation).

You can express pressure using two different terms:

- absolute pressure (e.g., psia or kPa[a]) and
- gauge pressure (e.g., psig or kPa[g]).

Most gauges measure only the pressure above atmospheric pressure. To find absolute pressure, add atmospheric pressure to gauge pressure (psig + atm = psia). Differences between absolute and gauge readings are shown below.



Note: *Atmospheric pressure is 14.7 psi at sea level and ~11.3 psi at Los Alamos (~7300-foot elevation).*

Pressure Gauges

Manometers. These simple gauges use columns of water or mercury but must compensate for temperature and, for open manometers, atmospheric pressure. Many mercury barometers are still used to measure atmospheric pressure. Pressure differences in air conditioning duct work are still measured in terms of inches of water.

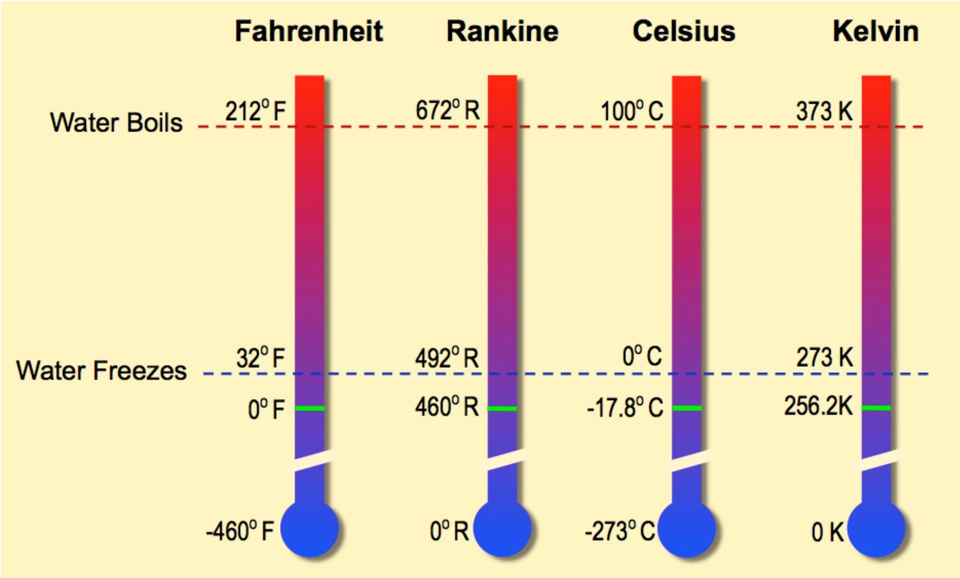
Absolute Pressure Gauges. These gauges, often used in research, measure pressure against a vacuum to eliminate the variable atmospheric pressure and provide relevant properties of the gas. Some require a vacuum line. Aircraft altimeters read absolute pressure against a sealed vacuum and have an adjustment that allows the pilot to match atmospheric pressure at the airport.

Crystal Pressure Gauges. These compact electrical gauges, often called *transducers*, measure the pressure applied to a crystal.

Temperature Scales

Temperature, both inside and outside of pressure systems, can affect the safety of operations. Temperature affects both the pressure of a fluid and the components of a pressure system. An increase in temperature will increase the pressure of any confined gas; at the same time, it may decrease the strength of a critical component.

Temperature can be measured in degrees Fahrenheit (°F) or Celsius (°C). Both temperature scales have their absolute temperature equivalents, Rankine (°R) and Kelvin (K), where zero is the coldest temperature possible. These four scales are represented below.



Temperature Conversions

To convert from one scale to another, use the appropriate equation from the following:

To convert degrees…	use this equation…
Fahrenheit to Celsius,	$T_C = 5/9(T_F - 32.)$
Fahrenheit to Rankine,	$T_R = T_F + 460.$
Celsius to Fahrenheit,	$T_F = 9/5\ T_C + 32.$
Celsius to Kelvin,	$T_K = T_C + 273.$

Pressure, Area, and Force

Area

Area is the measure of a two-dimensional surface.

For rectangles,

$$A = l \times w \quad ,$$

and for circles,

$$A = \pi \times r^2 \quad ,$$

where

A is area,

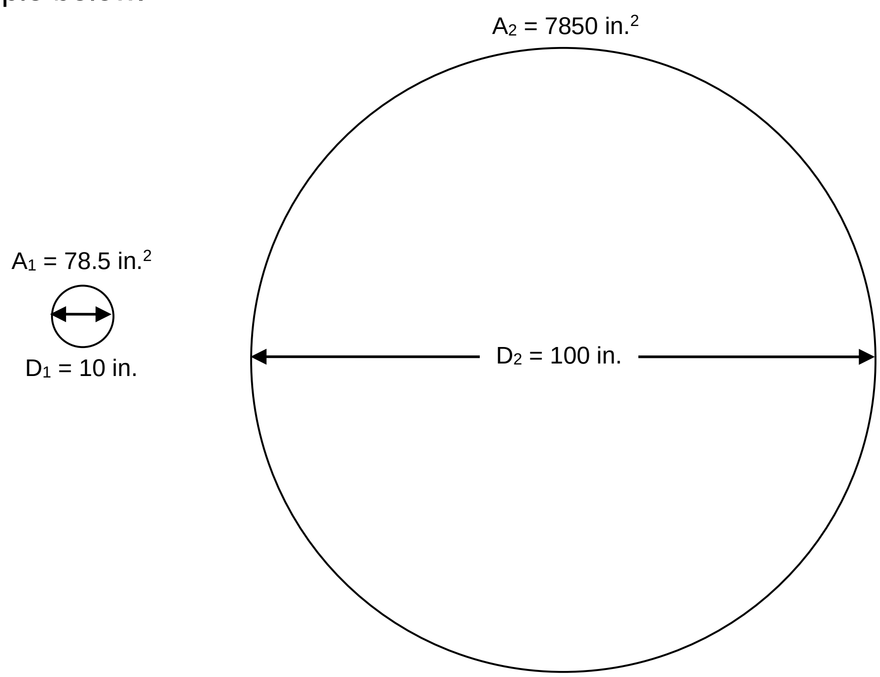
l is length,

w is width,

r is radius, and

π is approximately 3.14.

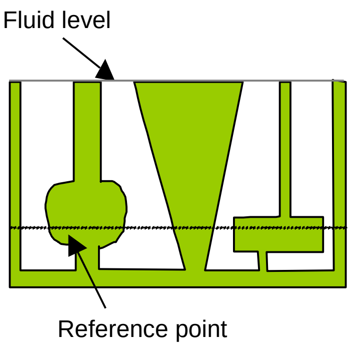
Therefore, if the diameter of one circle is 10 times the diameter of another, the circle will have *100 times* the area, as shown in the example below.



Under the same pressure, this larger area will bear *100 times* the force of the smaller area. As size increases, the area increases quadratically and so does the total force on components.

Pressure, Area, and Force—continued

Pascal's Principle



The relationships of pressure, force, and area are governed by Pascal's principle. According to this principle, a change in pressure in a contained fluid is transmitted equally in all directions and throughout the fluid up to the walls of the container.

$P = \frac{F}{A}$, typical unit: $psi = \frac{lb}{in.^2}$,

or pascal (Pa) $= \frac{Newton}{Meter^2}$

$F = P \times A$, typical unit: $lb = \frac{lb}{in.^2} \times in.^2$,

where

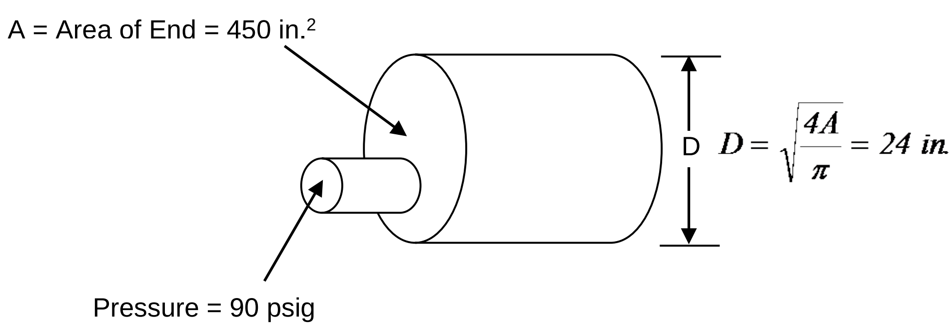
P is pressure,

F is force, and

A is area.

Force

The force that pressure places on any system component may cause it to fail and pose a hazard. For example, find the force on the end of the tank shown below.



$$\begin{aligned} F &= P \times A \\ &= 90\ psig \times 450\ in.^2 \\ &= 40{,}500\ lb \end{aligned}$$.

Pressure, Area, and Force—continued

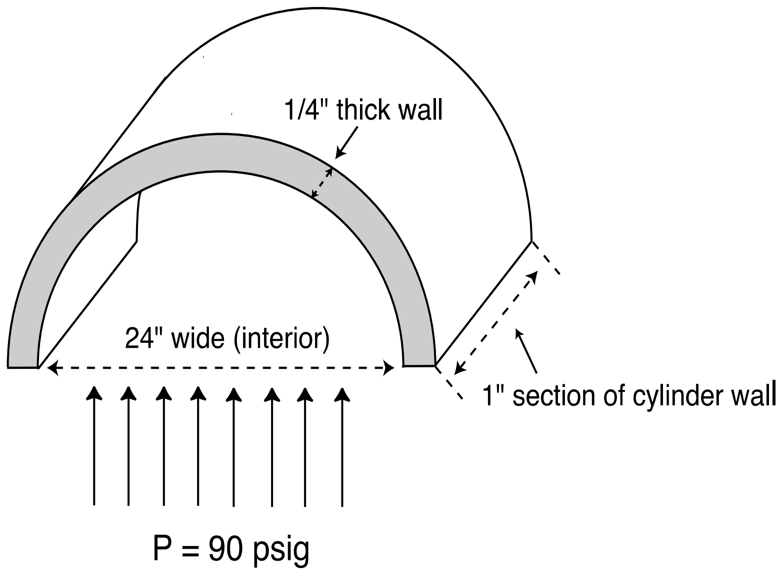
The diameter of the tank is about 24 in., and the force on a 1-in. section of the cylindrical portion is approximately

$$90\ psi \times 24\ in. \times 1\ in. \approx 2200\ lb \quad .$$

Therefore, if the walls could be only ¼ in. thick, the hoop stress would be

$$0.5 \times 2200\ lb/(1\ in. \times 0.25\ in.) = 4400\ psi \quad .$$

A more technical derivation can be found in the following reference: Urgal, A.C., *Stresses in Plates and Shells,* McGraw-Hill 1981, Section 2.4, "Uniformly Loaded Circular Plates," pages 32-35.



Typical tensile strengths of some common metals are listed in the following table.

Type of Metal	Tensile Strength	Maximum Safe Stress (FS = 4)
Aluminum (3003 rolled)	16,000 psi	4,000 psi
Carbon steel	25,000–65,000 psi	6,250–16,250 psi
304 stainless	80,000 psi	20,000 psi
Hastelloy C-276	113,000 psi	28,000 psi

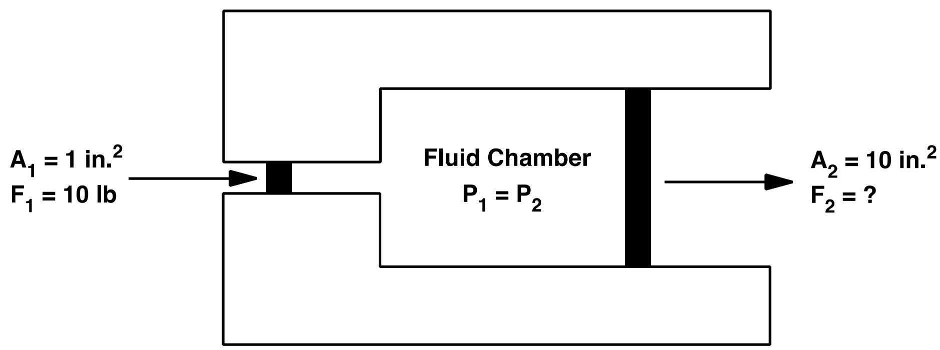
The above table shows that aluminum does not meet the tensile strength requirement because the maximum safe stress for this material has been exceeded. Carbon steels and Hastelloy meet the maximum safe stress requirement but may have corrosion problems with the cylinders' contents. So from the strength and corrosion perspective, 304 stainless steel may be the best choice.

Pressure, Area, and Force—continued

Other critical dimensions in specifying a pressurized cylinder are the end-plate dimensions. If this region is a flat circular plate, the thickness and diameter of the cylinder must be sized properly to prevent exceeding the yield stress σ_{yp} of the material. Bending affects the maximum stresses that may occur, and these stresses can be substantially greater than what is calculated here. So if the flat-end plate were only ¼ in. thick, the maximum stress would be greater than the ultimate tensile stress for any of these metals.

Example: Force Amplified

Some devices use pressure to increase force. Consider the device below, which uses a pressurized fluid between two pistons of differing diameters.



First find the pressure on the fluid.

$$P_1 = \frac{F_1}{A_1} = \frac{10\ lb}{1\ in.^2} = 10\ psi\ .$$

Then find the force on the larger piston.

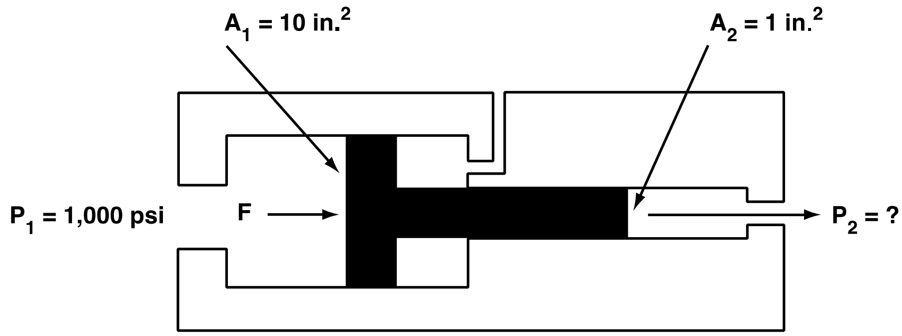
$$F_2 = P_1 \times A_2 = 10\,\text{psi} \times 10\,\text{in.}^2 = 100\,\text{lb.}$$

***Note**: This principle is used in barber chairs, hydraulic jacks, and car lifts.*

Pressure, Area, and Force—continued

Example: Pressure Amplified

A reverse of the above device is shown below. This device uses a solid piston to increase pressure.



First find the force on the piston.

$$\begin{aligned} F &= P_1 \times A_1 \\ &= 1000\ psi \times 10\ in.^2 \\ &= 10{,}000\ lb \quad . \end{aligned}$$

Then find the output pressure.

$$\begin{aligned} P_2 &= \frac{F}{A_2} \\ &= \frac{10{,}000\ lb}{1\ in.^2} \\ &= 10{,}000\ psi. \end{aligned}$$

Note: *This principle is used in compressors and pressure intensifiers. Also, the output pressure increases as the area* A_2 *decreases for a constant force, F.*

Pressure, Volume, and Temperature

Volume

Volume is the measure of an object or region in three-dimensional space.

For rectangular solids,

$$V = l \times w \times h \quad ,$$

and for cylinders,

$$V = \pi \times r^2 \times h \ ,$$

where

V is volume,

l is length,

w is width,

h is height,

r is radius, and

π is approximately 3.14.

Gas Laws

The relationships of pressure, volume, and temperature are governed by the following gas laws:

- Boyle's law (Law of Boyle and Mariotte),
- Gay-Lussac's or Charles' law, and
- the ideal gas law.

Boyle's Law

According to Boyle's law, at constant temperature, pressure is *inversely* proportional to volume of a gas. For example, as you increase volume, pressure decreases; as you decrease volume, pressure increases.

$$P \times V = C \quad ,$$

where

P is pressure,

V is volume, and

C is constant.

Pressure, Volume, and Temperature—continued

Gay-Lussac's Law

According to Gay-Lussac's law (law of Gay-Lussac and Charles), at constant pressure, the volume of a gas is *directly* proportional to temperature. For example, as you increase temperature, volume increases; as you decrease temperature, volume decreases.

$$\frac{V}{T} = C \quad ,$$

where

V is volume,

T is temperature, and

C is constant.

The Ideal Gas Law

The above laws can be combined into the ideal gas law (applicable to an ideal gas), which predicts what will happen to any of the three variables when the others are changed.

$$\frac{P \times V}{T} = C \quad ,$$

or

$$PV = nRT \, ,$$

where

P is absolute pressure,

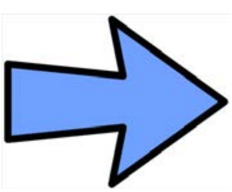
V is volume,

T is absolute temperature,

C is constant,

R is a universal gas constant, and

n is the amount of gas (in moles).



Note**: **At pressures above several thousand psi, real gases do not behave according to the ideal gas law.** At higher pressures, the unique compressibility of the individual gas must be taken into account. However, the ideal gas law gives useful and adequate answers quickly in many situations. **See the lessons learned at the end of this module.

Pressure, Volume, and Temperature—continued

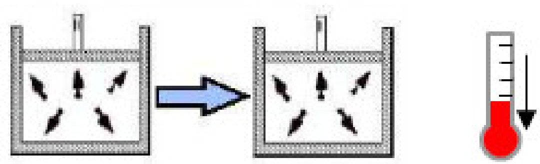
According to the Ideal Gas Law (PV/T = C), if a fixed quantity of gas is taken through any sort of process, then PV/T at the initial condition = PV/T at the final condition.*

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

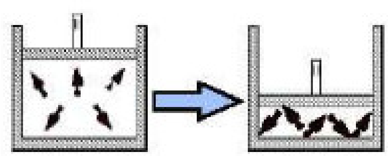
***Note:** Absolute pressure (14.7 psia = 1 atmosphere) and absolute temperature (Celsius + 273 = Kelvin and Fahrenheit + 460 = Rankine) must be used for P and T.*

For a confined gas:

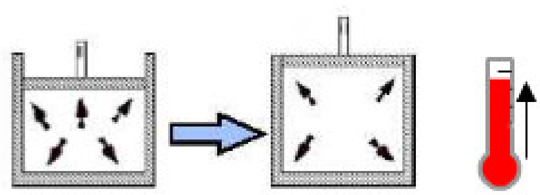
When volume is kept constant and temperature is decreased, pressure will decrease.



When temperature is kept constant and pressure is increased, volume will decrease.



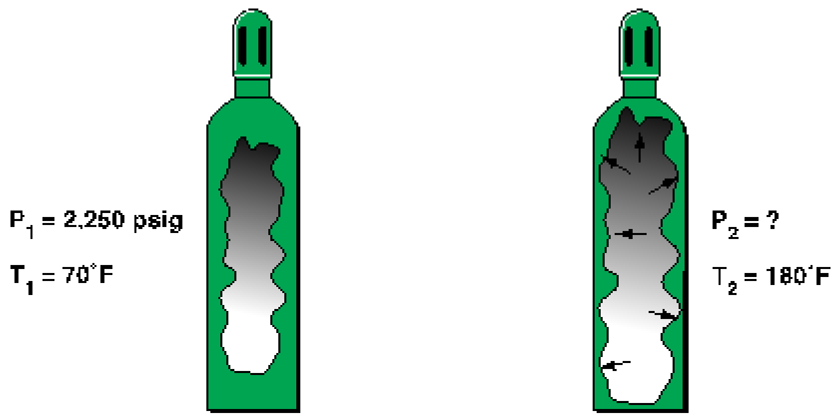
When pressure is kept constant and temperature is increased, volume will increase.



Pressure, Volume, and Temperature—continued

Example: Gas Pressure Increase

A vendor receives a cylinder of dry nitrogen. The temperature of the nitrogen is 70°F and the pressure in the cylinder is 2,250 psig. The cylinder is left near a radiator, and 8 hours later, the nitrogen is heated to 180°F. What is the new pressure in the cylinder?



First, convert pressure and temperature to absolute units.

$$P_1 = 2250\,psig + 14.7\,psi = 2264.7\,psia$$
$$T_1 = 70°F + 460 = 530°R$$
$$T_2 = 180°F + 460 = 640°R \quad .$$

Because the cylinder size should hardly change, you can eliminate volume from the Ideal Gas Law. Therefore,

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

$$\frac{2{,}264.7}{530} = \frac{P_2}{640}$$

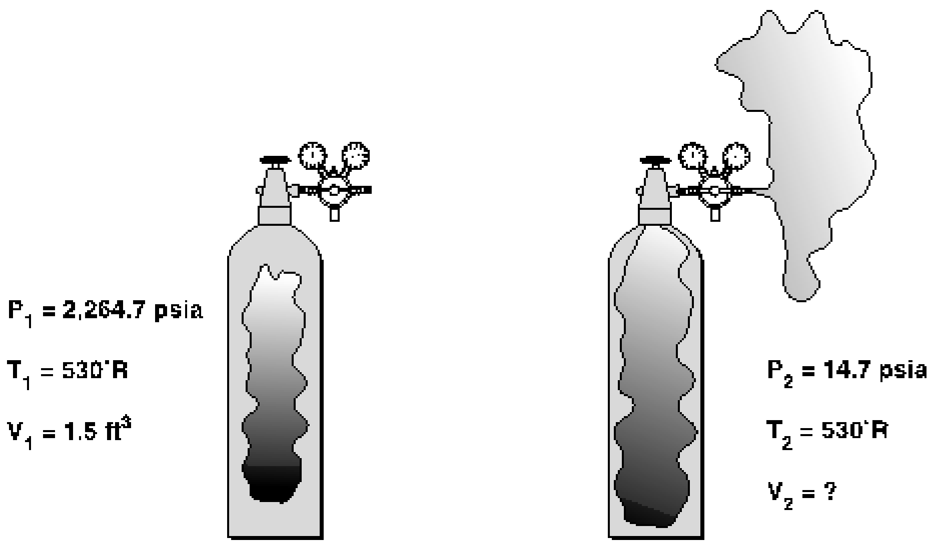
$$P_2 = 2734.7\text{ psia or }2720\text{ psig.}$$

Such pressure might be hazardous, depending on the strength of the cylinder and the nature of the gas.

Pressure, Volume, and Temperature—continued

Example: Gas Volume Expansion

If the cylinder on the previous page had a capacity of 1.5 cu ft, how many *standard cu ft*, or SCF (70°F and 14.7 psia), of gas does it contain?



Use the Ideal Gas Law to find SCF.

$$\frac{P_1 \times V_1}{T_1} = \frac{P_2 \times V_2}{T_2}$$

$$\frac{2,264.7 \times 1.5}{530} = \frac{14.7 \times V_2}{530}$$

$$V_2 = 231\ SCF \quad .$$

Note: *231 SCF is the volume of a cube ~6 ft to a side.*

The volume of stored gas is an important consideration if its release could displace oxygen or cause some other hazard.

Stored Energy

When a pressure system contains a fluid or gas at a higher pressure than the ambient atmospheric pressure, the system contains stored energy that can be released very rapidly. System failure occurs when the fluid pressure creates stresses that exceed the ultimate tensile strength of the vessel. The amount of damage that occurs relates to the energy stored and the proximity of people and material to the failure. Therefore, it is important to estimate the stored energy.

Energy Calculations

Energy in an ideal (B = constant) liquid can be calculated approximately using

Liquids

$$E = \left(\frac{1}{B}\right)\frac{P_1^2 V}{2},$$

and energy in a gas can be calculated using

Gases

$$E = \frac{P_1 V}{k-1}\left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}\right],$$

where

E is stored energy,

P_1 is maximum allowable working pressure (MAWP) (in psia units),

P_2 is atmospheric pressure,

V is volume,

B is liquid bulk modulus (in units of pressure), and

k is the ratio of specific heats.

Note: *B is a very large pressure, typically 2 $\times 10^3$ MPa, or 300 ksi. The compressibility of the liquid is 1/B.*

The ratio of specific heats is given as $k = \frac{C_p}{C_v}$

where

C_p is the specific heat for constant pressure and

C_v is the specific heat for constant volume.

Note*: C_p is always greater than C_v because it includes the heat needed to help the expanding gas do work.*

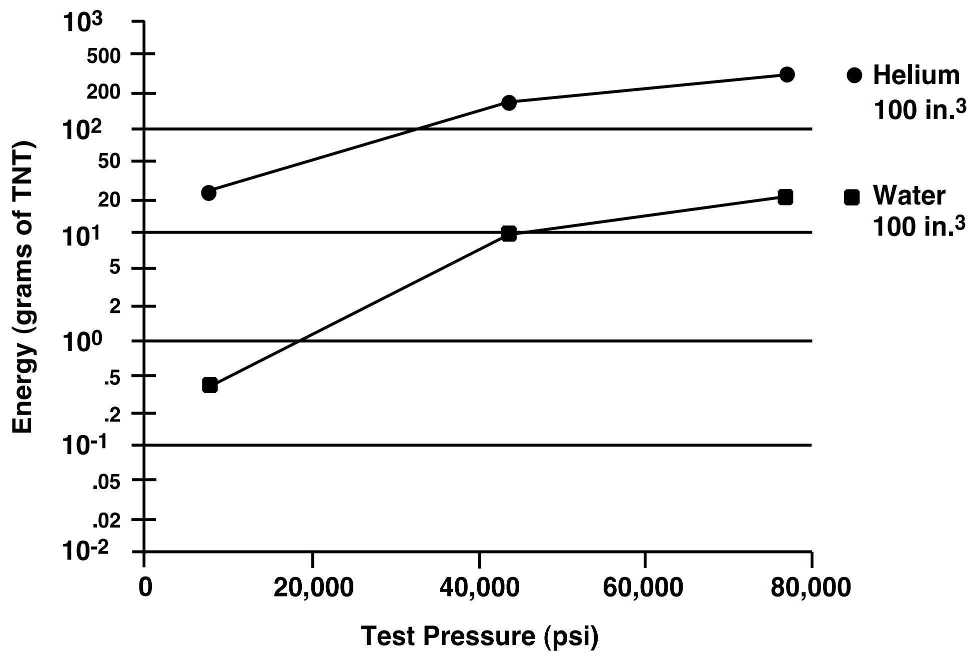
Stored Energy—continued

Compressibility and Stored Energy

Gases are far more compressible than liquids and therefore store far more energy when pressurized. For example, water reduces in volume by only about 0.3% for every 1,000 psi, storing relatively little energy when compressed. However, because of the large volume change that a gas can undergo, compressed gases store large amounts of energy that, when released suddenly, can cause severe damage and/or injury.

The graph below, adapted from the *Department of Energy Pressure Safety Manual*, compares stored energy levels in samples of helium and water. Note that the energy scale is logarithmic and that the energy of helium is many times greater than the energy of water.

Comparison of Stored Energy Levels in Helium and Water



Gases are more compressible than liquids and store far more energy when pressurized. Thus, the hazard is much greater in pneumatic circumstances. See also comment on p. 5 about why fragments from gas explosions are more lethal than from liquid explosions.

Fluid Comparison: Gas vs. Liquid

Liquid	Gas
Obeys Pascal's Law	Obeys Pascal's Law
Seeks own level	Fills a container regardless of shape
Relatively incompressible	Compressible

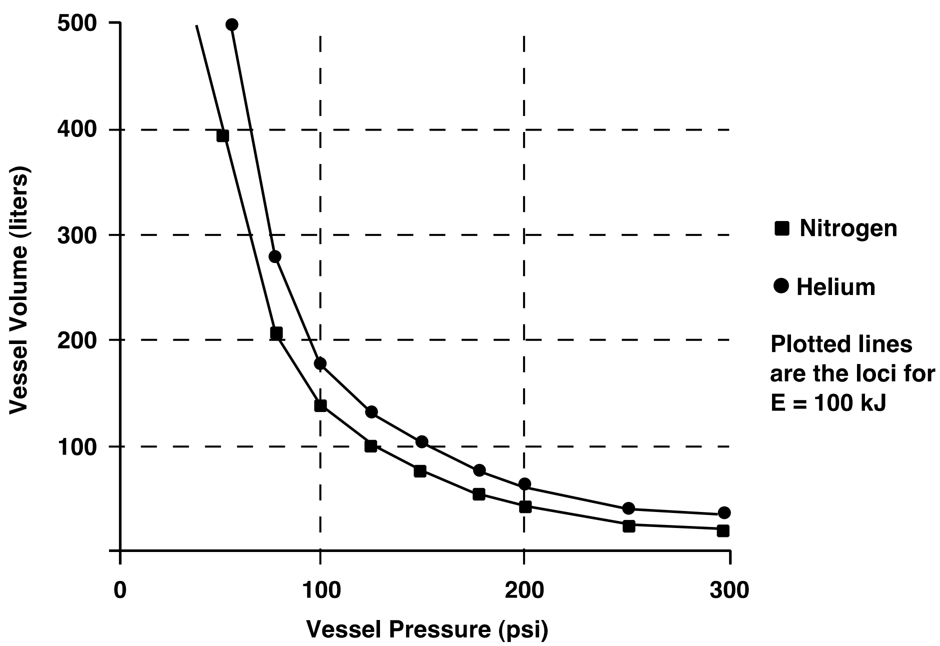
Stored Energy—continued

Low-Pressure/High-Volume Hazards

Because the stored energy of all fluids increases with both pressure and volume, low-pressure/high-volume systems can also pose severe hazards. These hazards are less obvious than those of higher-pressure systems. Failing to appreciate the dangers of low-pressure forces can result in serious accidents.

For example, an overpressure of only 5 psig on a 4-ft-diameter manhole cover on a large tank caused a fatality when the bolts were removed for routine maintenance.

The graph below, adapted from the *Department of Energy Pressure Safety Manual*, shows the pressures and volumes for two gases that contain equal amounts of energy (100 kJ). The area above each of the plotted lines corresponds to conditions for more than 100 kJ of stored energy for nitrogen or helium. ***The potential energy of ~20 liters of nitrogen at 300 psi is equivalent to ~400 liters of nitrogen at 50 psi.***



Note: *A 3,000-lb car moving at 27 mph has about 100 kJ of kinetic energy. A 3,000-lb block of concrete that is 25 ft above the ground has about 100 kJ of gravitational potential energy.*

Lessons Learned

Thermal Expansion Causes Larger-than-Expected Pressure Increase

Summary: The incorrect use of a formula or physical law in a design can result in unanticipated outcomes. When relying on formulas or physical laws in a design, the user should verify that they are applicable for the particular situation at hand. Specifically, the ideal gas law PV = nRT is useful in determining the behavior of most gases, such as pressure changes due to temperature variations: P1V1/T1=P2V2/T2. However, this is an equation of state for gases having molecules that are assumed to have zero volume and no attraction forces between them. ***Gases with complex molecules or under very high pressure or low temperature <u>do not act as ideal gases,</u> and the ideal gas law will not provide valid results for design calculations.***

In January 2014, unusual weather conditions with significant temperature swings caused a large pressure rise inside three natural gas storage cylinders at the Brookhaven Natural Laboratory (BNL) Compressed Natural Gas (CNG) fueling facility. On a Friday, BNL was closed because of a snowstorm. As the outside temperature fell to 14°F, the pressure in the storage cylinders fell below 3600 psig, which is the low-pressure set point on the CNG compressor control system. The compressor automatically filled the vessels to the specified set point of 4500 psig. When BNL reopened on Monday morning, the outside temperature was warming up, reaching 56°F just before 0800 hours. As a result, all three pressure relief valves for the CNG cylinders, set at 5500 psig, released high-pressure flammable gas to the atmosphere. When the relief valves failed to reseat, BNL declared an operational emergency for affected areas until the relief valves were isolated by Emergency Services.

Analysis: The incident investigation pointed to the large pressure increase due to thermal expansion of the gas as the root cause for the release. Lack of awareness of the behavior of real gases at high pressures had resulted in a vessel fill pressure setting of 4500 psig. For the 42°F temperature change experienced, according to the ideal gas law, an increase of 400 psi was expected, bringing the internal pressure to 4900 psig, which is well below the pressure relief valve (ASME-certified) set point of 5500 psig.

Gases behave almost ideally in two different situations: (1) at high temperatures, because molecules are flying past each other at extremely high speeds; and (2) at low pressures, because the volume of the molecules tends to become negligible in comparison with the total volume of the gas. However, at cold temperatures, molecules are moving relatively slowly past one another, allowing for the repulsive and/or attractive forces between molecules to take effect, resulting in deviations from an ideal gas. Gases also behave non-ideally at high pressures because then the volume of the molecules becomes a factor.

The term "compressibility" is used to describe the deviation in the properties of a real gas from those expected for an ideal gas. The compressibility factor “Z” is used as follows: Z =PV/RT and equals 1 for ideal gases. ***At low temperatures and high pressures, the behavior of gases with large and complex molecules (methane, carbon dioxide, Freon) deviates considerably from the ideal gas law, whereas those gases with small, simple molecules are closer to ideal (helium, hydrogen).***

Lessons Learned—continued

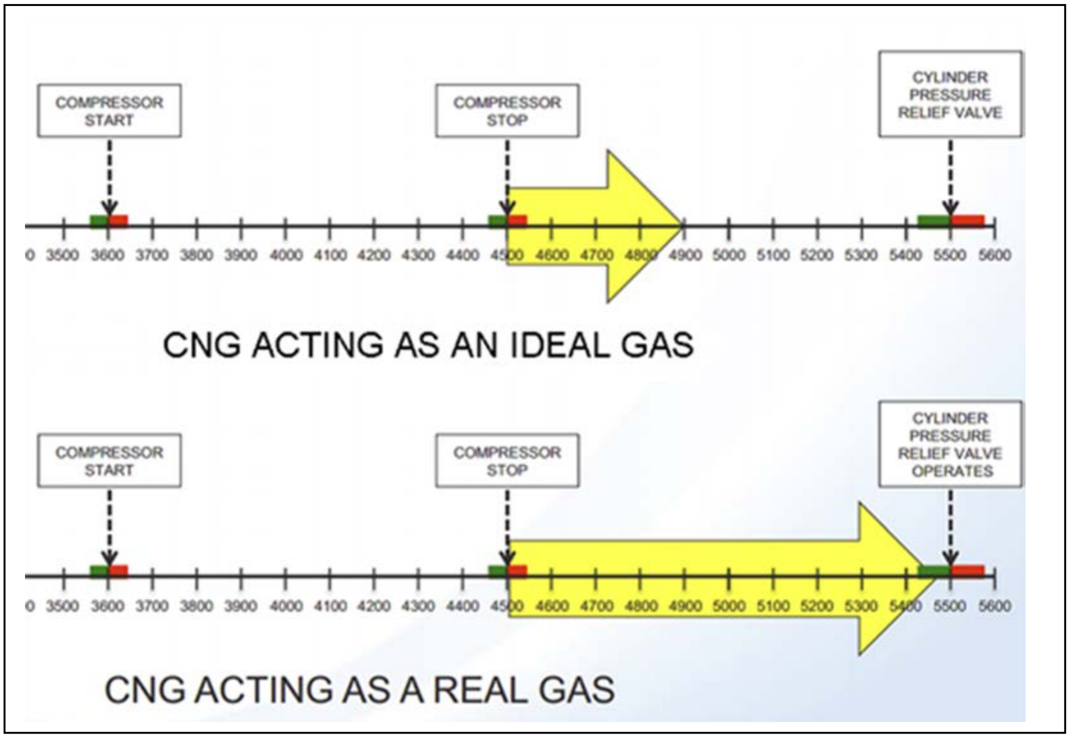
A model of a real gas's pressure volume temperature relation (p-v-T) is given by the Van der Waals equation *(shown at right),* where the parameters "a" and "b" take into account the interaction between the gas molecules and the nonzero size of the molecules, respectively. With appropriate values of these parameters, the equation gives a fair representation of p-v-T away from the liquefying pressure-temperature region of the gas.

$$(p + a/v^2)(v - b) = RT$$
$$\text{where } v = V/n$$

Van der Waals Equation

Using the Van der Waals equation, the 42-degree temperature change experienced during the incident would cause the pressure of the vessels to increase from 4500 psig to the pressure relief valve set point of 5500 psig, as shown below. As a result, the CNG facility fill pressure set point was reduced from 4500 psig to 4200 psig, allowing the system to withstand up to 70°F temperature variations without the risk of pressurizing the CNG vessels beyond the relief valve set point.

Effect of a 42°F temperature increase on the internal pressure of the natural gas vessels.



Recommended Actions: Personnel working with or designing high-pressure systems or experiments where large temperature variations can occur or where accurate pressure estimates are important should ensure that the real behavior of the particular gas has been taken into consideration. Examples of these activities include:

- selecting pressure-relief devices,
- determining set points for pressurized systems, and
- designing temperature compensated pressure systems.

-paraphrased from Lesson ID: 2014-BNL-CNG-0002

Module 4: Pressure Fittings and Equipment

Module Objectives

When you have completed this module, you will be able to recognize

- three categories of pressure systems at LANL;
- factors that affect determination of the MAWP of a system; and
- considerations that affect the selection and use of pressure system components, including pipes, tubing, flexible hose, fittings, valves, regulators, gauges, pressure relief devices, and configuration.

Pressure System Categories at LANL

Pressure systems at LANL fall into one of three broad categories:

A pressure system is considered . . .	if it contains a gas at pressures . . .	or a liquid at pressures . . .
low pressure	below 150 psia	below 1,500 psia.
intermediate pressure	from 150 to 3000 psia	from 1,500 to 5000 psia.
high pressure	above 3000 psia	above 5000 psia.

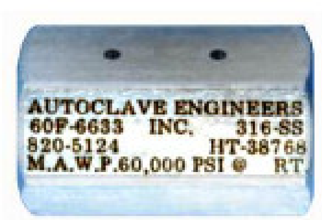
Maximum Allowable Working Pressure

The MAWP is the maximum pressure at which a system is safe to operate. The MAWP is limited by the weakest component in the system and is usually based on a manufacturer-determined safety factor of 4—the component-failure burst pressure of the weakest component being at least four times greater than the MAWP.

MAWP also

- includes an allowance for corrosion and erosion, which can be found in the *Corrosion Data Survey*, issued by the National Association of Corrosion Engineers;
- determines the maximum setting for the primary pressure-relief device (PRD) (less than or equal to MAWP); and
- determines the maximum operating pressure (MOP), which is the highest pressure expected during normal operation (usually 10%–20% less than the effective MAWP that is determined by the relief device).

Determining Maximum Allowable Working Pressures for Components



Some components are stamped or labeled with MAWP information, but many are not. Some references list more than one MAWP, based on different calculations. Use the lowest MAWP if two or more are listed. The MAWP stamped on a component is based on the most conservative calculation or on an actual pressure test.

When checking component MAWP, consider the following:

- engineering calculations,
- manufacturers' catalogs and data,
- national standards references,
- lot-sample pressure testing, and
- temperature (components are usually rated at 70°F).

***Note**: For ultra-high pressures above 10,000 psi, the use of materials thick enough to satisfy a safety factor may be impractical, and exceptions may be made for those systems. However, these systems must be used remotely.*

Pressure System Components

Pipes

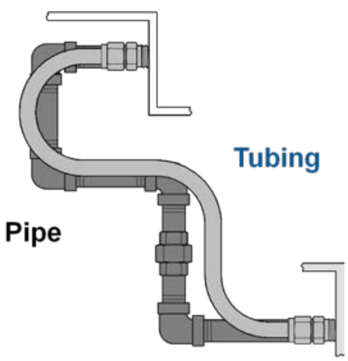
Pipes made from a variety of materials are classified as standard, pressure, line, water-well, and oil-country tubular goods. Standard pipe is produced in three wall thicknesses:

- standard weight,
- extra strong, and
- double extra strong.

The pressure rating for each type of pipe is determined by the ***pipe schedule*** (wall thickness) and whether the pipe is threaded. A higher schedule number refers to thicker-walled piping. Standard pipe sizes less than 12 in. in diameter are based on the inside diameter (ID) of a standard-weight pipe. Pipe sizes larger than 12 in. are based on the outside diameter (OD), with their inside diameters varying according to schedule number.

Tubing

Because tubing can be bent, it requires fewer fittings, which means easier installation and fewer chances for leaks. Tube sizes are based on the exact OD and a specified wall thickness, usually listed in hundredths of an inch or millimeters. Pressure rating is determined by the thickness and material of the wall.



Because tubing can be bent, it requires fewer fittings, which means fewer chances for leaks.

Tubing O.D. (mm)	MAWP* psi (Wall Thickness)					
	0.7	1.0	1.5	1.8	2.2	3.0
3	3349	4785				
4	2445	3596				
6	1545	2306	3597			
8	1134	1668	2602			
10		1305	2049	2505		
12		1073	1663	2049		
14		899	1402	1708	2148	3047
16		783	1206	1480	1840	2623
18		696	1058	1308	1621	2303
22		566	854	1047	1290	1828
25		493	754	912	1129	1582

**For training purposes only.*

Pressure System Components—continued

Pipe and Tubing Selection

Any pipe or tube can become a pressure vessel under the right circumstances, and all such materials must be rated for MAWP. When selecting pipe or tubing, consider the following:

- operating pressure;
- operating temperature;
- fluid compatibility (e.g., avoid copper or red brass with acetylene or carbon steel with hydrogen and cryogens);
- installation/maintenance requirements; and
- proper hardness and malleability, especially when compression fittings are to be used.

Temperature Derating Factors for Various Metals/Alloys*				
Temperature (ºF)	Copper Annealed	304 Stainless	Inconel 600	Hastelloy C-276
-20–100	1.0	1.0	1.0	1.0
150	0.85	0.98	1.0	1.0
200	0.80	0.95	1.0	1.0
250	0.80	0.92	1.0	1.0
300	0.78	0.89	1.0	1.0
350	0.67	0.87	1.0	0.99
400	0.50	0.86	1.0	0.99
450		0.86	1.0	0.96
…		…	…	…
900		0.79	0.80	0.89
950		0.77	0.53	0.88
1000		**0.75**	**0.35**	**0.87**

**For training purposes only.*

Pressure System Components—continued

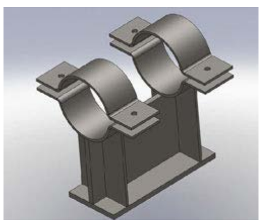
Example of Diminished Ultimate Stress at High Temperature

In October 2000, Sandia engineers pressurized a scale model of a lower-head assembly (the inverted steel dome that would hold damaged fuel during a partial or full core meltdown of a nuclear power plant) to about 770 psi, then increased the temperature until the assembly stretched like a balloon and finally burst. During the test, which lasted about 4 hours, the vessel's steel turned red-hot and began to deform as it was gradually heated to internal temperatures exceeding 2,780°F. The 3-in.-thick steel was thinned to a knife's edge at some places, and the 1-meter-diameter dome expanded by more than 11 centimeters at the spot of the rupture.

Pressure System Components—continued

Pipe and Tubing Support

A pressurized system must be properly secured to walls, ceilings, or floors. When designing the restraints, the engineer must consider component weights, seismic events, thermal expansion and contraction, fluid (i.e., water) hammer, and pipe whip. Each of these loads can create excessive stresses and strains on pipes, tubing, and associated fittings. Areas around unrestrained sections of pipes/tubes should be evaluated for the likelihood of localized damage and health and safety dangers from whipping.



Caution: *Specifications for pressure system supports may be based only on the size and weight of the pipe or tubing. However, to prevent movement under failure, the selection and placement of supports should also consider the system operating pressure and the system contents. Unistrut clamps are acceptable at low or intermediate pressures with some sizes of pipe or tubing and with some liquids. However, as pressures or line sizes increase, other types of clamps are more suitable. Before selecting clamps or other support devices, obtain information from the pipe/tubing manufacturer.*

Flexible Hose

Flexible hose should be used only where metal pipe or tubing is impractical. Flexible hose has a limited lifespan and must be inspected regularly for signs of deterioration.

When selecting flexible hose, consider the following:

- rated burst pressure;
- bend, torque, or tension restrictions;
- fluid compatibility (e.g., DO NOT use with toxic or radioactive liquids, which can permeate the hose); and
- expansion and contraction from temperature changes (as with pipes and tubing).

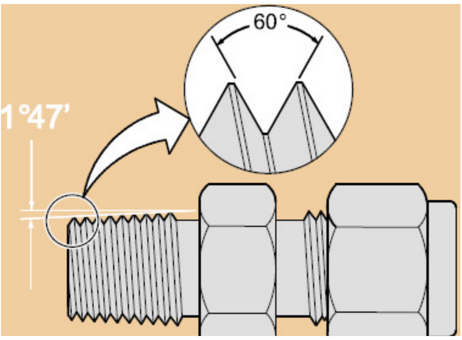
Upon failure, flexible hose can pose a serious whipping hazard. To prevent a broken hose from whipping, the hose must be secured at both ends and should be secured at least every 7 feet of length. Additionally, each 7-foot section (i.e., between restraints) should be evaluated for damage and dangers that could result from these sections whipping.

Pressure System Components—continued

Flexible hose restraint, courtesy of Slingco America, Inc.©

Fittings - American and International Thread Standards

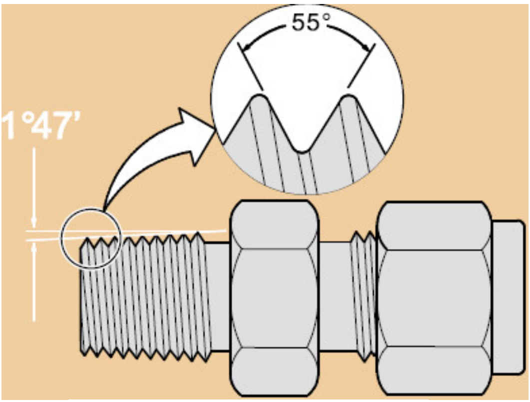
Most pressure fittings are threaded. Thread types are generally governed by two different standards: American Standard and International Organization for Standardization (ISO).



National pipe tapered (NPT) thread

American Standard includes national pipe tapered (NPT) thread and national pipe straight (NPS) thread.

Both NPT and NPS have the same included thread angle (i.e., 60º), shape, and pitch (threads per inch). However, NPT threads are tapered (i.e., 1° 47'), and NPS threads are straight (parallel). Both threads have flat peaks and valleys.



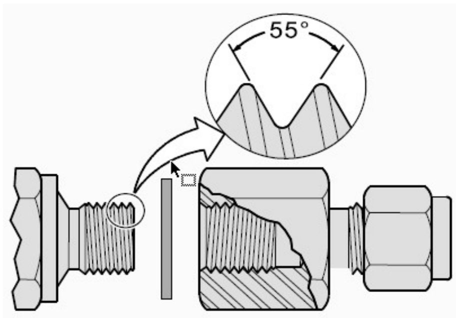
ISO 7/1 tapered thread

International Organization for Standardization (ISO) includes ISO tapered thread and ISO straight or parallel thread.

ISO 7/1 Tapered Threads

- 55° thread angle, pitch measured in inches
- Truncations of root and crest are round
- Taper angle 1° 47'
- Diameter measured in inches

Pressure System Components—continued



ISO 228/1 straight thread

ISO 228/1 Parallel (Straight) Pipe Threads

- 55° thread angle, pitch measured in inches
- Truncations of root and crest are round
- Diameter measured in inches

NPT is commonly found on ends of pipe, nipples, and fittings (i.e., couplings, elbows, tees, etc.). Thread sealant or tape is typically required to complete the seal. The main purpose of the thread tape is to reduce the shear stress applied to the threads. In principle, the taper provides the seal. Before the advent of Teflon tape, plumbers used a greaselike substance to connect tapered fittings.

Important: NPT and NPS threads will engage but will not seal properly with each other.

Selection of Threaded Fittings

Thread designations list the nominal size, the number of threads per inch, and the thread series. For example, the designation 3/8 18-NPT means a 3/8-in.-diameter fitting with 18 threads per in. of the NPT series.

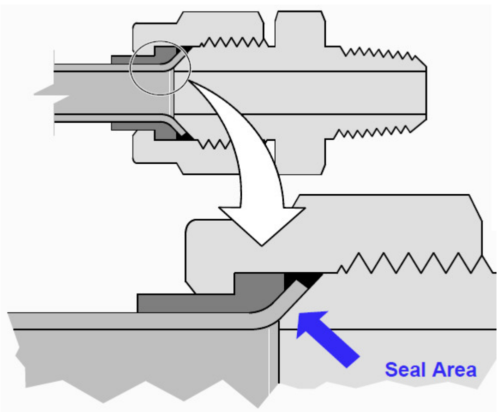
When selecting threaded fittings, consider the following:

- threads carry the loads and, for tapered threads, produce the seal;
- sealant or gaskets make the joint liquid- or gas-tight, and for tapered threads, the sealant lubricates the joint;
- minimum seal area reduces leakage (pressure on the seal = force ÷ area);
- operating temperature and fluid compatibility must be taken into account—elastomers used for O-rings, gaskets, and packings are especially sensitive; and
- thread types must NOT be interchanged!

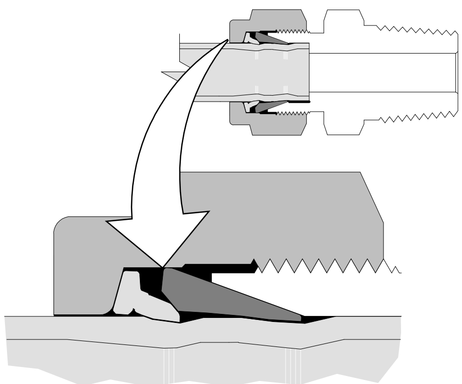
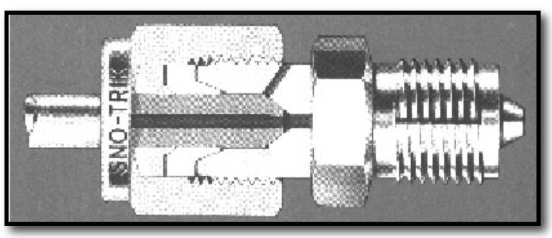
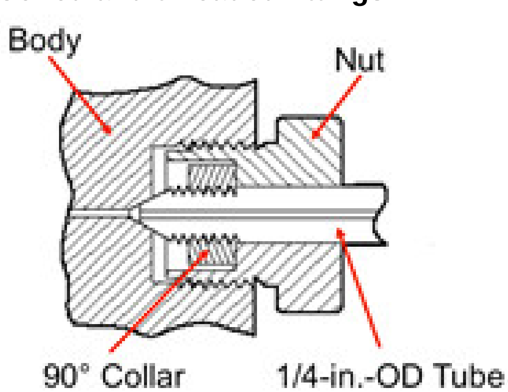
Pressure System Components—continued

Types of Fittings

The six common types of pressure fittings and considerations regarding their uses are listed in the following table. Obtain manufacturer information before selecting and using fittings.

Fitting Type	Uses and Considerations
Tapered thread fittings 	• Thread interference forms the seal. (Lubricants such as Teflon tape reduce the shear stress on the threads.) • Not suited for regular assembly and disassembly. • NPT and ISO fittings have different thread angles and must NOT be interchanged. • MAWP is 125 psi (brass) or 150 psi (steel), unless specifications indicate otherwise. • Used with pressures of 150–10,000 psi.
Straight or parallel thread fittings 	• Require a sealing device (e.g., a rad lab [RL] needs a flat rubber gasket, a vacuum coupling O-ring [VCO] needs an O-ring, and a vacuum coupling rad lab [VCR] needs a metal gasket). • Teflon tape should NOT be used on straight threads. • Seal more reliably in the higher-pressure ranges than tapered threads. • Can be assembled and disassembled many times. • NPS and ISO fittings have different threads and must NOT be interchanged. • Normally used with high pressures as high as 150,000 psi. • For toxic gases, used with lower pressures.
Flare fittings 	• Require special tools to flare the ends of tubing to seal fittings to the tubing. • Can be assembled and disassembled many times. • 45° two-piece fittings are often used in refrigeration applications. • 37° three-piece fittings are commonly used in automotive and hydraulic applications. • MAWP is based on the tubing MAWP, unless weaker elements such as threads reduce the pressure rating. • Used with pressures, usually below 1000 psi.

Pressure System Components—continued

Fitting Type	Uses and Considerations
Compression fittings 	• Require a ferrule that deforms the tubing wall to form a seal. • Do NOT use Teflon tape. • Can be assembled and disassembled many times. • Different manufacturers' components cannot be interchanged (even if manufacturer claims its products will fit others'); minimum and maximum tubing-wall thicknesses vary by manufacturer. • MAWP is based on the tubing MAWP, unless weaker elements reduce the pressure rating. • Used with pressures up to 8000 psi.
Bite-type fittings 	• May require thread lubricants (such as Teflon tape) for proper assembly. • Can be assembled and disassembled many times. • Different manufacturers' components cannot be interchanged (even if manufacturer claims its products will fit others'); minimum and maximum tubing-wall thicknesses vary by manufacturer. • MAWP is based on the tubing MAWP, unless weaker elements reduce the pressure rating. • Used with pressures up to 60,000 psi.
Coned and threaded fittings 	• Require special tools and thick-walled tubing coned to the precise angle of the fitting. • Coning provides a line-contact seal, resulting in a minimum seal area; left-hand threading of the tube positively locks the tube to the fitting, using a collar. • Can be assembled and disassembled many times. • Older 90°- and newer 45°-angle fittings cannot be interchanged. • American Standard and ISO fittings cannot be interchanged. • Reliable in thermal cycling. • Used with high pressures as high as 150,000 psi.

Pressure System Components—continued

Valves

Valves are used to control the flow of fluids within a system and are usually labeled by their function or construction. Several different valve types might work for a particular application. When selecting valves, consider the following:

- operating pressure;
- operating temperature;
- fluid compatibility;
- end-connection type and size;
- flow control type (shutoff, regulating, metering, or relief);
- flow-rate requirements;
- flow pattern; and
- potential for leakage.

Where an absolute isolation between systems must be guaranteed, a double block-and-bleed arrangement must be used. See page 51.

Types of Valve Stems

Different types of valve stems provide appropriate flow control of various pressure system contents. Stem types include

- vee stems, which provide on/off service with no throttling;
- regulating stems, which control flow rates more accurately and provide good throttling and shutoff; and
- micrometering stems, which allow for precise control of small flows but require shutoff valves upstream.

***Note**: High-pressure valves often use nonrotating stems to prevent scratching of the valve seat.*

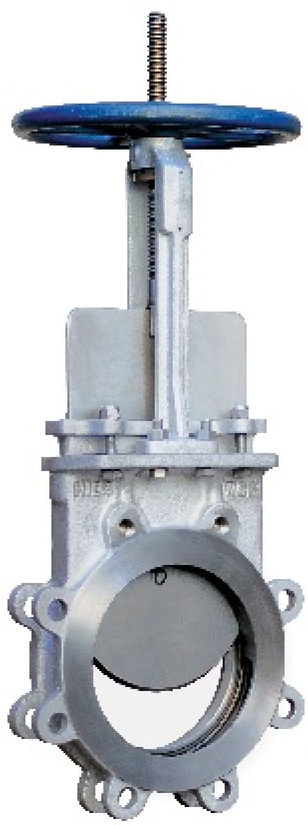
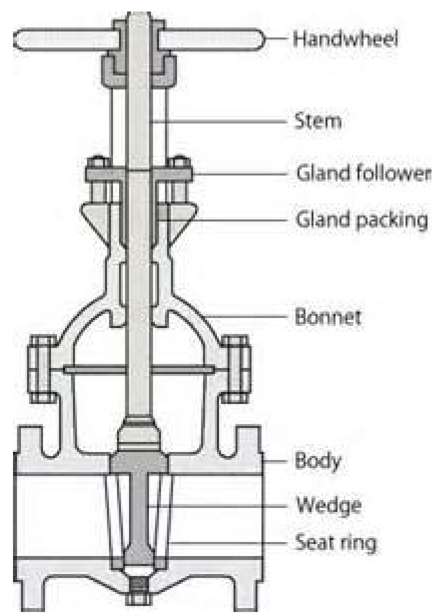
Types of Valves

The most commonly used valves, and considerations regarding their uses, are listed in the following table. Before selecting and using valves, define the system requirements and obtain information on particular valves from the manufacturer.

Pressure System Components—continued

Valve Type	Uses and Considerations
Ball valves 	• High-capacity flow with 1/4-turn operation. • Nondirectional. • Simple construction, low cost. • Used only wide open or fully closed. • For on/off service, fluid mixing, and manifold switching; no throttling.
Plug valves 	• High-capacity flow with 1/4-turn operation. • Directional. • Simple construction, O-ring seals. • Full throttling, with interim positioning.
Regulating valves (not regulators) 	• Needle-like stem point fits into orifice. • Different stem tips available. • For throttling and shutoff on instrumentation lines. • Combined V-stem with needle like stem point. • Combines throttling and shutoff on instrumentation.

Valve Type	Uses and Considerations
Diaphragm-actuated valves 	• Packless, hermetically sealed. • Soft stem tip. • Frequently offer higher pressure ratings.
Bellows valves 	• Packless, hermetically sealed. • Bellows welded to body for leak-tight service. • For vacuum systems, cryogens, toxics, corrosives, and/or radioactive fluids.
Toggle valves 	• Rotating the toggle handle moves the stem up and down. • Reduces leakage by minimizing galling and scoring. • Vee stems for on/off service, no throttling.

Valve Type	Uses and Considerations
Metering valves (also referred to as a needle flow valve [NFV]) 	• Contoured, needle-like stem points fit into small orifices to match desired regulating characteristics. • Precise control of liquids or gases. • Fluids must be filtered. • Require shutoff valves upstream.
Gate valves 	• For fluids, especially water, with pressures up to 150 psi.  • Shows the parts of a typical gate valve

Pressure System Components—continued

Regulators

A regulator reduces pressure from its source to its application. A regulator designed to handle the particular gas and pressure must be used on each gas delivery system, along with appropriate relief devices as part of a ***safety manifold system*** (see page 50). Common types of regulators and their uses are shown below.

Regulator Type	Uses
Single-stage regulators	• Used where delivery pressure does not have to be kept constant while the source pressure changes. • Allow high flow rates.
Double-stage regulators	• Provide constant delivery pressure, even while source pressure changes. • Provide more reliable control.
High-purity regulators	• Reduce contamination of high-purity systems. • Provide reliable control of corrosive and toxic gases. • Provide minimum internal friction and unpurged internal volume.
Dome-loaded regulators	• Allow remote adjustment of delivery pressure to increase personnel safety. • Used for high-pressure inert gases or toxic gases and liquids. • Allow high flow rates. • Provide constant delivery pressure.

Gauges

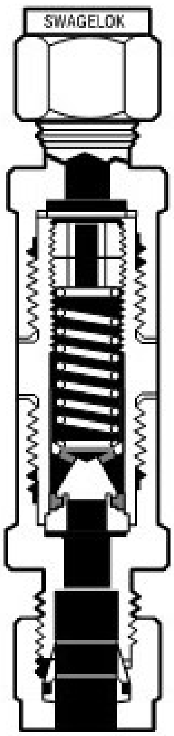
Gauge with snubber

Gauges are precision instruments available in varying degrees of accuracy; they deliver pressure to a thin metal Bourdon tube or to a bellows, which actuates the needle mechanism. Because of possible pressure surges and the thinness of the metal mechanism, gauges can pose hazards if not selected correctly and should be

- selected to read up to approximately 2 × MAWP and never less than 1.2 × MAWP,
- protected with a PRD,
- protected with a snubber from pressure surges or pulses (as on a compressor discharge),
- compatible with the system fluid, and
- designed with shatterproof faces and blowout backs.

Note: *High-pressure systems often use pressure transducers instead of pressure gauges.*

Pressure System Components—continued



Pressure relief device

Pressure-Relief Devices

Each part of a pressure system that can be isolated or pressurized separately must be protected by a PRD carefully selected to match system requirements. No valve may be placed between the relief device and the pressurized area it protects. In addition, PRDs

- must be set to operate at pressures equal to or less than the MAWP;
- must have sufficient flow capacity when open to prevent the system pressure from increasing more than 10% above MAWP (this percentage may be increased where allowed by ASME Section VIII, Division 1, Part UG-125);
- must be safely vented; and
- should be tagged with operating information and the calibration due date.

See P342, *Engineering Standards Manual, Chapter 17*, for more information about PRDs.

On high-hazard vessels such as cryogenic Dewars, PRDs should be used in parallel. On these vessels, a spring-loaded relief valve is backed up by a rupture disc set to relieve at a higher pressure. PRDs are *not* used if a release of the fluid would pose a hazard (i.e., toxicity). In these situations, other design considerations are required. If a system can be designed to sustain the maximum pressure conceivable under any credible fault condition, no PRD is required.

Unintended Overpressurization Ruptures Sealed Vial

In April 2010, a researcher placed 5 ml of methyl iodide (boiling point 42°C) in a 15 ml, closed-glass vial, along with another nonhazardous compound. The researcher then put the vial in a Pyrex oil bath containing silicone oil, heated the glass vial containing the two compounds to 150°C, and left for the night. The oil bath was located in a fume hood. In the morning, the oil bath was discovered broken. The glass vial had ruptured because it was not pressure rated for the potential 255 psi pressure generated when the compound was heated to a temperature above where it converted from a liquid to a gas, and *the vial was not outfitted with a pressure relief valve*.

The use of Pyrex containers for oil baths heated to temperatures above 100°C is discouraged. Oil baths heated in excess of 100°C should be carried out in either a porcelain or metal bath container with silicone oil that is changed frequently. Repetitive heating of silicone oil has been known to lower the flash point.

-paraphrased from Lesson ID: 2010-BNL-CO-0001

Pressure System Components—continued

Pressure Relief for Various Gases

Different gases require different PRDs to handle their particular characteristics and degrees of hazard. The following table lists gases and the PRDs they require.

Gas	Relief Device
Acetylene	Fusible-plug device
Propane MAPP (mix of methane and other gases)	Spring-loaded device
Argon Carbon dioxide Helium Nitrogen Oxygen	• Frangible-disc device (cylinders) • Spring-loaded device (systems)
Arsine Chlorine Fluorine Phosgene	No relief device used
Hydrogen	Frangible-disk, fusible-plug device (cylinders under 65 in.)

Pressure Relief Devices

Ensure that pressure relief devices and vent valves are safely exhausted away from personnel and allow easy access to the shutoff valves.

Pressure System Components—continued

Less than Adequate Configuration Control of Boiler Drain Line Leads to Injury

In October 2014, a LANL pipefitter sustained a second-degree burn to his left ankle when he was sprayed with scalding water while performing blowdown activities on a boiler. The boiler was in a cold state and had to be drained before restart. The low-point drain valve was opened to drain the boiler and was inadvertently left in the open position in the morning. That afternoon, boiler operators began the blowdown operation. As the pipefitter actuated a fast acting valve and began opening a slow acting gate valve, 320°F water was discharged directly toward his ankle from the low-point drain valve. The pipefitter was able to close the fast-action valve and subsequently closed the slow-action valve to stop the flow of hot water.

Lessons Learned

- Workers should verify the valve configuration(s) of boiler/steam-condensate systems [and any other pressure systems] before startup or troubleshooting operations to identify drain pipe openings that can potentially expose them to injury from the inadvertent flow of hot water, steam, or condensation.
- Work control documents or operating procedures must address configuration hazards and controls.

-paraphrased from Lesson ID: LANL-2014-ADNHHO-3430

The low-point drain valve *(circle)* is pointed at the worker's foot

Pressure System Components—continued

Check Valves

Check valves and back-flow preventers can be used to prevent problems with back flow. They allow only one-way flow and require a minimal drop in pressure, or “cracking” pressure, of ~10 psi.

***Note**: Check valves must NOT be used in place of PRDs.*

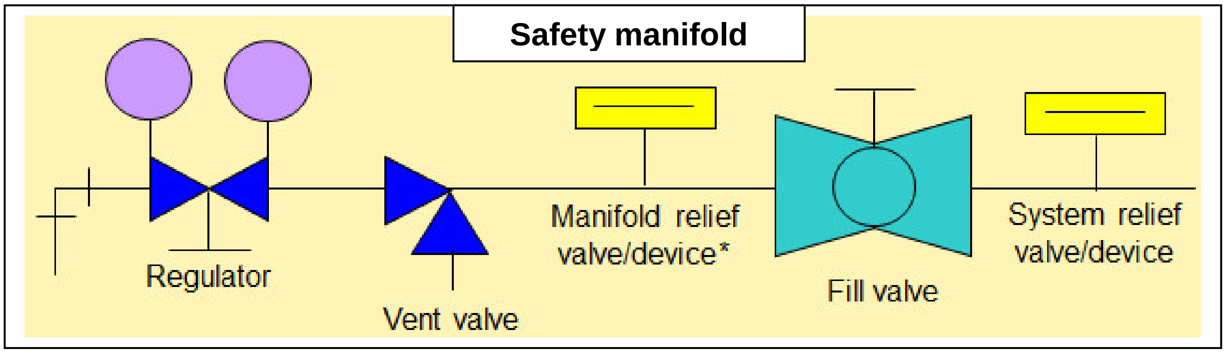
Flash Arrestors

Flash arrestors can be used to prevent undesirable ignition in pressure systems containing flammable gases. They dissipate heat that might otherwise result in ignition of flammable mixtures. Flash arrestors are used in oxyacetylene systems.

Pressure System Component Configurations

Safety Manifold

A safety manifold is required to reduce the pressure from a standard cylinder and provide relief protection for the downstream system. The safety manifold consists of a regulator, a vent valve, a fill valve, and a relief valve. In some situations, the positions of the fill valve and relief valve may be reversed.

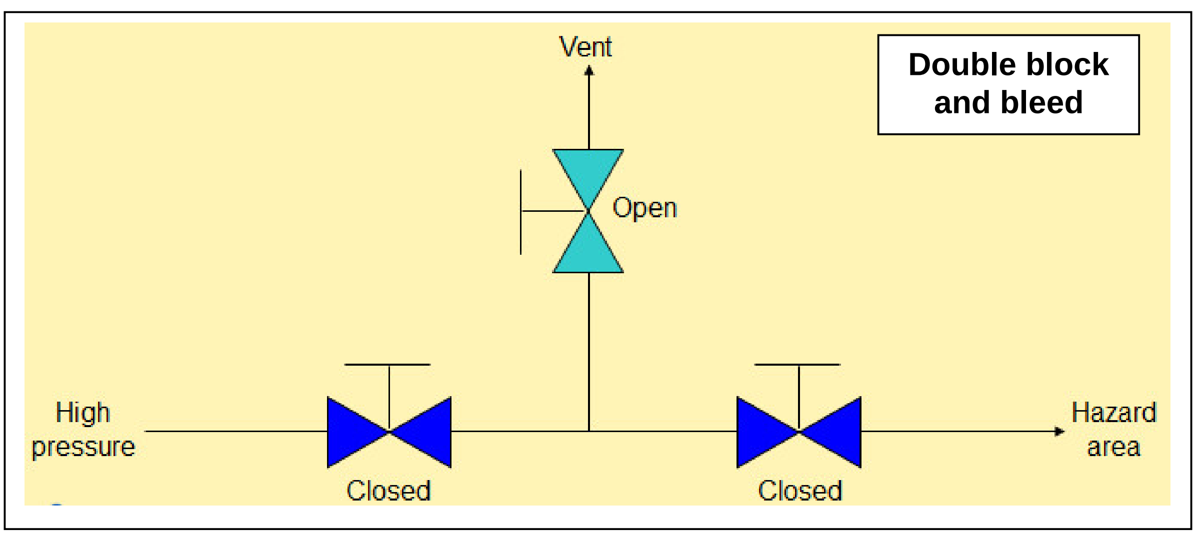


Required by the LANL Engineering Standards Manual (ESM), Chapter 17.

Double Block and Bleed

Note: Symbols used for pressure system components vary among organizations and industries.

Double block and bleed is used where critical isolation is needed to ensure that leakage does not occur. Double block and bleed is defined by OSHA as "the closure of a line, duct, or pipe by closing and locking, or tagging, two in-line valves and by opening and locking, or tagging, a drain or vent valve in the line between the two closed valves."



Module 5: Pressure Safety Practices

Module Overview

Pressure systems pose numerous hazards, but attention to safety can minimize the potential for accidents and injuries. Safety practices described in relevant LANL requirements and guidelines are based on the mechanics of the systems and the components used. Information presented in previous modules underscores the need for the pressure-safety requirements covered in this module.

Module Objectives

When you have completed this module, you will be able to

- identify requirements and considerations that affect the design of pressure systems,
- recognize requirements and recommendations for the testing and inspection of pressure systems,
- recognize practices for working safely with pressure systems, and
- recognize warning signs and signals associated with pressure system malfunction.

System Design

System design includes the following considerations:

- **National codes and standards**

  Strict adherence to national codes and consensus standards is essential to ensure the safe design and operation of pressure systems. Such codes and standards cover the following areas:

  – specifications for pressure vessels and systems;

  – corrosion and erosion allowances to preclude derating of the MAWP over the realistic operating life of the system or vessel;

  – manufacturing tolerance, which is subtracted from wall thickness before the corrosion allowance is subtracted and the MAWP is calculated; and

  – pipe supports and restraints on flexible lines.

Corrosion allowance is an added thickness to walls after MAWP is determined.

System Design—continued

Note: *Specialized systems must be reviewed by the PSC.*

- **Material Selection**

  The materials used for pressure systems must be compatible with the contents of the system. The appropriateness of the materials in relation to the environment is also important—particularly in cases of open or partly open systems. Considerations include

  – external vibrations and vibrations due to pressure fluctuations of the flowing fluid,

  – susceptibility to cracking and general corrosion,

  – low-temperature embrittlement in many alloys,

  – hydrogen embrittlement (a concern at LANL because of the frequent use of hydrogen), and

  – inappropriate use of carbon steel with hydrogen or cryogens.

Note: *Ductile materials are more forgiving than brittle ones; they strengthen when they are cold-worked and stressed beyond their yield point.*

- **Pressure Relief and Venting**

  Every pressure system must have

  – a safety-manifold system;

  – vent valves that can depressurize any part of the system when it needs repair;

  – discharge lines directed away from occupied areas;

  – double block-and-bleed shutoff combinations, if a shutoff leak would be hazardous; and

  – PRDs installed in every section that could become confined and pressurized separately.

- **Schematics**

  Schematics are essential to the proper operation and maintenance of a pressure system. Ensure that schematics are clear, legible, and updated when changes are made to a system.

The absence of readable schematics has caused many pressure system accidents, some of which have resulted in fatalities and serious injuries.

System Design—continued

Functional schematics, which indicate the function of the system, tend to be drawn with single lines. Locational schematics show where equipment parts are located. Use functional schematics with the minimum number of crossed lines whenever possible. Schematics with rated pressures should be posted near systems.

Pressure Testing

Pressure testing a vessel or system is necessary to ensure its safety, reliability, and leak-tightness at pressures up to its MAWP. All pressure systems must be pressure tested before initial operation and after any changes or repairs have been made to the system or components. These tests must have an IWD and must be witnessed and recorded as specified in the *Engineering Standards Manual* P342, Chapter 17.

Proof Testing

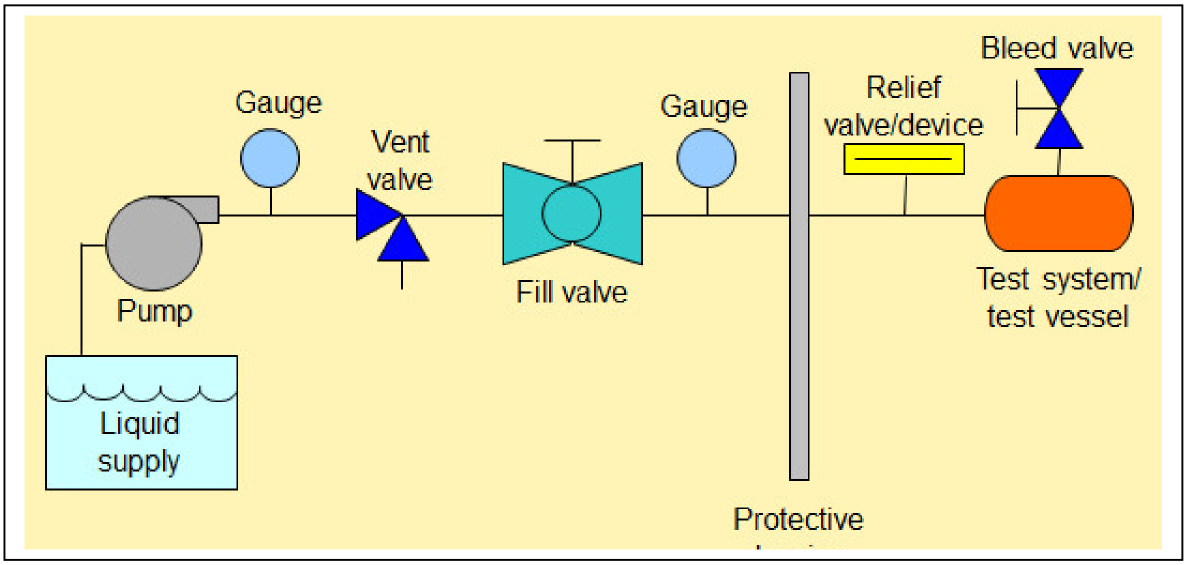
A proof test is performed to test system integrity by raising the pressure in steps, usually to 1.5 × MAWP. Proof tests are very dangerous and must be performed remotely or in restricted and safely barricaded test areas. A detailed IWD must be followed for all proof tests. ***Whenever possible, proof tests should be done with liquids instead of gases to minimize the stored energy.***

Failure of tubing at 3300 psig water *(above)* and 3200 psig gas *(below)*

Pressure Testing—continued

Hydrostatic Proof Testing

Pressure testing with liquids is safer than with pressurized gas because of the far greater compressibility of gases. In a hydrostatic test, all air or gas must be displaced from the system. Additional high-point vents or low-point drains may be needed to accomplish this function.

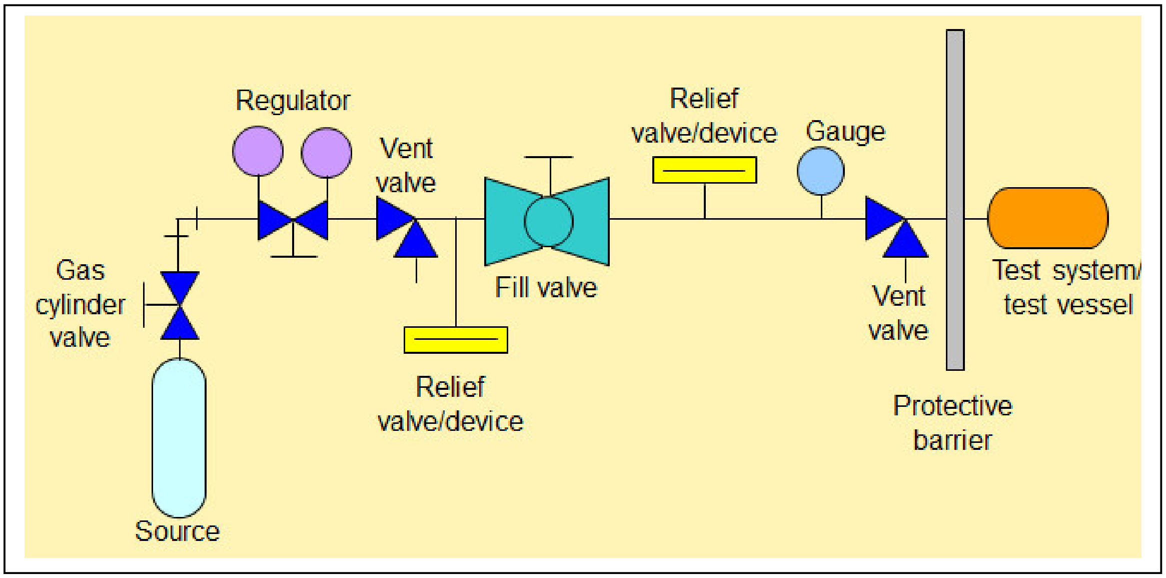


Cracked vessel from a failed hydrostatic test
- from www.wermac.org

Pressure Testing—continued

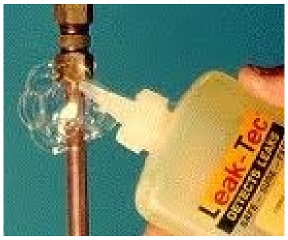
Pneumatic Proof Testing

Testing with pressurized gas is considerably more hazardous than with liquid because of the stored energy of pressurized gas. No one should enter the test area until the pressure has been reduced to less than half the maximum achieved. At that point, leak testing may begin.



Unexpected result of a pneumatic pressure test on a newly manufactured tank - *from www.wermac.org*

Pressure Testing—continued



Leak Testing

After proof testing is completed and the system is depressurized, the system should be tested for leaks. When leak testing a system, ensure that you have taken the following precautions:

- use polymer soap solutions or helium sensors;
- begin with low pressures and increase in steps to the MAWP;
- before repairing leaks, completely depressurize the system; and
- after repairs, perform the leak test again.

Inspection

All pressure systems should be inspected regularly. Corrosive-service systems should be inspected internally and externally. Inspection procedures should include

- using inspection methods approved by national codes (e.g., National Boiler Inspection Code (NBIC) NB-23/API-520);
- visually examining all components;
- measuring critical thicknesses;
- assessing corrosion or erosion rates;
- testing and calibrating relief devices;
- reviewing current and planned applications; and
- maintaining records of all inspections.

Note: *Inspections must be scheduled according to the recommendations of the manufacturer or design criteria.*

Working Safely with Pressure Systems

Courtesy of Smartsign.com (800) 952-1457, S-0513

Before starting work, ensure the following:

- The design of the system has been reviewed by knowledgeable persons, and hazards and controls have been identified. A systematic approach for hazard identification such as a hazard and operability (HAZOP) study or what-if/checklist can be very beneficial.
- System hazards and controls are explained in IWDs or the equivalent.
- Personnel who work on or around the system are familiar with the hazards and controls specified in the IWD(s).
- Warning labels identify the operating pressure and contents of pressure vessels and systems.
- Access to the area is restricted as appropriate.
- The system is reassessed if the design or use changes significantly, and the IWD is revised or updated as needed.

When working on or around pressure systems, always follow safe work practices, including the following:

- Wear eye protection at all times (safety glasses with side shields or goggles and a face shield if necessary).
- Store and dispose of compressed-gas cylinders safely. (See *Gas Cylinder Safety*, course # 9518).
- Keep foreign particles out of the system by keeping unused lines capped and/or using particulate filters.
- Avoid temperature extremes, which can cause excessive pressure changes or component failures by reducing tensile strength or causing embrittlement.
- NEVER use any part of your body to test for pressure or fluid flow.
- NEVER attempt to fix a pressure system while it is under pressure; instead, depressurize the system, and use lockout/tagout, if needed.
- Use the *Procedure for Pause/Stop Work,* P101-18, if unanticipated hazards arise.

Warning Signs and Signals

Even before pressure systems or equipment begin to malfunction or fail, they often exhibit telltale signs. You may notice these signs during regular use or during scheduled inspections. If you do, assume that the pressure system is not working properly and act to protect yourself, other workers, and other equipment. Treat the following conditions as danger signals:

- leaks and/or drips,
- jets of escaping gas,
- vibrating pipes or vessels,
- sticking gauge needles,
- “pegged” gauge needles, and
- power outages.

During assembly/disassembly, look for the following danger signs:

- flattened or nicked pipes or tubing,
- worn threads or fitting nuts,
- deformed ferrules,
- extruded packing,
- lost or interchanged parts, and
- cracked gauges.

Glossary

atmospheric pressure. The pressure exerted by the surrounding atmosphere on any object or substance, 14.7 psi at sea level and an average of 11.3 psi at Los Alamos.

Backflow. Backflow is the undesirable reversal of the flow of water or mixtures of water and other undesirable substances into the distribution pipes of the potable water system. Backflow occurs as a result of a “cross-connection” within the water system, which exists when there is any actual or potential connection between a potable water system and any other source or system through which it is possible to introduce into the potable system any used water or other substance.

benign service. Any pressure system service that is sufficiently compatible with the materials of construction so that no component of the pressure system loses more than 0.001 in. of thickness per year of operation to any type of corrosive or erosive attack. See *corrosive service*.

Boyle’s law. The gas law governing the relationship between pressure and volume when temperature is kept constant.

compressed gas. A gas stored at pressures greater than nominal atmospheric pressure.

compressibility. The ability of a substance to be reduced in volume under pressure; also, the coefficient that relates the fractional change in volume of a substance to pressure change.

corrosion allowance. The extra thickness of material required to allow for loss of material from corrosion.

corrosive gas. A gas that destroys or irreversibly alters various materials that it contacts.

corrosive service. Any pressure system that, because of chemical or other interaction with the container’s materials of construction, contents, or external environment, causes the pressure container to lose more than 0.01 in. of thickness per year of operation. See *benign service*.

cryogenic system. A system containing liquefied gases, usually below 200 K.

Dewar. A simple, open-mouthed, nonpressurized, vacuum-jacketed or otherwise insulated vessel designed to hold cryogenic liquids (P101-5).

> ***Note:*** *A pressurized, double-walled, insulated container used to hold either cryogenic liquefied gas or refrigerated liquefied gas is not a Dewar but is simply referred to as a Cryogenic Container (P101-5).*

energy. The ability to exert a force over a distance; that is, the ability to do work.

fatigue. The weakening or failure of material resulting from repeated or continuing stress.

flammable gas. A gas that will burn in a normal concentration of atmospheric oxygen.

fluid. A substance that is able to flow through an orifice.

fluid hammer. Also called water hammer, it is a pressure surge or wave caused when a fluid (usually a liquid but sometimes also a gas) in motion is forced to stop or change direction suddenly (momentum change). This also occurs when there is a sudden change in phase from gas to liquid of very high flow; or from liquid to gas, resulting in a pressure shock wave.

force. An influence on an object that causes it to accelerate in the direction of application or that results in compression, stretching, or breaking of the object.

frangible. Capable of being broken or ruptured at some prescribed pressure.

fusible. Capable of being fused or melted with a prescribed amount of heat.

gas. A fluid substance that is able to take on the shape and volume of its container.

Gay-Lussac’s law. The gas law governing the relationship between volume and temperature when the pressure is kept constant.

ideal gas. A gas where the molecules have zero size and do not interact with each other; also, a *perfect* gas that obeys the Ideal Gas Law.

ideal gas law. The law governing the equation of state of an ideal gas; that is, the relationships of pressure, volume, and temperature ($PV = nRT$). The law is valid for real gases at sufficiently high temperatures and sufficiently low pressures.

joule (J). A unit of energy, or work, equal to a force of 1 newton acting over a distance of 1 meter.

leak test. A test of a pressure system to determine whether any substance under its operating pressure will escape from the containing members of the system.

liquid. A fluid that seeks its own level and has a free surface. A liquid is relatively incompressible compared to a gas.

liquefied gas. A substance that is a gas at standard pressure and temperature, transformed to a liquefied state by either extreme low temperature, high pressure, or both.

maximum allowable working pressure (MAWP). The highest pressure at which a system can operate safely.

maximum operating pressure (MOP). The highest pressure at which a system should be operated, usually 10%–20% below MAWP.

newton (N). A unit of force that can accelerate a mass of 1 kilogram 1 meter per second in 1 second.

Newton's laws. A set of three laws of classical physics governing the motion of objects.

oxidizing gas. A gas that supports combustion of material.

pascal (Pa). A unit of pressure equal to 1 newton per square meter.

pipe schedule. The wall thickness of a pipe, given the outer diameter.

pipe whip. Occurs when a pressurized pipe is severed and the fluid escaping from the open end exerts a thrust on the pipe with the result that the free end is displaced large distances at high velocity. The impact damage is a function of both the kinetic energy of the pipe at the instant of impact and additional work done by the load transmitted to the target by the continuing thrust. This phenomenon also occurs with pressurized tubing and flexible hoses.

pounds per square inch absolute (psia). The unit of pressure referring to the absolute pressure; that is, the pressure reading of a system as measured by a gauge surrounded by a vacuum.

pounds per square inch gauge (psig). The unit of pressure referring to the pressure of a system over and above the ambient atmospheric pressure.

pressure. The distribution of force over an area.

pressure-relief system. A system designed to relieve excess internal pressure from a pressure system by allowing the escape of a substance when the pressure exceeds a prescribed value.

pressure test. A test of a pressure system, at pressures higher than operating or expected pressure, to check for leaks or any deformation of the system.

proof test. The pressure testing of a system to between 125%–150% of its designated MAWP.

reactive gas. A gas that reacts with other materials (including water), producing products such as heat or flammable or toxic gases.

real gas. A gas where the molecules interact with each other and where its behavior deviates from the Ideal Gas Law.

rupture disc (a.k.a. burst disc, bursting disc, frangible disc, or burst diaphragm). A one-time-use membrane that fails at a predetermined differential pressure (either positive or vacuum). Rupture discs are used as pressure relief devices.

safety factor. The ratio of component-failure burst pressure to the MAWP, usually equal to four.

snubber (pressure snubber). A device that will protect pressure gauges from vibration-generated pressure variations in a pressurized system. The pressure snubber works by evening out the rate at which the fluid or gas being measured arrives. Snubbers do not alter the line pressure; rather, they lessen the pulsations on the line, which improves the consistency of the gauge reading and extends the lifetime of the gauge.

stored energy. Energy in a form that can be released to do work or be transformed into a different form; also, the hazardous property of a pressure system that is a function of pressure, the material pressurized, and the system volume.

strain. A fractional change in the normal size or shape of material, resulting from stress.

stress. The force per unit area on or within a solid material.

temperature. That property of a substance that is a measure of its average energy concentration resulting from random motions of its molecules.

throttling. A process in which the flow of fluid is restricted by partially closing the valve and results in a drop in pressure. The pressure drop in the fluid is often accompanied by a large drop in temperature.

toxic gas. A gas that is harmful or deadly to living organisms.

vacuum. An isolated space in which pressure is far below atmospheric pressure.

volume. The measure of an object or region in three-dimensional space.

water hammer. See fluid hammer.

work. The energy expended when a force is applied to an object over a distance.

References

"ASME Boiler and Pressure Vessel Code," Sections I–XI, American Society of Mechanical Engineers.

Braker, W., and Mossman, A. L., *Matheson Gas Data Book*, 6th Edition, Matheson Gas Data Products, Secaucus, NJ, 1980.

"Code for Pressure Piping," ANSI/ASME B31.X series, American National Standards Institute/American Society of Mechanical Engineers.

Compressed Gas Association, *Handbook of Compressed Gases*, Reinhold, NY.

Department of Energy Pressure Safety Manual, M-089, Draft, December 1993.

"Environmental Protection, Safety, and Health Protection Standards" Department of Energy Order 5480.4.

"Fire Protection for Laboratories," NFPA 45, National Fire Protection Association.

Schmidt, P. E., *Accident Prevention Manual for Business & Industry, Engineering and Technology*, 10th Edition, Laing, P. M., Editor, National Safety Council, 1992.

Title 29, Labor, Code of Federal Regulations, Part 1910, General Industry Standards.

Title 29, Labor, Code of Federal Regulations, Part 1926, Construction Standards.

Title 49, Transportation, Code of Federal Regulations, Parts 106–180, Department of Transportation requirements.

Urgal, A. C., *Stresses in Plates and Shells*, Section 2.4, "Uniformly Loaded Circular Plates," pp. 32–35, McGraw-Hill, 1981.