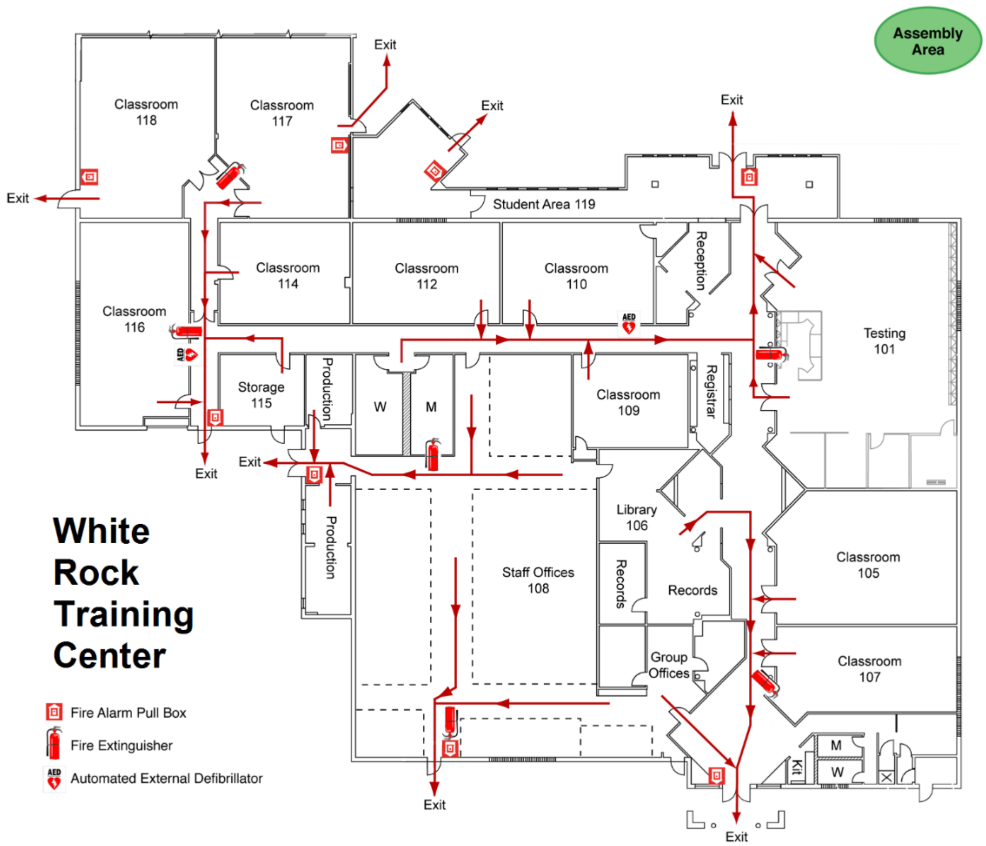
PRESSURE SAFETY: ADVANCED LIVE #11459

STUDENT MANUAL

MARCH 2026



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Introduction

Course Overview

This course provides an overview of

- Basic physics principles of pressure
- Hazards associated with pressure sources and systems
- The hierarchy of documents that governs the pressure safety program at LANL and use of documents by pressure system designers, testers, and inspectors
- System design and component selection
- Testing and inspection

Course Objectives

After completing this course, you will be able to recognize:

- basic principles, quantities, and relationships that govern pressure and its effect on containers and surrounding environments;
- common causes of pressure system failures related to design, maintenance, and construction of a pressure system;
- flow down from federal to LANL-specific documents that govern the safety program at LANL and guide the design, maintenance, and operation of a pressure system at LANL;
- design aspects of a pressure system including the limits of a pressure system, the considerations for component selection, and the function of common pressure components; and
- various types of pressure system testing and the factors that determine which to select.

Target Audience

This course is required for employees who design, test, and inspect pressure systems at LANL. It is recommended for employees who use FS1 or FS2 hazard category pressure systems.

Program Owner

This course was developed under the direction and technical oversight of Engineering Services-Pressure Safety Program, the functional program owner for this training.

Training Requirements

Course 769: Pressure Safety Orientation is the prerequisite for this course.

Acronyms

ASME	**American Society of Mechanical Engineers**
FS	**Fluid Service**
ISO	**International Organization for Standards**
ID	**Inner diameter**
MAWP	**Maximum Allowable Working Pressure**
NPS	**National Pipe Straight**
NPT	**National Pipe Tapered**
OD	**Outside Diameter**
PRD	**Pressure Relief Device**
PRV	**Pressure Relief Valve**
PSO	**Pressure Safety Officer**
RFO	**Restrictive Flow Orifice**
SCFM	**Standard Cubic Feet per Minute**
UHV	**Ultra-High Vacuum**

Module 1

Physics of Pressure

Introduction

To understand pressure systems, their hazards and controls, we must first establish some base-level terminology and relationships for pressure. Even though this is the "advanced" class, you can think of that as just being more information with the understanding that there is much, much more involved in any one of these topics. It can be difficult in some cases to give an explanation of pressure that is both simple *and* correct. Many times, the simple explanation only applies under certain circumstances, and the correct explanation is complicated. If you are new to pressure systems, be encouraged that most people acquire their pressure systems knowledge through experience, so ask questions whenever possible. The Pressure Safety Program's e-mail for pressure questions is pressuresafetyhelp@lanl.gov.

Quantities and Relationships

Fluid: can be either a gas or a liquid
Units: Standard cubic feet per minute (SCFM) (flow); Cv= flow coefficient
Pressurized systems mostly contain either gas or liquid. The term fluid is used for both because there are similarities in how they behave. For example, the flow of fluid through a pressure system will create turbulence in the current, have pressure drops in corners, will exert a force on the system, and will cause an erosion of the material.

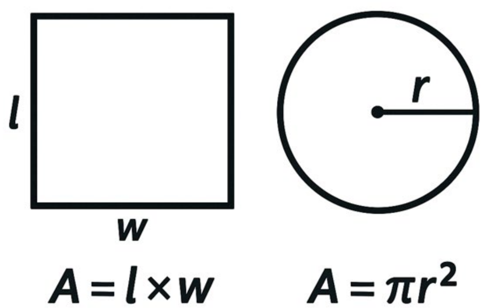
Force: push or pull on an object
Units: Pounds (lb.); Newtons (N)
In pressure systems, force is produced by gas or liquid molecules running into the walls of a vessel. The higher the pressure, the more frequent those collisions take place because the particles are compressed together. Talking about the force of an individual particle by itself doesn't make much sense, so we have the quantity of pressure.
The distinction between weight as a *force* and weight as a *mass* sometimes appears. In these cases, the units will indicate a force as "lbf" and a mass as "lbm."

Temperature: the average speed of particles
Units: Fahrenheit (^oF); Celsius (^oC); Kelvin (K)
Temperature is the measure of how fast the molecules are moving. When we think about the particles hitting the side of their container, you can see that the force is affected by two things: how many particles are hitting and how fast they are running into it. This is why increased temperatures will increase the pressure in the container.

The main difference between the temperature scales (Fahrenheit, Celsius, and Kelvin) is where 0 is, and this is particularly important when using quantities in equations. Having a 0 in an equation can cause it to "blow up" if it is in the denominator or just go to zero if it is multiplying other quantities. That usually does not represent what is physically happening. The Kelvin scale is known as the "absolute zero scale" which means that zero means zero- no (or little) movement of particles. This is what is used when using numbers for calculations.

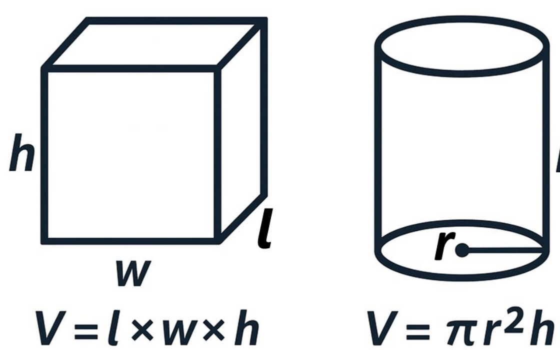
Size: how much space something takes up
The two measures of size that are applicable to pressure are *area* and *volume*.

- *Area* is a 2-dimensional measurement. Containers have both volume and surface area.
  Units: square inches ($in.^2$); square feet (sq-ft); square millimeters (mm^2)



- *Volume* is a 3-dimensional measurement and usually refers to the container or vessel that is pressurized. Unless it is a moving system, the volume is fixed.

Units: cubic feet (cu-ft; $ft.^3$); liters (l); cubic inches (cu-in; $in.^3$); cubic meters (cu-m; m^3)



Number of particles
Units: Depending on the equation being used, this might be an actual number (a very big number) or moles (mol) which is defined as 6.0221408×10^{23} particles/mole.

Pressure: force over area and other relationships
Units- see table

Table 1: A selection of pressure units with a comparison to 1 atmosphere and an application that uses the unit.

Pressure Unit	Name	Comparison to 1 atm	Common Applications
psi	Pounds per square inch	14.7 psi	Default
Pa	Pascal	101325 Pa	Science/SI units
mmHg/Torr*	Millimeters of mercury/Torr	760 mmHg or Torr	Vacuum
inH_2O	Inches of water	0.354 inH_2O (" W.C.)	Facility natural gas
atm	Atmosphere	1 atm	Space
bar	bar	0.98692 bar	Meteorology
***These are not exactly the same but are very close.**			

Pressure has a large number of units. Why is that? Humans have been exploring pressure relationships systematically for several hundred years. Over the centuries and across applications, different calibrations of pressure have emerged. Various applications of pressure have chosen their preferred units, but each unit measures fundamentally the same thing. In order to talk about the quantity of pressure, we must look at the relationships pressure has with the other quantities.

Relationships

The Ideal Gas Law

$$\frac{pressure \times volume}{temperature} = number\ of\ moles \times constant$$

There are four variables (things that change) in this equation which makes it a very complicated relationship. This equation is called the ideal gas law; however, pressurized gases do not behave in an ideal way. This still gives intuition about how the quantities interact with each other, and it may give a starting point for calculating quantities.

The simulation used in the class activity is found here:
https://phet.colorado.edu/sims/html/gases-intro/latest/gases-intro_all.html

In the simulation, only certain quantities are allowed to change in response to an action; however, when we let nature take over, the quantities can change freely and will behave in hard-to-predict ways. This should be taken as a caution to not over-simplify a pressure system. Intuition about how a pressurized system will respond to different variables can be turned on its head with a different context.

Examples of assumptions that must be checked:

- ambient temperature over the course of the year
- the effect of altitude
- humidity
- direct sunlight

$$Force = Pressure \times Area$$

Because pressure's effect on the surroundings depends on an area of interaction, there is not a cutoff for what constitutes a "dangerous" amount of pressure. This is illustrated in the activity in class where the force on an area is held constant while the area and pressure are varied. The point is that small pressures can contribute to large forces if there is a large area. Alternatively, this is also why pressure has so many useful applications.

Pascal's Principle

Pascal's principle tells us that the pressure of an enclosed fluid is the same everywhere in the fluid. Using this principle, we can give a simple example of how pressure can be used.

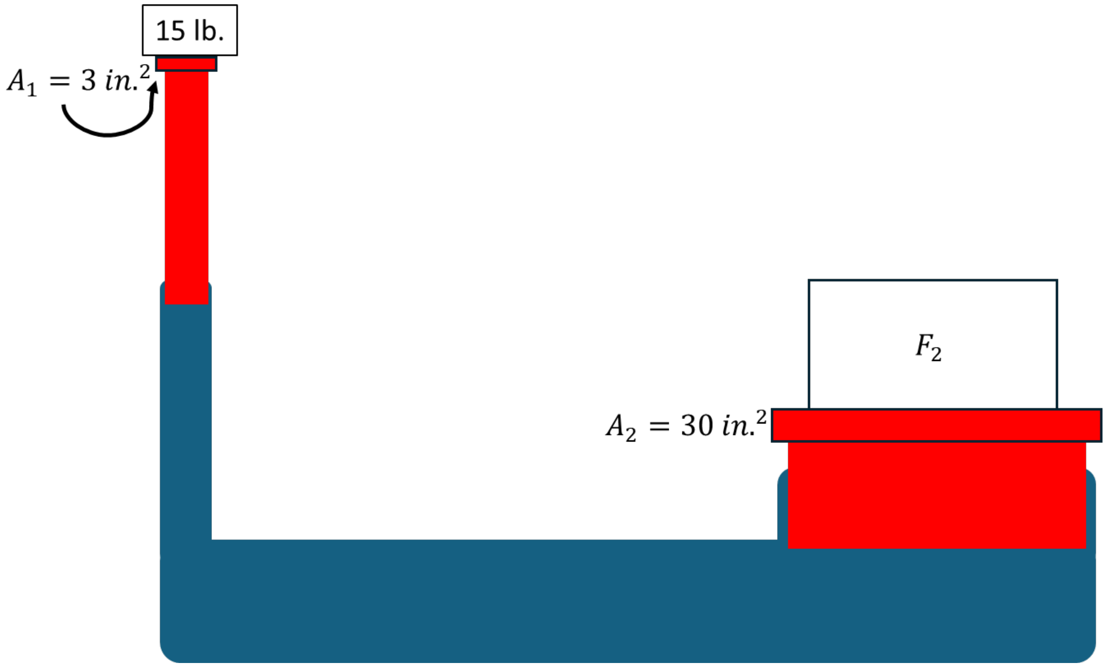


Figure 1: This is a very simple hydraulic system which illustrates the force multiplication that can be achieved using pressure.

In this simple hydraulic example, the 15 lb. weight is put on a plunger with an area of 3 in^2. This creates pressure throughout the hydraulic fluid which can be calculated as

$$Pressure = \frac{Force}{area} = \frac{15\ lb.}{3\ in.^2} = 5\ psi$$

We use that pressure to then calculate the force on the larger plunger

$$Force = Pressure \times area$$

$$F_2 = 5\frac{lb.}{in.^2} \times 30\ in.^2 = 150\ lb.$$

This is the general principle used in hydraulic systems such as automotive brake systems and salon chairs.

While having a force multiplication of 10 seems too good to be true, the tradeoff is how much fluid is displaced. The tall, narrow plunger will move fairly far in comparison to the large, broad plunger. To have a significant movement on the larger side, the smaller side needs to be quite a bit taller.

Fluid Depth

There is a caveat regarding equal pressure throughout a contained fluid. The depth of the fluid also contributes to the pressure of the fluid at that point. This is the same explanation for why pressure builds as one moves farther down in the ocean and also why there is less atmospheric pressure in the mountains compared to at sea level. In a relatively small container, this effect is minimal, but, in a large storage tank, it must be taken into account.

Energy: ability to do work/amount of destructive potential
Units: Joules (J); pound-feet (lb-ft); pounds of TNT (lb of TNT); British thermal units (Btu); kilowatt-hour (kW-hr)
In pressure systems, energy, or stored energy relates to the hazard of the system. It tells us how much harm can be caused if there is a sudden release of that energy regardless of the contents of the system.

Safe Threshold of Energy

1000 lb-ft is often given as the threshold of the lowest hazard energy. This is not inherently safe, but it gives a limit where most safety controls are sufficient (safety glasses, protective clothing, minimal barriers). The table below shows the distances for three typical injuries that one can sustain from the energy release.

Table 2: This table shows the distances of damage that can be caused by an uncontrolled release of 1000 lb-ft of energy in one direction.

Maximum distance for debris/missile damage	13 ft.
Maximum distance for eardrum rupture	12 in.
Maximum distance for lung damage	5 in.

The threshold of 1000 lb-ft of energy is somewhere between the energy in a BMX bike tire (915 lb-ft) and 16-gram CO2 cartridge (1,263 lb-ft). Comparing the stored energy to common items may not give much intuition since most people have not experienced them exploding.

Energy stored

Because of this difference in compressibility between gas and liquid, there is much more stored energy in pressurized gas than in pressurized liquid. The graph below shows the difference between the energy of both gas and liquid at the same pressures. The vertical axis gives the stored energy in *grams of TNT* which elicits the idea of explosion. Not only do you see that the helium is always higher than the water, but also the vertical axis of the graph is *logarithmic* which means that each of the increments is *ten times bigger* than the previous one. This means, when comparing the first point on each curve, the helium is about *a hundred times bigger* than the water at the same pressure. This implies that the destructive potential is much, much higher in a pneumatic system. This is the reason that codes for pneumatic systems are more stringent than for hydraulic systems. Certainly, this does not mean that hydraulic systems are safe, just saf***er*** than pneumatic systems.

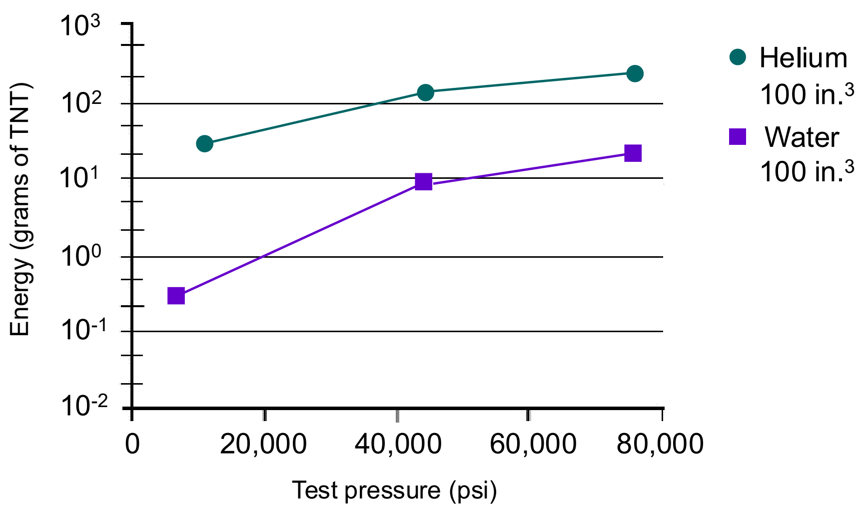


Figure 2: This graph shows the amount of energy stored in equal volumes of helium and water. The graph illustrates how much more energy is stored in gas as compared to liquid at the same pressure.

A practical way this appears is that hydrostatic testing is the preferred method for testing whenever possible. If pneumatic testing is necessary, a barrier evaluation must be performed for safety.

Gas vs. Liquid

Both gas and liquid are used to create pressure; however, they are treated very differently in terms of codes and regulations. This is illustrated by the graph above, but the reason for it has to do with differing compressibility.

Compressibility

Pneumatic (gas)

Particles in an ideal gas do not interact. When given the opportunity, they space themselves away from each other and take up the space of their container. Under those conditions there is quite a bit of empty space in the volume. The gas particles can be pushed much closer together under increasing amounts of resistance (pressure). When allowed to go back to their preferred state (much larger volume), the gas will expand quickly (violently).

Hydraulic (liquid)

Particles in a liquid state are much closer to each other and therefore have almost no empty space between them. Sometimes liquids are considered incompressible. When compressed, they can occupy *slightly* less volume with increasing resistance (pressure), but they build pressure more quickly with less compression. When allowed to go back to their preferred state, they will expand rapidly; however, the difference between the starting volume and ending volume is much lower than with gas.

Pressure, Volume, and Energy

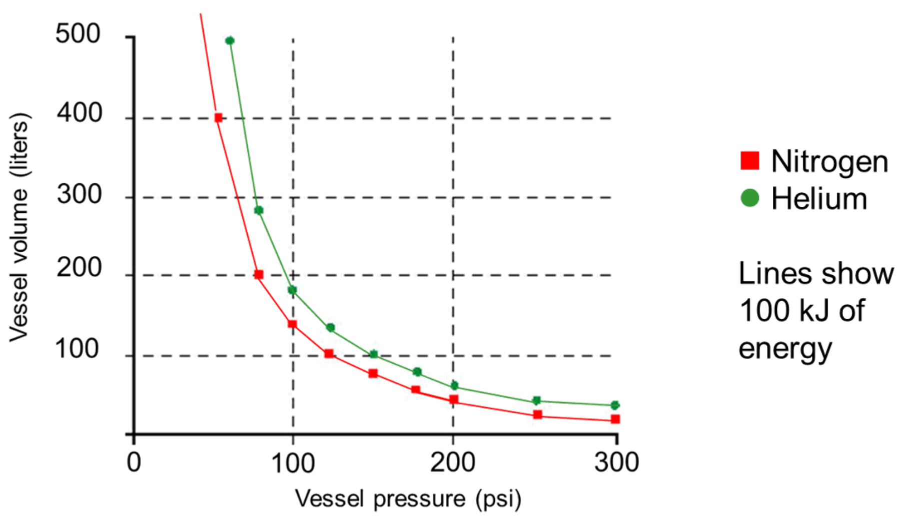


Figure 3: This graph shows lines of equal energy on a volume versus pressure graph. The point is that a vessel can have a large amount of energy, even at low pressure, due to the volume of gas.

As pointed out earlier, the relationship between pressure, volume, and temperature is complicated. Before, we looked at what happens when volume is held constant and pressure changes. The graph above shows what happens when the temperature is held constant and the energy in the system is held constant (the curves on the graph are E=100 kJ). You'll notice that the lower pressure can still contain a lot of stored energy if the volume is large.

Figure 4: Large tanks containing gas have a lot of energy even at lower pressures.

Module

2

Hazards of Pressure

Causes of Pressure Incidents

The incidents used in class can be found in Lessons Learned. Looking at safety incidents can give a sobering reminder of the hazard that is always present in pressurized systems. The failure of a system will happen in its operation, but the cause of the failure could be from any point in the lifetime of the system.

Design: From the beginning, the design of the pressure system must use sound engineering principles to ensure the system works as intended and can handle the variables such as temperature, working conditions, and environment. Needing to modify a system because of real-world conditions could lead to decisions that impact the safety of the system.

Material selection: The material of the system must not only meet the requirements for pressure but also content compatibility, temperature variation, and flow rate. Material that is incompatible with the contents may work for some amount of time but will ultimately degrade and fail. Choosing material that only meets the strict initial specification of the system will result in a short system lifetime. There needs to be a corrosion allowance in material that will take into account the expected lifetime of the system.

Material/component failure: Everything will break under the right/wrong circumstances. The component may have a flaw from manufacturing that does not appear initially, or it might work well for its intended lifetime. The possibility of component failure initially is addressed by testing the system to higher than the maximum pressure at the beginning of its usage.

Construction/installation: It is possible that systems are constructed or installed incorrectly.

Operation: Systems at LANL will have operating specifications and procedures for their operation. Existing systems could be old enough to pre-date the strict use of procedures and the usage history may be unknown. If systems are run outside of their specifications, it could cause premature degradation of the system.

Maintenance: All systems must be maintained to ensure operability. Neglecting maintenance will shorten the life of the system and increase chances of failure.

LANL Hazard Categories

P101-34 Pressure Safety divides pressure hazards in Fluid Service (FS) categories (see table below).
FS categories take into account:

- The content hazard
- The pressure hazard
- The vessel hazard

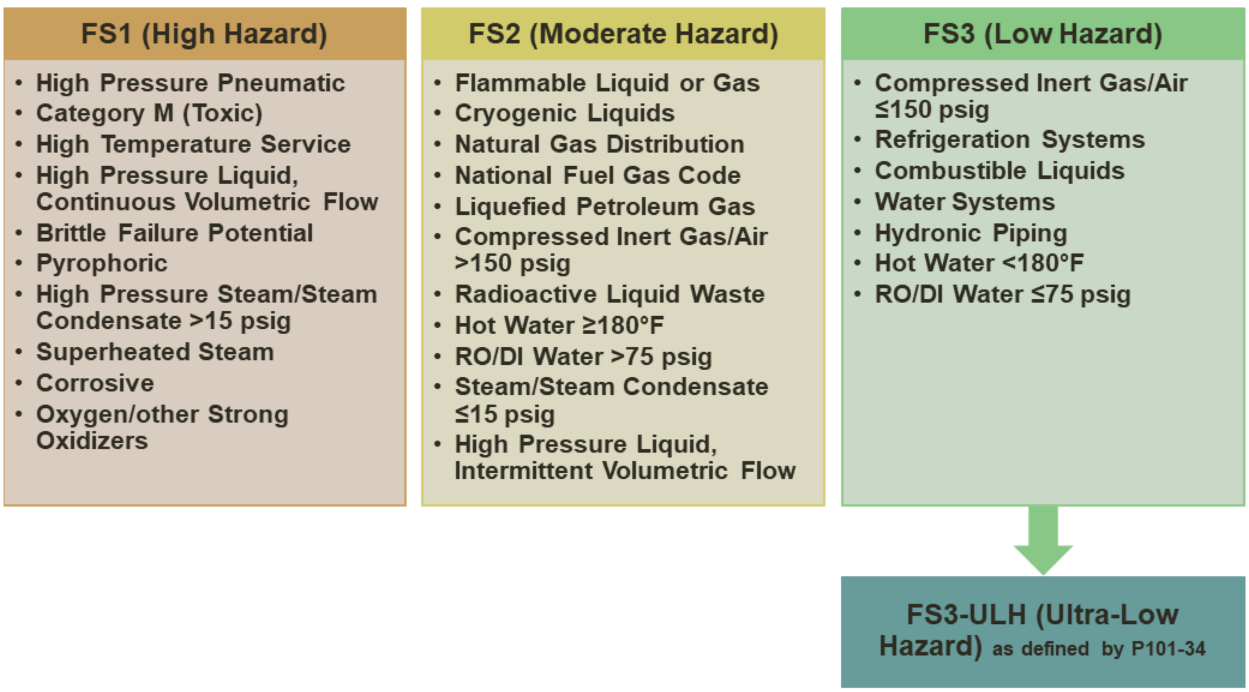


Figure 5: Fluid service categories indicate the level of hazard of a pressure system based on contents, pressure vessel, and pressure.

The hazard level of the system corresponds to the level of Pressure Safety Officer (PSO) assigned to review and approve the system.

None of these categories is entirely based on the amount of pressure in the system. The fluid service categories consider all of the hazards associated with the system. The amount of pressure for each category depends on the contents that are under pressure.

Module

3

Documents and Policy

Document Flow Down

10 CFR 851 is the federal document that directs DOE facilities safety programs. It stipulates compliance with specific codes and standards. Los Alamos National Laboratory is a contractor of the Department of Energy and is obligated to comply with the directives of the document. Some specific codes called out in 10 CFR 851 regarding pressure safety are:

- ASME B31 piping codes (e.g., B31.3, B31.5, B31.9)
- ASME Boiler and Pressure Vessel Codes (e.g., Section I, Section IV, Section VIII)

LANL's oversight of hazards is directed through a series of documents. The diagram below shows the flow down of documents to the pressure safety program.

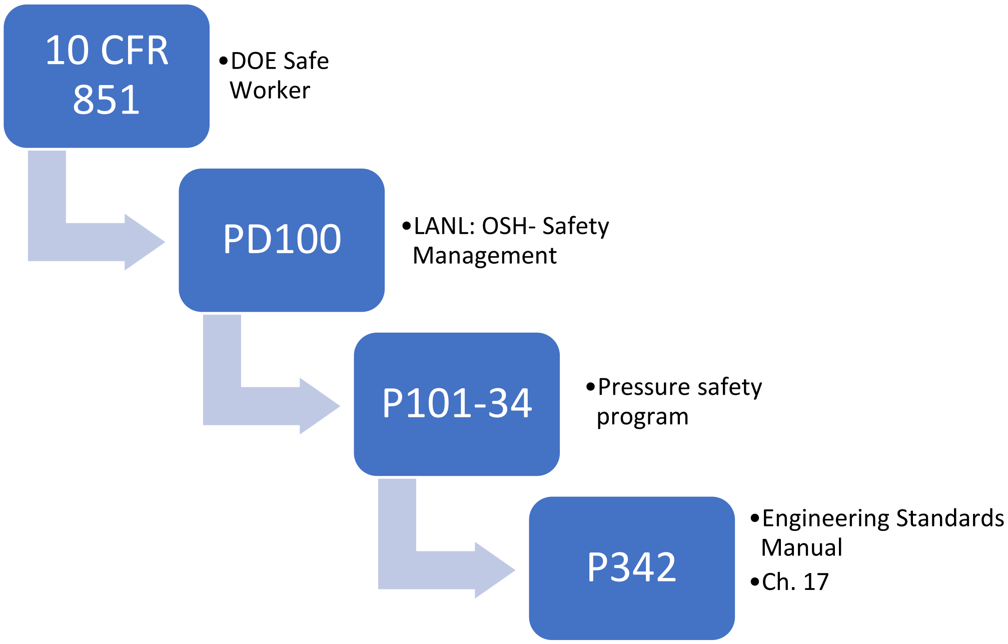


Figure 6: This chart shows the flow down of documents from the federal level to LANL policy.

What is a pressure system?

According to 10 CFR 851:

"Pressure system(s) means all pressure vessels, and pressure sources including cryogenics, pneumatic, hydraulic, and vacuum. Vacuum systems should be considered pressure systems due to their potential for catastrophic failure due to backfill pressurization. Associated hardware (e.g. gauges and regulators), fittings, piping, pumps, and pressure relief devices are also integral parts of the pressure system."

However, not all pressurized piping systems are considered Pressure Systems subject to the requirements of LANL's Pressure Safety Program. P101-34, *Pressure Safety*, defines pressurized piping systems that are excluded from the scope of the Pressure Safety Program.

P101-34 *Pressure Safety* includes the roles and responsibilities of the personnel in the program, how the hazards are defined and controlled, and procedures for design, testing, and maintenance of systems.

The level of Pressure Safety Officer (PSO) needed to approve the different FS hazard categories is shown in the table below. LANL uses a graded approach to approving pressure systems which allows the higher-level PSOs to focus on the highest hazard systems.

Table 3: This table indicates the level of Pressure Safety Officer (PSO) that is needed for the different hazard categories.

Table 1. Authorized Reviewer/Approver for FS Hazard Categories			
	FS Hazard Category		
PSP SME	**FS1 (High)**	**FS2 (Moderate)**	**FS3 & ULH (Low & Ultra-Low)**
CPSO/DCPSO	R	√	√
Duty Area B PSO	-	R	√
Duty Area A PSO	-	-	R
R Minimum required level of reviewer/approver √ May approve/review - May NOT approve/review			

System Lifecycle

The lifecycle of pressure systems at LANL is represented in the diagram below. A new or modified system will go through the same Acceptance for Use (AFU) process, and existing systems are in operations and maintenance until they are either modified for another use or disassembled. The AFU process is detailed in P101-34 Pressure Safety, Attachment A.

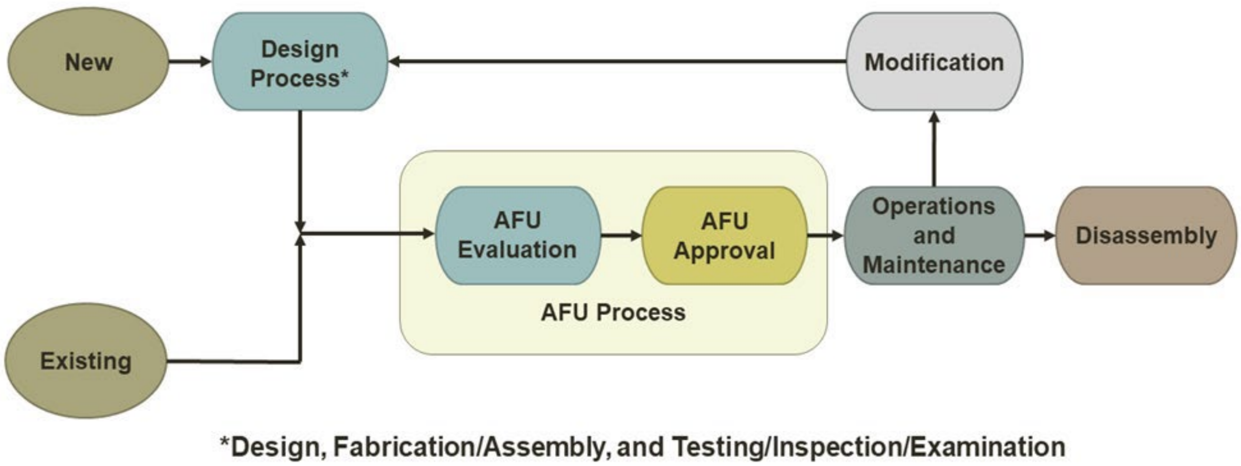


Figure 7: This diagram shows the lifecycle of pressure systems at LANL.

Design Process

Engineering Standards Manual, Chapter 17, *Pressure Safety* outlines requirements and guidance for the design, fabrication, assembly, examination, inspection, and testing of new or modified pressure systems.

ESM Ch. 17 is comprised of three primary documents (PS-GENERAL, PS-REQUIREMENTS, and PS-GUIDE) and thirteen supporting attachments (two GEN, nine REQ, and two GUIDE). The context for the attachments is explained in their associated primary documents.

Table 4: This table gives the attachments and design guidance in the Engineering Standards Manual: Chapter 17.

Section/Title	Rev.	Date
PS-GENERAL - General Information (READ FIRST)	1	06/11/25
Attachment GEN-1, Abbreviations and Definitions	3	06/11/25
Attachment GEN-2, National Board Inspection Code NB-23 Application	1	09/22/23
PS-REQUIREMENTS - Pressure Safety Requirements for New and Modified System Design	1	06/11/25
Attachment REQ-1, Category M Fluid Service and Lethal Service	1	09/22/23
Attachment REQ-2, New or Modified System Design Document Requirements	2	06/11/25
Attachment REQ-3, ASME Boiler and Pressure Vessel Code Application	1	09/22/23
Attachment REQ-4, Piping Code and Regulation Application	2	06/11/25
Attachment REQ-5, ASME B31.3 Non-Metallic Equivalent Safety Evaluation	3	09/22/23
Attachment REQ-6, ASME B31.3 Metallic Equivalent Safety Evaluation	3	09/22/23
Attachment REQ-7, ASME B31.9 Equivalent Safety Evaluation	1	09/22/23
Attachment REQ-8, OSHA Requirements for Pressure Systems	2	06/11/25
Attachment REQ-9, Approved Flexible Hose Restraints and Thrust Load Evaluations	1	09/22/23
PS-GUIDE - Pressure System Design Guidance	1	06/11/25
Attachment GUIDE-1, Overpressure Protection Evaluation Guide	2	06/11/25
Attachment GUIDE-2, Oxygen System Design Guide	0	09/22/23

Procurement

Restricted Items

Restricted goods require pre-approval before procurement. Restricted goods are identified on the LANL ASM Form 3041.00.0410 “Goods or Services Requiring Internal Review & Approval” list and the Purchase Card Restricted Purchase List and require pre-approval prior to their procurement. Restricted items are as follows:

- Power Boilers, ASME BPVC Section I
- Heating Boilers, ASME BPVC Section IV
- Pressure Vessels, ASME BPVC Section VIII
- Fiber-Reinforced Vessels, ASME BPVC Section X
- DOT Transport Tanks, ASME BPVC Section XII
- Overpressure Protection, ASME BPVC Section XIII
- Non-ASME-code-stamped pressure vessels
- Manufactured pressure systems other than ASME (e.g., European Union (EU) regulated pressure systems)
- Air compressor packages that include air receivers
- DOT vessels intended for permanent installation in a pressure system (i.e., 3A3000, cryogenic Dewars)

- Non-steam or non-boiler related pressure regulators and relief devices, ASME stamped or not
- Steam or boiler related pressure regulators and relief devices, ASME stamped or not
- Commercial and Domestic Water Heaters (not boilers) and their relief devices
- Non-domestic pressure components or systems for example European (PED) or Canadian (Canadian Registry)

Non-Restricted Items

COTS Equipment (Commercial Off-the-Shelf):

- Must be publicly purchasable without modification
- Must have part number & published pressure/temperature ratings
- Any modification voids COTS status

Other Non-Restricted Items:

- Rental pressure systems
- Analog pressure gauges
- Flex hoses & hose restraints
- Gas cylinders, tube trailers, calibration gases, cryogenics
- Any other pressure system component not listed as restricted above (e.g., pipe, tube, fittings, most valves)

Approval process governed by:

- **Form 2309**: Regulator & Relief Device Procurement Pre-Approval
- **Form 2310**: ASME Vessel Procurement Pre-Approval

Note: Supporting documentation must accompany the form(s).

At PSO’s discretion, alternative equivalent information may be used:

- Example: Email or new construction design package reviewed by a PSO.

Approval must be performed by a **PSO listed in ASM 410** for the pressure safety category.

Acceptance for Use Process (Attachment A P101-34)

Type of pressure system	Description
New	< 1 year of operating history
Modified	A change in the form, fit, or function of a pressure system; typically involves one related to design parameters (e.g., requirements, criteria,

	characteristics, etc.), physical configuration, and/or operational conditions. (3.3.7)
Existing	>1 year of operating history

System Condition Verification or In-Service Leak Test

- **Existing** pressure systems
- A pressure system has a good operating history if it has been in service for at least one year with no boundary failures, no design-basis-exceeding transients, and no personnel injuries. Physical condition is assessed via external visual inspection for damage, corrosion, wear, or leaks, documented on **Form 2303**. If history or condition can't be verified (e.g., inaccessible piping), an in-service leak test is required, documented in a **Form 2304** test plan and approved by a **PSO**. See **ESM Chapter 17** for leak testing procedures.

Owner's Inspector Approval

- **New** or **modified** permanent pressure systems
- Per ASME code, the "owner" is responsible for ensuring all required inspections and tests confirm system compliance with design. Approved owner's inspector delegates are listed in the Welding and NDE Database. Inspection results may be recorded on **Form 2305** or an equivalent form, provided it captures the same information and is maintained as a record.

Inspector Approval

- **New** or **modified** temporary pressure systems
- Inspector responsibilities align with Attachment A, Section 3.2.3.a, but ASME owner's Inspector qualifications are not required. Inspections may be documented on **Form 2305** or an equivalent form. Inspectors must meet the same qualification level as the AFU reviewer per FS category, per P101-34, Attachment A, Section 3.2.10. The Inspector may also serve as the AFU reviewer, though it's not required.

Maintenance Plan

- **All** permanent pressure systems
- Most LANL pressure systems include components requiring routine preventive maintenance. The Pressure Safety Program mandates lifecycle maintenance of safety-critical components (e.g., relief valves, rupture disks, pressure vessels, boilers). Permanent systems with at least one preventive maintenance item must have a **Maintenance Plan** per **P101-34, Attachment A, Section 3.2.4**. Systems without such items do not require a Maintenance Plan.

Pressure and/or Leak Testing

- **New** or **modified** pressure systems

- Leak testing ensures pressure system integrity at design pressure and temperature. **Form 2304** documents the test plan and results. Minimum documentation requirements are outlined in **ESM Chapter 17, Pressure Safety**.

System Drawing or Sketch

- **<u>All</u>** pressure systems
- An as-built drawing/sketch is the primary method for documenting a pressure system's design. It must include, as applicable:
    - Pressure source(s) with fluid and max pressure (psig), including PSID number for external sources
    - Pressure relief devices (PRDs)
    - Restrictive flow orifices (RFOs)
    - Regulators
    - Boilers/pressure vessels
    - Process equipment connected to the pressure system
    - Valves and in-line components
    - PSID(s) for connected systems

Overpressure Protection Evaluation

- When is it needed: all pressure systems
- Pressure relief devices prevent over pressurization during abnormal conditions and are specified during system design. All pressure systems must undergo an overpressure protection evaluation, including those without relief devices. For systems without relief devices, calculations must justify the absence or demonstrate adequate worker protection via a barrier. Key relief device attributes for sizing and maintenance include:
    - Manufacturer, model number, and inlet size
    - Setpoint pressure (psig)
    - Flow capacity at setpoint (e.g., SCFM, GPM, lb/hr)
    - For rupture disks:
        - Burst pressure
        - Max operating ratio
        - Reverse ratio
        - Damage ratio
        - Cv or flow rate of the rupture disk assembly

Barrier Evaluation

- When is it needed: If applicable, all pressure systems
- For pressure systems with components lacking a known pressure rating or unable to prevent overpressure, an engineered protective measure (e.g., barrier) is required to protect workers from potential failure and shrapnel release. The barrier must be sized according to the system's stored energy. See **P101-34, Attachment A, Section 3.3.8** for stored energy calculation guidelines.

System Operating Documents

- When is it needed: if applicable, all pressure systems
- Operating documents (e.g., IWDs/WCDs) specify safety and operational requirements for pressure systems. These documents are required for AFU when administrative controls or safety barriers are used to protect workers. Examples include valve position requirements before pressurization, locked open stop valves between pressure sources and relief devices, and locked open cryogenic stop valves to prevent liquid lock.

Acceptance for Use Checklist

- When is it needed: All pressure systems
- Explanation: After uploading required pressure system information to the PSD (or referencing another repository), **Form 2307, Acceptance for Use Checklist**, must be completed by the PSR and approved by the designated AFU reviewer.

Module

4

Pressure System Design and Component Selection

This module covers specifics of pressure systems including:

- Maximum pressure
- Operating pressure
- Design considerations
- Common pressure system components

System Pressure

Maximum pressure and safety factor

All systems will have a maximum pressure that is allowed to be in the system. This maximum is generally based on the threshold of failure. A safety factor is used to determine how close to failure the system or component is.

$$safety\ factor = \frac{failure}{maximum}$$

The upper limit of the component or system can be referred to as

- Maximum Allowable Working Pressure (MAWP)
- Design Pressure
- Pressure Rating

The maximum pressure of a whole system cannot be any higher than the weakest component of the system, but it is not *required* to be as high as the weakest point in the system. The MAWP can be set at any point lower than that and takes into consideration the application and purpose of the system.

MAWP does not represent the pressure at which a component will fail. MAWP is based on a factor of safety of approximately 4 to 1, though it varies by code and manufacturer standards. However, it is ALWAYS greater than 1.

There are a few things about the safety factor to note:

- The initial safety factor is the best expected performance of a component that is new and free of defects.
- The actual safety factor will fall over a component's lifetime due to any corrosion, erosion, and wear and tear on the system from operation.
- The safety factor allows for imperfections throughout the entire pressure system lifecycle, such as permissible manufacturing tolerances and defects and imperfections in the assembly process.
- The presence of a safety factor ultimately permits the use of simplified rules for design, construction, testing, etc. outlined in piping codes, which saves a lot of time and money compared to bespoke, case-by-case detailed engineering design for each unique pressure system.

Operating pressure

The operating pressure is the expected pressure of the system during normal operations. The stability of the operating pressure will depend on the system and the pressure source.

If a pressure relief device is present in the system, operating pressure should not exceed 80-90% of the relief device set pressure to prevent inadvertent activation of the relief device.

If a pressure relief device is NOT present in the system, operating pressure cannot exceed system MAWP or design pressure.

Designer Considerations

When designing a pressure system, designers should consider, in order of importance from top to bottom:

- Designing a system that is safe for workers to operate and be around
- Designing a system to meet functional requirements
- Designing a system at the lowest possible cost

Designing a system that is safe for workers is most easily achieved by following national consensus codes and standards such as ASME B31 piping codes, whose design rules ensure safety and quality. However, other options are outlined in ESM Ch. 17, *Pressure Safety*. After this, functional requirements provided by the customer need to be met. Finally, consider factors that reduce overall costs such as:

- Material cost
  - E.g., if the corrosion resistance of stainless steel is not needed, consider less expensive materials such as copper, brass, or carbon steel.
- Availability of materials
  - E.g., if large quantities are needed, secure quotes in advance.
- Standardization of components
  - E.g., if using ball valves, use a single manufacturer/model when possible.
- Reduce specialized training necessary for assembly
  - E.g., can mechanical joints be used instead of welds?

Pressure System Components

There are three main safety considerations when selecting components for pressure system:

- Design pressure
- Design temperature
- System contents

Each component must first be evaluated based on these criteria, then secondly on other considerations depending on its function. This section provides an overview of the function, characteristics, and safety concerns of several types of components that are commonly found in a pressure system.

The components covered in this student manual are:

- *Piping/tubing*
- *Joint connections*
  - *Mechanical*
  - *Permanent*
- *Valves*
- *Regulators*
- *Gauges*
- *Pressure Relief Devices*
- *Restrictive Flow Orifices*

Piping/tubing

Function

Pipes and tubes transport fluids from source to process.

Characteristics

Pipes and tubes are most commonly made from metal, but nonmetallic options are available and sometimes preferable. *CAUTION: when using nonmetallic piping or tubing such as* *thermoplastics, the pressure and temperature ratings are usually much lower than metallic piping or tubing.*

While both pipes and tubes can be bent, pipe bending requires highly specialized tooling, training and processes, whereas tube bending is possible with simpler tooling from the manufacturer.

The three main characteristics of pipes and tubes are the material, outside diameter, and wall thickness.

Material: The substance from which the pipe or tube is made (e.g., steel, copper, PVC). It determines properties like strength, corrosion resistance, and suitability for specific applications.

Outside diameter (OD): The total width of the pipe or tube measured from the outer edge of one side to the outer edge of the opposite side. It is a key dimension used for sizing and fitting connections. The size of the pipe or tube controls the flow rate of the contents.

Wall thickness: The distance between the inner surface and outer surface of the pipe or tube wall. It influences the pipe's strength, pressure rating, and flow capacity.

Pipe schedule: The schedule of a pipe is a measure of the pipe's strength through comparison of the outer diameter and the wall thickness. The pipe schedule indicates the wall thickness which corresponds to the strength of the pipe.

Nominal Pipe Size: the OD of piping is commonly referred to as Nominal Pipe Size, NPS. E.g., 2" NPS refers to "2 inch" pipe, but the OD is 2.375". 2 NPS Schedule 40 pipe has a nominal wall thickness of 0.154" and Schedule 80 has a nominal wall thickness of 0.218". The higher the pipe schedule, the stronger the pipe, the lower the flow capacity, and the higher the cost.

Table 5: This tables give the measurements of pipe by the Nominal Pipe Size (NPS) which includes the outer diameter (OD) and the wall thickness.

NPS	OD (inches)	Pipe Schedules Wall Thickness (inches)			
		10	40	80	160
1/2	0.840	0.083	0.109	0.147	0.187
3/4	1.050	0.083	0.113	0.154	0.218
1	1.315	0.109	0.133	0.179	0.250
2	2.375	0.109	0.154	0.218	0.343
3	3.5	0.120	0.216	0.300	0.437
4	4.5	0.120	0.237	0.337	0.531
6	6.625	0.134	0.280	0.432	0.718
8	8.625	0.148	0.322	0.500	0.906

Source: ASME B36.10M

Safety Considerations

The main concern for a pipe or tube failing is an uncontrolled release of energy. A properly designed, fabricated, examined, and tested piping system mitigates this risk.

Piping and tubing must be properly supported to account for the weight of the pipe/tube and its contents and, when applicable, stresses induced by thermal displacement, seismic events, wind loads, and snow loads. Failure to properly support the pipe/tube will lead to premature failure. To mitigate damage in the event of failure, piping code specifies the support needed.

As the temperature of a material increases, the yield and tensile strength decreases. As a result, the ASME B31 code Allowable Stress, *S*, decreases as well. When using code equations that involve the Allowable Stress, it is important to use the most conservative (lowest) value based on anticipated worst-case temperature.

Put more simply, the allowable pressure is “derated” at higher temperatures compared to base temperature (-20 to 100°F for metallics). The Allowable Stress “derating” varies because the basis for Allowable Stress can vary between the different ASME B31 piping codes. The table below is shown as an example of derating factors corresponding to temperature. Manufacturers of components suitable for higher temperatures similarly provide derated allowable pressures as a factor of temperature.

Table 6: This table shows the derating factor applied to different metals at various temperatures. Any derating factors are for training purposes only.

Temperature Derating Factors for Various Metals/Alloys (for training purposes only)				
Temperature (°F)	**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	0.38	0.86	1.0	0.96
…	…	…	…	…
900	Not permitted	0.79	0.80	0.89
950	Not permitted	0.77	0.53	0.88
1000	Not permitted	0.75	0.35	0.87

Nonmetallic materials are more significantly affected by temperature as shown below.

Table 7: This table shows the derating factor applied to different nonmetals at various temperatures. Any derating factors are for training purposes only.

Temperature Derating Factors for Various Nonmetallics (for training purposes only)				
Temperature (°F)	**Chlorinated Polyvinyl Chloride (CPVC)**	**Polyvinyl Chloride (PVC)**	**Polyvinylidene Fluoride (PVDF)**	**Polyethylene (PE)**
73	1.0	1.0	1.0	1.0
80	1.0	0.9	0.9	0.9
90	0.9	0.8	0.9	0.9
100	0.8	0.6	0.8	0.8
120	0.7	0.4	0.7	0.7
140	0.5	0.2	0.6	0.4
160	0.4	Not permitted	0.5	Not permitted
180	0.3	Not permitted	0.5	Not permitted
200	0.2	Not permitted	0.4	Not permitted
220	Not permitted	Not permitted	0.4	Not permitted
250	Not permitted	Not permitted	0.4	Not permitted
280	Not permitted	Not permitted	0.3	Not permitted

Additional Considerations

Wherever practical, install piping and tubing runs where the whole system can be accessed for future maintenance, inspection, and repair. Where this is not practical, ensure all parts of the system that need to be interacted with by workers (e.g., valves) are fully accessible.

Joint Connections

Function

To join different components like pipes, valves, gauges, etc. together, pressure systems require joint connections. There are a variety of joint connection types, including but not limited to:

- Threading
- Bolting
- Welding
- Brazing
- Soldering
- Solvent Welding
- Heat Fusion

Characteristics and Safety Concerns

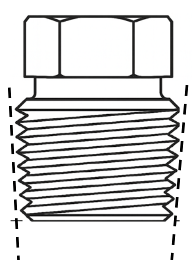
Threading: the most common joint connections have threads. Threads can provide different functions. In some cases, the threads provide the seal for the connection. In other cases, the threads are holding the fitting in place for another seal area (like in the case of straight thread, flared fittings, and compression fittings). Threaded joints can be assembled at LANL with minimal to no training required.

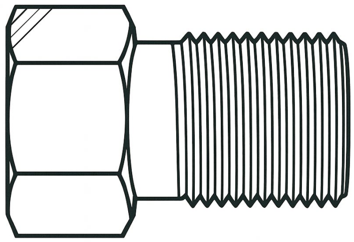
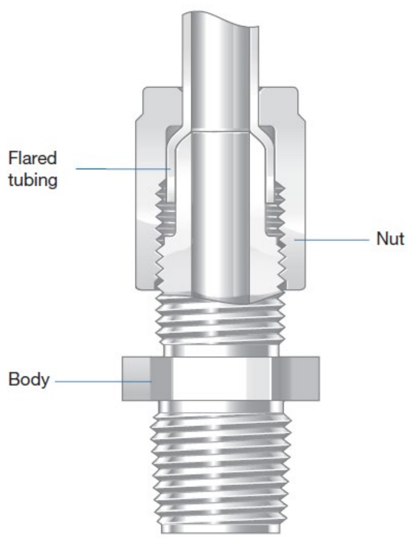
Thread types are generally governed by two different standards: American Standard and International Organization for Standardization (ISO).

- American Standard includes national pipe tapered (NPT) and national pipe straight (NPS) threads.
- ISO has both tapered and straight (or parallel) thread, similar to NPT and NPS. ISO fittings are most commonly found on equipment procured outside the United States.

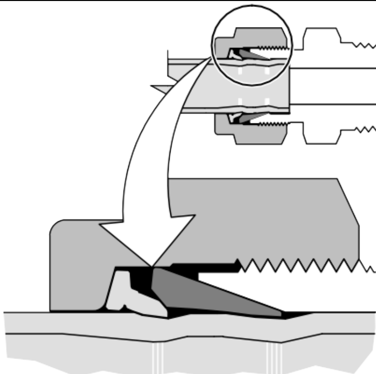
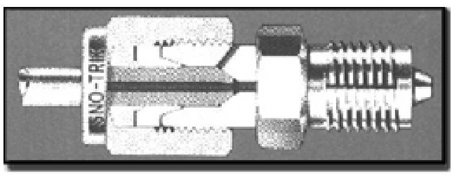
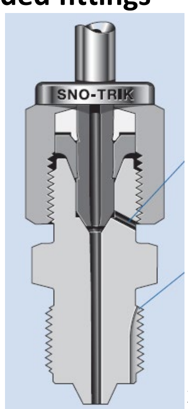
CAUTION: the dimensions of American Standard NPT/NPS and ISO are NOT the same, so they must not be interchanged. Fittings to adapt between American Standard and ISO are available and must be used when necessary.

Table 8: This table illustrates various fittings and gives some uses and considerations for each.

Fitting Type	Uses and Considerations
Tapered thread fittings  ChatGPT generated	• Thread interference forms the seal. (Lubricants such as Teflon tape reduce the shear stress on the threads and help provide a better seal.) • Not suited for regular assembly and disassembly. • NPT and ISO fittings have different thread angles and must NOT be interchanged. • Used with pressures of 150–10,000 psi.

Straight or parallel thread fittings  ChapGPT generated	• 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  [1]	• 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.
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.

[1] Picture take from Swagelok product catalog- *High-Purity PFA; Fine Thread Flare Fittings*. www.swagelok.com

	• MAWP is based on the tubing MAWP, unless weaker elements reduce the pressure rating. • Used with pressures up to 8,000 psi. • Swagelok are the only pre-approved compression fittings for use at LANL.
Bite-type fittings  Uses principle of Minimum seal area	• 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 [2]	• 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.

Bolting: Bolted joints connect piping systems using bolts, nuts, and gaskets to provide a robust and leak-tight joint. They can be disassembled and reassembled many times and are ideal for situations where future maintenance is necessary. Bolted joints can be assembled with minimal to no training required but often require the use of special tooling (e.g., torque wrenches) and assembly methods to ensure a leak-tight connection.

[2] Picture taken from Swagelok product catalog- *Medium- and High-Pressure Fittings, Tubing, Valves, and Accessories*. www.swagelok.com ©Swagelok Company

Examples of bolted joints include:

- Flanges
    - Flanges create a leak-tight connection by compressing a gasket between two flange faces. The flange body and bolts provide structural strength, while the gasket provides the seal.
- Mechanical couplings (e.g., Victaulic)
    - Mechanical couplings use mechanical force to seal two grooved components' ends together. A rubber gasket forms a leak-tight seal between the component ends, and a two-part metal housing encases the gasket and engages the grooves, providing structural integrity, and containment. Nuts and bolts are then tightened to compress the housing onto the gasket, creating the joint.
- Ultra-high vacuum (UHV) flanges (e.g., ConFlat)
    - UHV flanges create an all-metal, extremely leak-tight seal in vacuum systems by compressing a soft copper gasket between two knife-edges on the stainless steel flanges. UHV components are not rated for use outside of vacuum applications.

<u>Welding:</u> Welding is a process that permanently joins two pieces of metal by heating them to their melting point, with or without the addition of filler material. Because the base metals are melted, the resulting joint is typically as strong as or stronger than the original material. Welding requires strict safety controls due to risks of high temperatures, sparks, fumes, and UV radiation.

<u>Brazing:</u> Brazing joins metals by melting and flowing a filler metal into the joint at a temperature above 450°C (840°F) but below the melting point of the base metals. The filler metal is drawn into the joint by capillary action. Brazed joints are strong, leak-resistant, and can join dissimilar metals. Since the base metals are not melted, brazing causes less thermal distortion than welding. Safety considerations include exposure to heat, flux fumes, and hot metals.

<u>Soldering:</u> Soldering is similar to brazing but uses filler metals with a melting point below 450°C (840°F), such as tin-lead or lead-free alloys. It is commonly used in electrical and plumbing applications where high strength is not required. Soldering depends on proper cleaning and flux application to achieve good adhesion. Safety concerns include flux fumes, hot solder, and lead exposure (if using lead-based solders).

<u>Solvent Welding:</u> Solvent welding is a joining method used for thermoplastic materials in which a liquid solvent (or a solvent-based cement) is applied to the surfaces being joined. The solvent softens or partially dissolves the polymer at the joint, allowing the surfaces to fuse together. As the solvent evaporates, the polymer chains from each part interdiffuse and re-entangle, forming a strong, permanent bond.

<u>Heat Fusion Welding:</u> Heat fusion welding is a process used to join thermoplastic components by heating the surfaces to a molten state and then pressing them together so the polymer chains intermingle. As the material cools, a homogeneous joint is formed with strength similar to or greater than the base material. The two most common methods of heat fusion are:

- *Butt Fusion*: Pipe ends are aligned and pressed against a heated plate until the surfaces soften. The plate is removed, and the softened ends are pressed together under controlled pressure until the joint cools. This method is widely used for large-diameter polyethylene (PE) pipes.

- *Electrofusion*: Special fittings containing embedded electrical resistance wires are slipped over the pipe ends. When current is applied, the wires heat the surrounding plastic, melting both the fitting and pipe surfaces. Once cooled, a strong, integrated joint results.

NOTE: Welding, brazing, and soldering of pressure systems at LANL requires qualified personnel and procedures. See ESM Chapter 13, Welding, Joining & NDE*, for more information.*

Valves

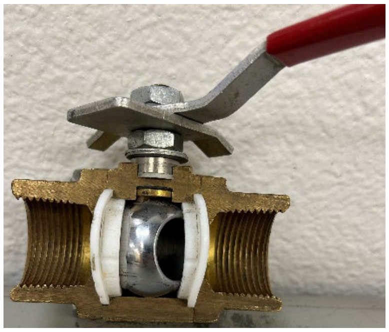
Function

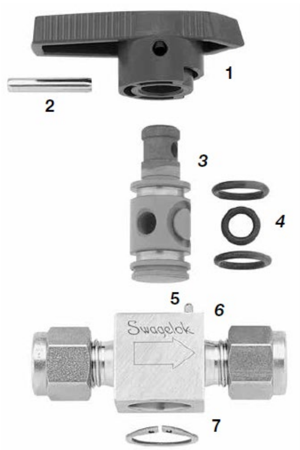
Valves control the flow of the contents of a system. There are many different types of valves, with each specialized for particular functions.

Characteristics

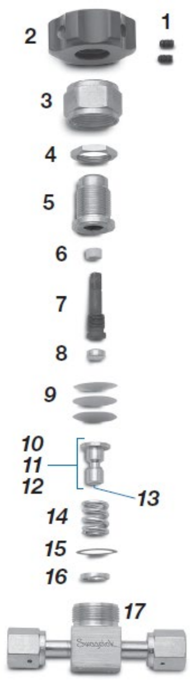
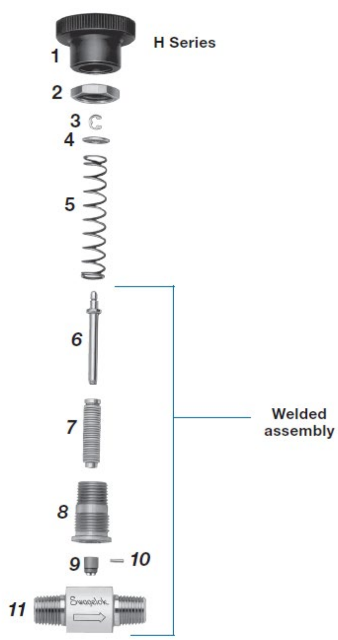
The most commonly used valves, and considerations regarding their uses, are listed in the following table. Before selecting and using valves, define the system requirements and obtain information on particular valves from the manufacturer.

Table 9: This table illustrates various types of valves along with their uses and considerations.

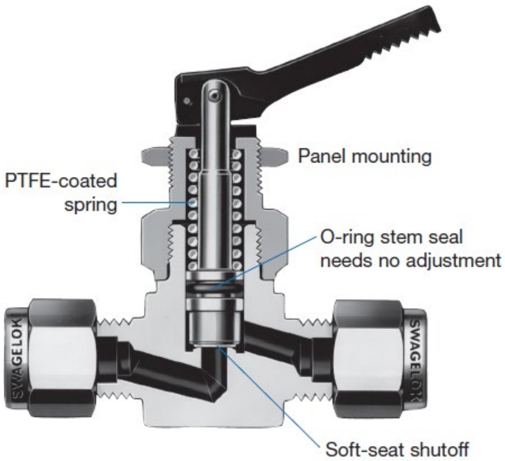
Valve Type	Uses and Considerations
Ball valves 	• High-capacity flow with 1/4-turn operation • Nondirectional • Simple construction, low cost • Used only wide open or fully closed • For on/off service, fluid mixing, and manifold switching; no throttling

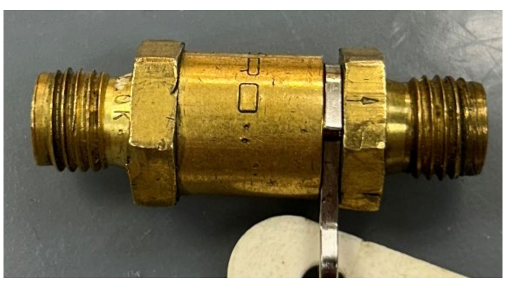
Plug valves  [3]	• High-capacity flow with 1/4-turn operation • Directional • Simple construction, O-ring seals • Full throttling, with interim positioning
Flow regulating valves (not pressure regulators) 	• Needle-like stem point fits into orifice • Different stem tips available • For throttling and shutoff on instrumentation lines • Combined V-stem with needle-like stem point • Regulate flow, not pressure

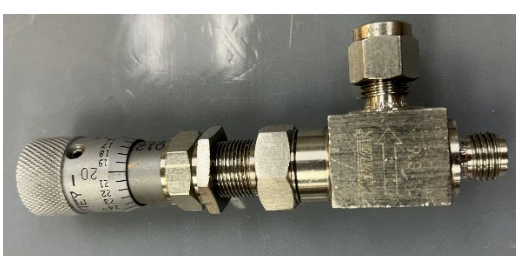
[3] Picture taken from Swagelok product catalog- *Plug Valves.* www.Swagelok.com ©Swagelok Company

Diaphragm-sealed valves [4]	• Packless, hermetically sealed • Soft stem tip • Frequently offer higher pressure ratings
Bellows-sealed valves [5]	• Packless, hermetically sealed • Bellows welded to body for leak-tight service • For vacuum systems, cryogens, toxics, corrosives, and/or radioactive fluids

[4] Picture taken from Swagelok product catalog- *Diaphragm Valves*. www.swagelok.com. ©Swagelok Company
[5] Picture taken from Swagelok product catalog- *Bellows-Sealed Valves*. www.swagelok.com. ©Swagelok Company

Toggle valves  [6]	• 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

Check valves

	• A one-way valve that normally permits fluid to flow through it in only one direction
	• Opens when the designated cracking pressure (i.e., differential pressure) is reached
	• Essential when the backflow of fluid in a system must be prevented
	• Various methods of operation:
	  ○ Spring (shown at left)
	  ○ Lift
	  ○ Swing
	  ○ Butterfly
	• NOT to be used as a pressure relief device

Metering valves (also called 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 • NOT to be used as an isolation valve; requires shutoff valves upstream

[6] Picture taken from Swagelok product catalog- *Toggle Valves.* www.swagelok.com. ©Swagelok Company

Gate valves 	• For fluids, especially water, with pressures up to 150 psi • Requires multiple turns to open or close • Typically used in larger diameter systems
Butterfly valves 	• Similar function to gate valves, but with different operating method • Typically quarter-turn for fast opening/closing • More compact and lightweight compared to other valve types performing a similar function • Typically used in larger diameter systems

Safety Considerations

As with other types of components, valves need to be compatible with the service conditions (fluid type, pressure, and temperature). For example, in cryogenic service, ball valves suitable for such service are required because they are designed with extended valve bonnets to prevent valve stem freezing and relieve pressure build-up due to liquid lock inside the ball when the valve is closed.

There is often a “best” type of valve for a given application. Valves misused outside of their intended purpose can lead to premature valve wear or failure. For example:

- Gate valves and ball valves are best suited as fully opened/closed valves, but not for throttling.
- Globe valves are best suited for flow control, but not fast open/close cycling.

Valves designed to fully close, providing isolation, can **never** be assumed to be 100% leak tight. When absolute certainty of isolation with no leakage is required, a double block-and-bleed setup is required.

Valve orientation and installation direction is often a key characteristic. Some valves are designed for one-directional flow, while others might have higher allowable pressure differential across the seat on one side of the valve.

Designers are cautioned to specify valve locations that are accessible for both operations and future maintenance.

Pressure Regulators

Function

Pressure regulators are devices used to reduce and control the pressure of a fluid (gas or liquid) from a high-pressure source to a safe, usable level downstream. They automatically maintain a nearly constant outlet pressure despite fluctuations in inlet pressure or changes in flow demand; however, fluctuations can still occur. Regulators are widely used in compressed gas cylinders, piping systems, pneumatic tools, fuel gas systems, and process equipment.

Figure 8: This picture shows a regulator used for compressed air.

Characteristics

<u>Types</u>: Common designs include single-stage and two-stage regulators. Single-stage regulators reduce pressure in one step, while two-stage regulators provide more stable output.

Operation: A typical regulator uses a spring-loaded diaphragm to balance downstream pressure against a set spring force. As pressure rises, the valve closes; as pressure drops, the valve opens.

Adjustability: Most regulators allow manual adjustment of outlet pressure via a control knob or screw.

Performance Factors: Key characteristics include accuracy (how closely the set pressure is maintained), flow capacity, sensitivity, and response time.

Flow Coefficient (Cv): The Cv of a pressure regulator is a unitless coefficient that defines the regulator's capacity for a fluid to flow through it. Cv is the primary characteristic used to determine overpressure protection needs of pressure systems that use pressure regulators.

Safety considerations

Over pressurization: If a regulator fails, downstream components may be exposed to full supply pressure, risking rupture or explosion. Relief devices are installed downstream of regulators.

CAUTION: Some pressure regulators have integral pressure relief devices. These devices only protect the regulator from damage; they DO NOT provide overpressure protection to the downstream pressure system.

Improper Selection: Using a regulator not rated for the gas, pressure, or flow can cause malfunction or hazards.

Leaks: Worn diaphragms, seals, or fittings may leak hazardous gases. Regular inspection is essential.

Creep: A gradual rise in outlet pressure due to seat leakage may lead to unsafe conditions if undetected.

Back-pressure Regulators

Function

Back-pressure regulators operate similar to pressure regulators, except they sense upstream pressure (instead of downstream pressure) and open when necessary to maintain a stable upstream pressure.

Characteristics

Same as Pressure Regulators, above.

Safety Considerations

Same as Pressure Regulators, above. Additionally, back-pressure regulators are NOT to be used in place of pressure relief devices.

Pressure Indicators

Function
Pressure indicators measure the pressure of the system at the point of the system they are installed. Gauges must be designed into a system as there is no way to externally measure pressure.

Characteristics
Analog Pressure Gauges

Analog pressure 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, analog pressure 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,
- compatible with the system fluid, and
- designed with shatterproof faces and blowout backs.

Pressure Transducers

Transducers measure the physical pressure of a liquid or gas and converts it into a standardized electrical signal, such as voltage or current. This signal can be sent to a monitoring system, computer, or display. Transducers are often used on higher pressure systems or on systems that require data logging or monitoring.

Pressure transducers can accurately indicate pressure over their entire range, so the best practices that apply to the indicating range for analog gauges do not apply to transducers.

Digital pressure gauges use pressure transducers to sense pressure and, like analog gauges, provide their readout on the dial at the point of installation.

Safety Considerations
Pressure indicators have a finite life span. Indicators experience fatigue due to pressure cycling, vibration, temperature fluctuations, and mechanical wear. Over time they will lose accuracy, become stuck, or fail completely.

Pressure indicators that are normally operating very close to their maximum full-scale value are subject to overstressing and premature wear or failure.

Routinely inspect pressure gauges for signs of damage or unreadable conditions. If there are visible signs of damage (e.g., front dial cover broken or missing, missing liquid in a liquid-filled gauge, indicator needle “pinned” at full-scale pressure value), replace the indicator immediately. Additionally, any indicators with pressure readings that are inconsistent with known pressure conditions elsewhere in the system or outside of expected normal operating conditions should be suspected as defective and replaced.

When feasible, install an isolation valve between the pressure system and pressure indicator to accommodate replacement in the future without depressurizing the system. For steam service, use a pigtail siphon to protect the pressure indicator from direct high-temperature steam exposure.

When long-term pressure indicator accuracy is a critical characteristic, indicators should be calibrated once per year. Calibration services can be provided by LANL's Metrology and Calibration Laboratory or a vetted third-party calibration laboratory.

Pressure Relief Device

Function

A PRD passively protects pressure systems from overpressurization during beyond-design-basis abnormal conditions. PRDs are considered the "last line of defense" critical safety devices to protect workers from the hazards of pressure system overpressurization.

Characteristics

The two most common types of pressure relief devices used on pressure systems are relief valves and burst discs:

- Pressure relief valves (PRVs) are considered "reclosing" relief devices. They are typically spring-loaded to counteract the force of the pressure on the inlet side of the system, then open when the force meets or exceeds the spring force. The PRV closes when enough pressure is relieved for the valve seat to re-seal.
- Hard seats (e.g., metal-to-metal) have a leak tightness of about 80-85% of relief valve set pressure.
- Soft seats (e.g., silicone-to-metal) have a leak tightness of about 90-95% of relief valve set pressure.
- Burst discs (a.k.a. rupture discs) are considered "nonreclosing" relief devices. The activation of a burst disc opens a permanent, open relief venting path. Burst discs must be replaced after a relief event.
- Burst discs are leak-tight up to the burst pressure, but manufacturers specify an operating ratio (typically 80-95% of burst pressure) above which extensive operation is not recommended for long-term disc life.

Based on the leak tightness and operating ratio information above, when PRDs are present in a system it is recommended that the maximum operating pressure be no higher than 80% to 90% of PRD set pressure.

Safety Considerations

Every pressure system must have an overpressure protection evaluation to determine if pressure relief devices (PRDs) are necessary.

With some exceptions addressed in ASME codes, PRDs shall have a pressure setting not higher than the component in the system with the lowest pressure rating (i.e., system MAWP or design pressure). In addition, PRDs:

- Must have sufficient flow capacity (meeting or exceeding the worst-case flow rate from the pressure source) to prevent system pressure from increasing beyond acceptable limits. The acceptable limit defaults to 10% above MAWP, with some exceptions addressed in ASME codes.

- Must be safely vented (often requiring consultation with Occupational Safety and Health and/or Fire Protection).

- Must be tagged with relevant data and the maintenance due date.

While pressure relief devices are the most common and simplest way to prevent overpressurization and potential failure of a pressure system, it is not always the ideal method to protect workers. For example, toxic or corrosive fluids cannot always be safely vented, even remotely, if a facility cannot support the introduction of such fluids into exhaust systems or directly into the atmosphere outside the building. In instances where pressure relief devices are not feasible, other methods of overpressure protection need to be considered, such as designing the system with an MAWP or design pressure that meets or exceeds the worst-case abnormal conditions.

Restrictive Flow Orifice (RFO)

Function

RFOs are passive, flow-limiting devices. The two most common uses of RFOs are:

- Passively limit flow from a pressure source during a fault or failure condition (e.g., failed pressure regulator). They generally do not limit flow during normal operations but do limit flow during a fault or failure condition. Used when other passive flow limitations (e.g., pressure regulator flow coefficient, Cv) is not sufficient for the PRD(s) specified in a system.

- Passively limit flow during normal operations. This can be useful when process equipment requires low fluid flow input to help reduce waste.

Characteristics

An example when an RFO is beneficial to protect against overpressurization:

> Ex. A pressure regulator with a Cv of 0.06 is installed on a nitrogen gas cylinder with a fill pressure of 2265 psig. The user wants to install a PRV with a set pressure of 50 psig and relief capacity of 53 standard cubic feet per minute (SCFM). The worst-case flow rate through a regulator with Cv of 0.06 is 82.32 SCFM:

DETERMINING REGULATOR FLOW BY Cv		
EQUIVALENTS AS AIR		
REGULATOR	SOURCE	Nitrogen
	SOURCE PRESSURE (psi)	2265
	C_v	0.06
	FAILURE FLOW RATE AS AIR (SCFM)	82.32

The above situation is NOT SAFE, because the pressure source maximum flow rate (82.3 SCFM) exceeds the relief capacity of the selected PRV (53 SCFM). To fix this, an RFO can be added to limit worst-case flow. An RFO of 0.035” diameter limits flow to 38.4 SCFM, which is less than the PRV relief capacity:

DETERMINING REGULATOR FLOW BY ORIFICE			
EQUIVALENTS AS AIR			
	Diameter (in)	C_v	
Diameter to Cv	0.035	0.028	(This diameter and
REGULATOR	SOURCE		Nitrogen
	SOURCE PRESSURE (psi)		2265
	Equivalent C_v (if not listed)		0.028
	FAILURE FLOW RATE AS AIR (SCFM)		38.42

NOTE: The Microsoft Excel calculation tool pictured above can be found in the “Calculations and Excel Tools” folder of the ESM Ch. 17 Reference Data [SharePoint website](#).

Safety Considerations

The RFO’s material is an important consideration for both material compatibility with the system fluid and the RFO pressure rating. For example, a brass RFO with a 2,000 psig pressure rating cannot be installed upstream of a pressure regulator with a gas cylinder that is filled to 2,265 psig. A stainless steel RFO with a 4,000 psig pressure rating would be necessary.

Flashback Arrestors

Flashback arrestors are safety devices most commonly used when mixing oxygen with a fuel (e.g., acetylene, hydrogen, methane). These devices prevent flames from propagating back into the pressure source (flashback), such as gas cylinders.

Pressure System Component Configurations

Safety Manifold

Pressure systems that connect to gas cylinders are required to include a safety manifold that consists of:

- Pressure regulator
- Vent valve
- Isolation valve
- Pressure relief device (if necessary)
- Restrictive flow orifice (if necessary)

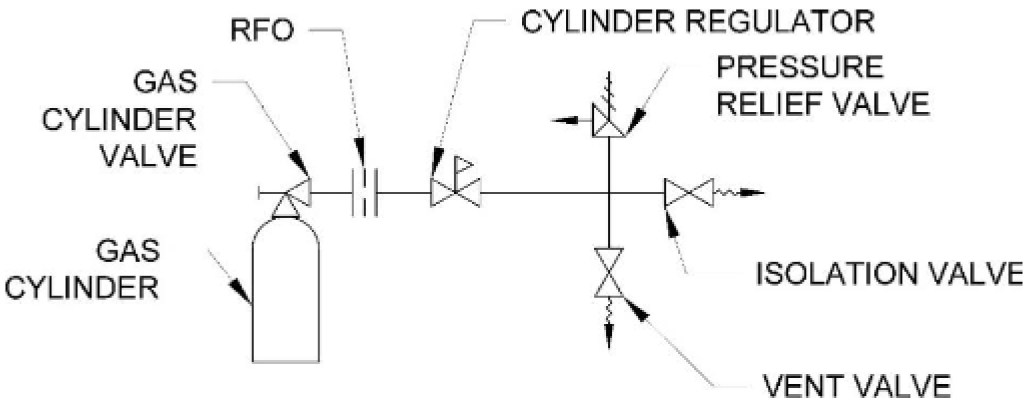


Figure 9: This is an example of what a safety manifold can entail. The main goal of the safety manifold is to control the pressure at its source for safe and reliable delivery to the system.

Double Block and Bleed

A double block and bleed (DBB) configuration 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.”

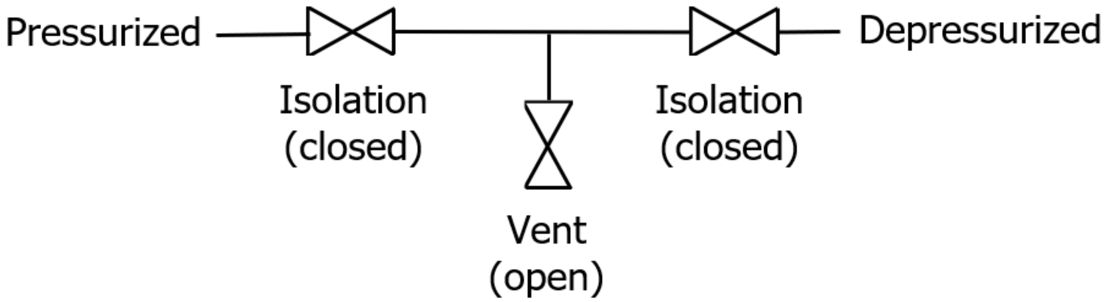


Figure 10: This shows a diagram of a double block and bleed configuration of valves. This configuration is used to ensure isolation between parts of the system.

A single isolation valve can NEVER be considered sufficient when critical isolation is required. No single valve is 100% leak tight even in the best conditions. This is considered an administrative control due to the procedure of opening and closing the correct valves. A DBB could be used as a lock-out-tag-out control as long as there is proper labeling of the valves and a procedure in place.

Module

5

Testing and Inspection

Inspection

Inspection prior to testing

All new or modified pressure systems need to be inspected prior to testing. Inspection is a critical quality assurance step that helps ensure safety, reliability, and regulatory compliance. The primary purpose of inspection is a final check that all design elements have been correctly implemented into the pressure system construction before proceeding with testing.

When the design basis includes ASME B31 code(s), inspections must be performed by a qualified owner's inspector as defined in the applicable B31 code(s). When the design basis does not include ASME B31 code(s), inspections may be performed by LANL personnel meeting the criteria defined in LANL Engineering Standards Manual Ch. 17.

Inspection throughout service life

Some pressure systems need to be inspected at regular intervals throughout their service life. Examples of required service life inspections include:

- Yearly inspections of ASME Boiler & Pressure Vessel Code boilers.
- Inspections of ASME Boiler & Pressure Vessel Code pressure vessels. Inspection frequency is 3 to 10 years, depending on type of inspection and system fluid used in vessel.
- Pressure systems with system fluids considered corrosive to the materials of construction, as defined in P101-34.

Testing

Prior to beginning normal operations, all pressure systems need to undergo testing to ensure their safety, reliability, and leak tightness throughout their service life. The following four types of tests are the most commonly utilized at LANL:

Hydrostatic: Testing with water or other nonhazardous liquid substitute. System is filled with liquid at ambient conditions, all air is expelled from the system, then system is pressurized using a hand or electric pump.

Pneumatic: Testing with gas, usually with air, nitrogen, or other inert substitute. Only use when hydrostatic is not feasible, as the stored energy of a pneumatic test is considerably higher than hydrostatic. Pneumatic testing requires larger personnel exclusion zones or safety barriers to keep workers separated from hazards. The system is pressurized using a compressed gas cylinder or portable air compressor.

Initial Service: Testing at normal operating conditions with system fluid. Restricted to low-hazard systems with nonhazardous fluids.

Sensitive: Exclusive to ASME B31.3. A supplemental test beyond hydrostatic or pneumatic. Sensitive leak tests are good for detecting very small leaks when a low, known leak rate is important – 10^{-3} std mL/sec is the standard acceptable leak rate. Examples of situations where sensitive leak tests may be necessary include systems using toxic fluids or processes like ultra-high vacuum that require a high degree of leak tightness.

Pressure Testing

The primary purpose of pressure testing is to verify the mechanical strength of the pressure system by testing above design pressure for a defined hold time. For hydrostatic tests, this is typically at a minimum of 1.5 x design pressure. For pneumatic tests, this is typically at a minimum of 1.1 x design pressure. Required pressures may vary depending on the ASME B31 piping code being used. Hold time is typically 10 minutes, though some piping codes and situations require longer hold times.

During a pressure test, personnel are at a higher risk because the mechanical strength of the piping assembly has not yet been verified. If a failure is going to occur during testing, it is much more likely during a pressure test than a leak test. All nonessential personnel must be excluded from the area around piping being tested during the pressure test.

Leak Testing

The primary purpose of leak testing is to detect and sometimes quantify unintended leakage that needs to be repaired. Leak testing occurs at or below design pressure. Essential testing personnel are permitted to be around the piping to check for leaks when needed.

When undesirable leaks are found, the system must be **completely depressurized** before making repairs.

Some methods used for leak checking include:

- Visually checking joints for water seepage
- Applying a bubble-forming soap solution (Swagelok Snoop or similar) to all joints being tested
- Using an extended test pressure hold time, checking for pressure decay using a calibrated gauge
- Helium mass spectrometer

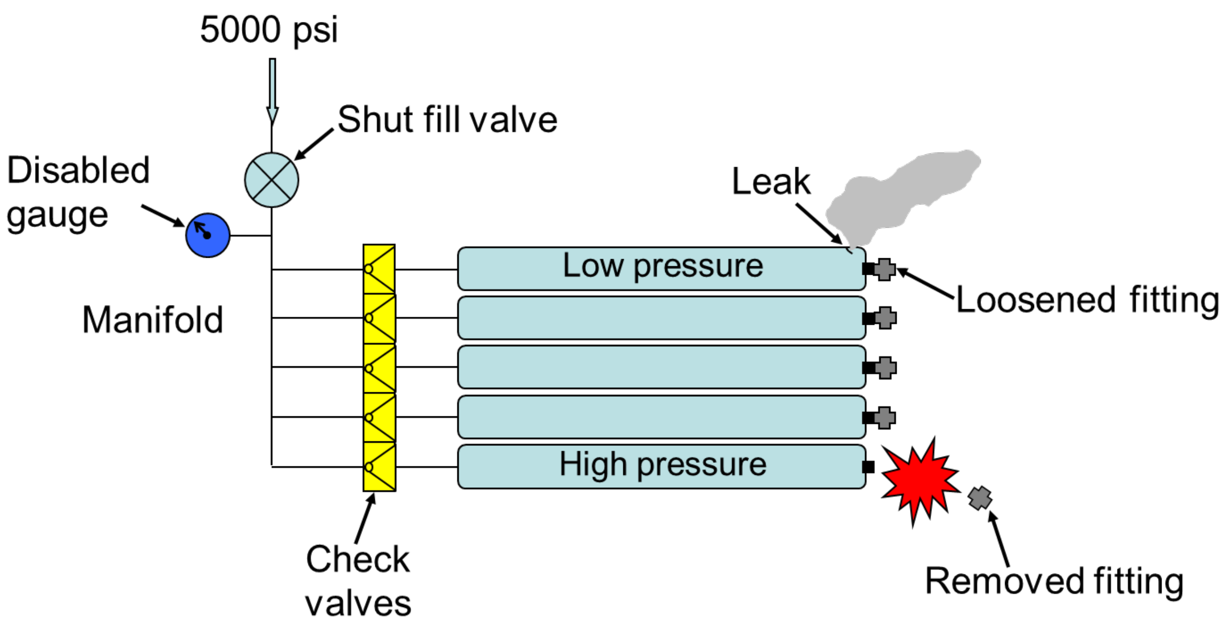
Note: Most ASME B31 piping codes combine pressure and leak testing under the term Leak Testing. Hydrostatic and Pneumatic Leak Testing in those codes starts with a strength test above design pressure, then instructs to reduce to design pressure prior to checking for leaks. B31.5 is the most notable exception to this, as it has separate paragraphs for Pressure Test and Leak Test.

Appendix

A

Lessons Learned

Lessons Learned 1: Hanford Testing Incident



In April 1996, pipe fitters at the Hanford Nuclear Facility were hydrostatically pressure-testing a tubing bundle at 5000psig 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 200psig. In addition, the procedure required a vent valve on the tubing run.

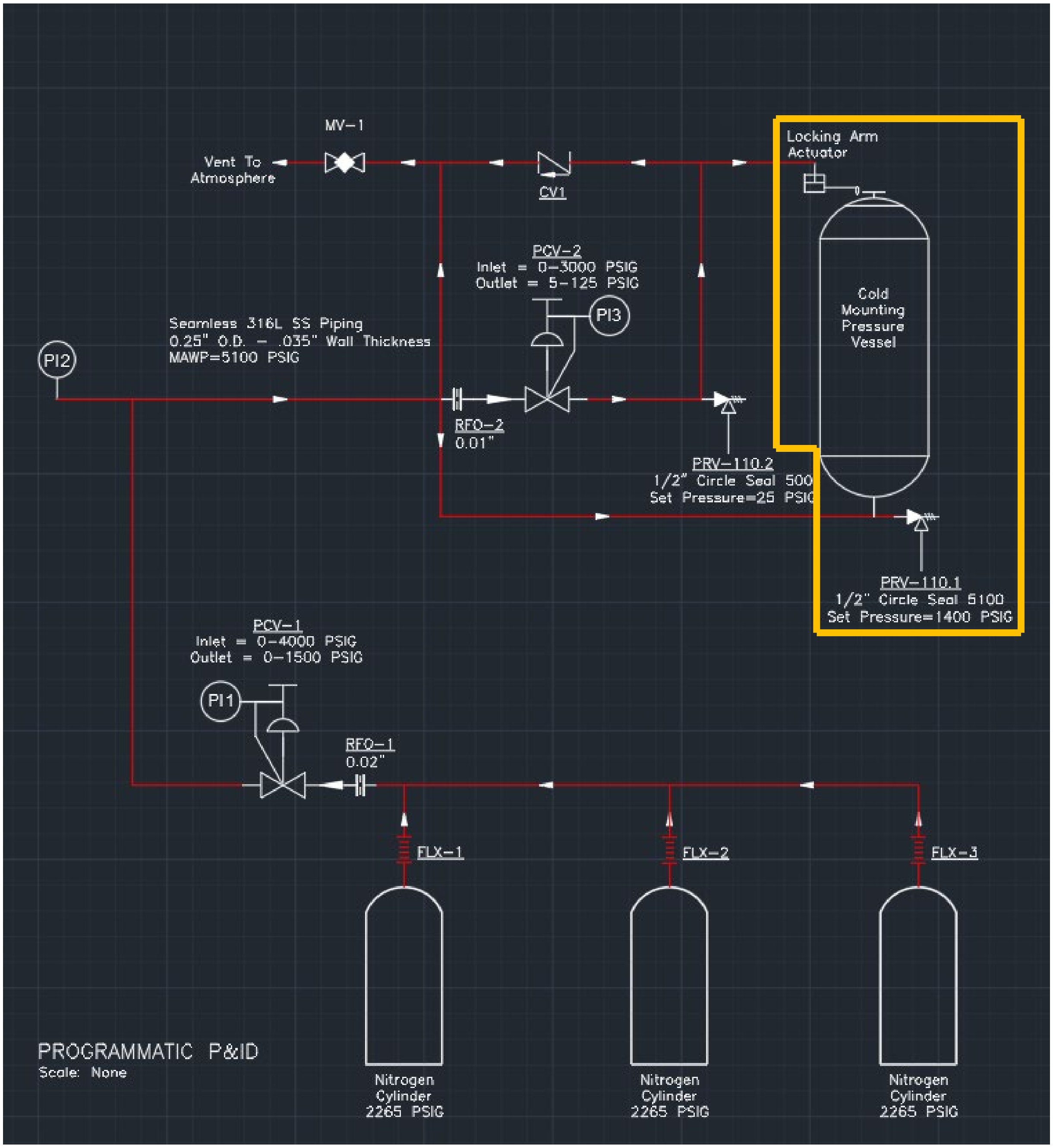
The investigation also determined that the pipe fitters should have recognized that the tubing run was pressurized between the check valves and the end caps. This incident underscores the importance of attention to detail when working with high-pressure systems.

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.

Lessons Learned 2: Pressurized epoxy curing vessel



A pressure system had been in service since 1993 to encapsulate metallographic samples in epoxy. It was an existing system that had been repurposed for a different process. The new process used a pressure vessel supplied with nitrogen gas to force epoxy into cracks, pores, and voids of the samples for better material characterization and evaluation. In 2012, updated pressure relief devices and components with known pressure ratings were installed to bring the system up to pressure safety program standards.

The process involved placing uncured epoxy in mounting cups with the metallographic samples, then placing the cups in a rack that was lowered into the vessel prior to filling the vessel with nitrogen gas at 600-1000psig. While hazards analyses were conducted throughout the system's life as required, the hazard that caused an incident a few years ago was never identified.

After attempting to vent the vessel as normal and retrieve the cured samples, workers were unable to open the quick-acting vessel closure with typical effort. The closure was forced open, violently releasing the vessel's pressure.

What went wrong?

- The vessel was both filled and vented through an opening at the bottom of the vessel.
- No pressure gauges were present on the vessel itself, instead relying on gauges PI1 and PI2.
- The operators were unaware that two mounting cups had spilled epoxy into the bottom of the vessel and later hardened, plugging all means of venting pressure and verifying the vessel's pressure.
- The workers were not aware that the vessel had not been successfully vented of pressure prior to opening the vessel.

Though this operation occurred for about 30 years without incident, it only takes a single unidentified hazardous event occurring to place workers at risk of injury.

What could have been done to avoid this incident?

- Identifying the hazard of epoxy spilling and curing that might block the gas flow path throughout several IWD review cycles. Identifying this hazard would have led to corrective actions that would have prevented the incident.
- Utilizing a vessel that provides a gas flow path at or near top of the vessel. This would also ensure a pressure gauge and overpressure protection can never be isolated from the vessel.

Lessons Learned 3: Leak Testing Failure

In November 2023, construction workers were leak testing a new piping system connecting an existing facility nitrogen gas system to new tube trailers. The test pressure was 2,750psig, which is higher than the most common test pressures of less than 500psig. During the test, a flexible hose that was part of the "test rig" supplying pressure to the system being tested failed. The noise from this failure caused a nearby worker to recoil backward, causing minor injury.

What went wrong?

- Flexible hose was found to be rated to 800psig working pressure and 4,000psig burst pressure.
    - Working pressure rating is the maximum allowable pressure for the end-user.
    - Burst pressure rating is the failure condition of a new hose in laboratory test conditions – i.e., it is a factor of safety that well-made components have. That factor reduces over time, as the product incurs wear-and-tear and degrades.
- Testing personnel failed to follow test plan requirements to use items rated for *working pressures* at or above test pressure.
- "Test rig" setup was not reviewed by a pressure safety Subject Matter Expert (i.e., a PSO). Temporary setups for things like leak testing are pressure systems too.

What went right?

- The flexible hose was secured by externally fastened hose whip restraints, which prevented potential further injury when the hose failed. Flexible hose failing while under pressure, resulting in the hose whipping around, is a *significant* worker safety hazard. Potential injuries of flexible hose failure include bruises, lacerations, fractures, hearing damage, and skin-penetrating fluid injection.

What could have been done to avoid this incident?

- Testing personnel having a better understanding of working pressure rating vs. burst pressure rating.
- Testing personnel taking time to consider additional hazards of a higher leak test pressure of 2,750psig, compared to the <500psig tests they are more familiar with.
- The "test rig" being reviewed by a pressure safety SME prior to its use.

Short VIDEO of a demonstration of hose whip and two means to prevent uncontrolled hose whip. The first example is normal flex hose that is restrained. It still whips, but in a controlled manner that limits potential for injury. Note, the LANL pressure safety program requires external hose restraints when the hose is *both* in service above 150psig AND greater than 12 inches in length. Alternately an "inherently safe" hose like one described below negates the need for external hose restraints.

The second example is a flex hose with internal valves (made by a company called Lifeguard) that immediately stops flow when the hose fails. The hose in the second example is "inherently safe" and does not require the use of external hose restraints. Hazards of Pressure.

References

10 CFR 851. 2006. Worker Safety and Health Program. *Code of Federal Regulations*, U.S. Department of Energy.

ASME Code for Pressure Piping, B31

P101-34 *Pressure Safety*

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