Liquids at Rest

Introduction

Description

The condition identified as Liquids at Rest can also be defined as static condition. These are the generally accepted terms for a condition where water is not flowing. It does not mean that the water is completely quiescent. For example, water in a storage tank is considered to liquid at rest. However, in most instances water is flowing into and out of the tank. While a few other issues will be discussed in this chapter, the majority of the chapter is devoted to the calculation and measurement of pressure and force in a static condition.

Pressure

Description

Pressure is a relationship between the weight of a substance and the height of a column of the substance, atmospheric pressure. Since atmospheric pressure is relatively constant for a specific elevation, it is not included in most calculations. Its impact at various elevations is discussed later in this chapter.

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In genera,l pressure can be expressed as a function of:

P = wh

Where:

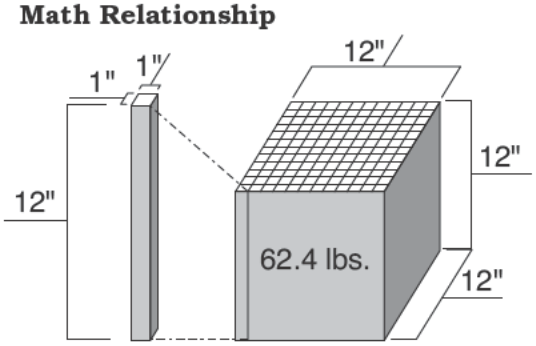
P = Pressure or force per unit of area

w = weight per unit volume of a substance (specific weight)

h = height of the column

Pressure – Head Relationship

Math Relationship



Pressure gauges usually indicate a pressure in pounds per square inch (psi). While this is a useful measurement, in water hydraulics we commonly refer to pressures in feet-of-head or more commonly just head. There is a mathematical relationship between pressure in psi and pressure in feet-of-head. This relationship can be derived from a cubic foot of water. One cubic foot of water has a weight of 62.4 pounds. A cubic foot of water can be divided into 144 columns of water 1 inch square and 1 foot tall.

(1 ft = 12 inches, 12 in x 12 in = 144 in^2)

$$\text{Wt of column} = \frac{62.4 \text{ lbs / ft}^3}{144 \text{ inches}^2/\text{ft}^2} = 0.433 \text{ lbs/in}^2/\text{ft (psi/ft)}$$

Therefore, 1 ft of water = 0.433 psi.

Weight of 1 in^2 of Water

The weight of a one-square inch column of water one foot high is 0.433 lbs.

Feet to Pressure

Another relationship often used is 2.31 feet of water equals 1 psi. This relationship is derived from the one above as follows:

$$\frac{1 \text{ psi}}{0.433 \frac{\text{psi}}{\text{ft}}} = 2.31 \text{ ft}$$

Therefore 2.31 feet of water equals 1 psi of pressure and the conversions are written as:

$$0.433 \ {}^{\text{psi}}/_{\text{ft}} \text{ and } 2.31 \ {}^{\text{ft}}/_{\text{psi}}$$

Application

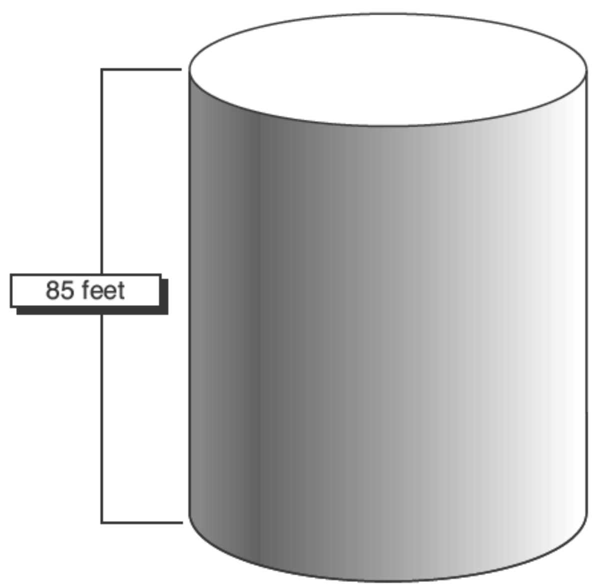
Example psi to feet

The pressure reading at the discharge of a pump is 85 psi. How many feet of head does this represent?

$$\frac{85 \text{ psi}}{0.433 \ {}^{\text{psi}}/_{\text{ft}}} = 196.3 \text{ ft}$$

Example feet to psi

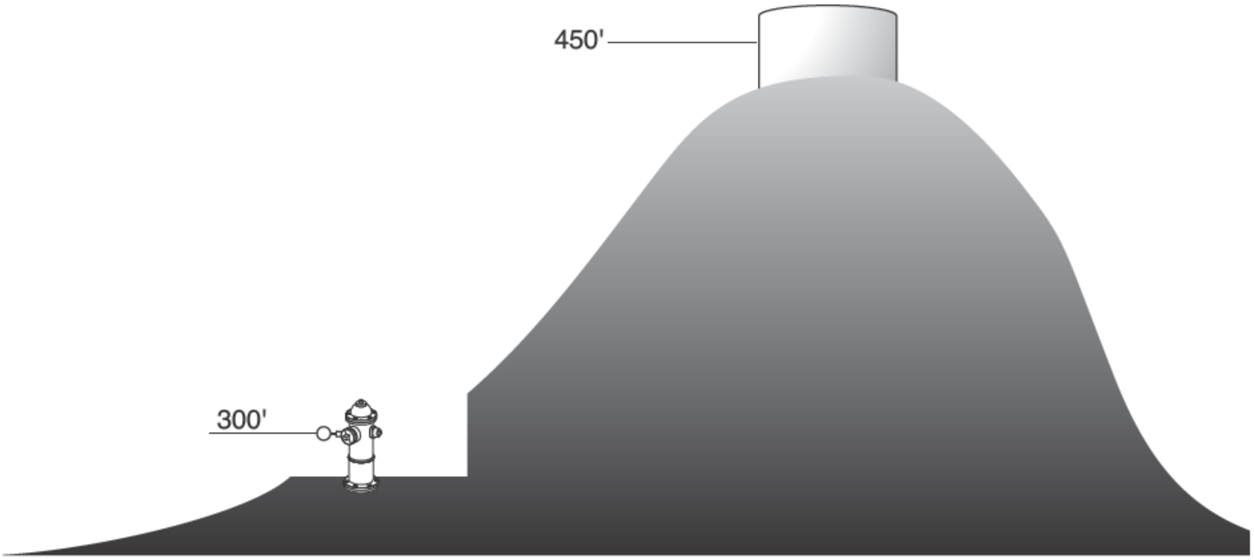
A reservoir is 85 feet tall. What is the pressure in psi at the bottom of the reservoir (assuming that the reservoir is full of water)?



85 ft X 0.433 psi/ft = 36.8 psi

Elevation to Pressure

A distribution system storage tank is located on top of a hill. The elevation at the top of the water in the tank is 450 feet. A fire hydrant on this same distribution system is located at an elevation of 300 feet. What would be the expected pressure, under a static condition, at the fire hydrant?



The difference in the elevations is;

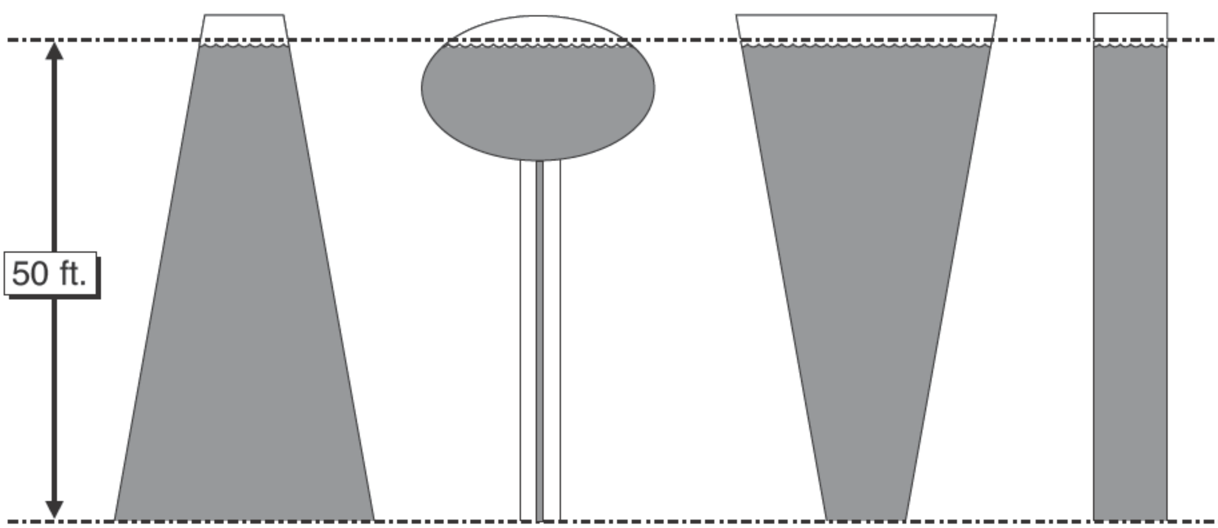
450 ft – 300 ft = 150 ft

Convert the feet of head to pressure in psi.

150 ft X 0.433 psi/ft = 65 psi

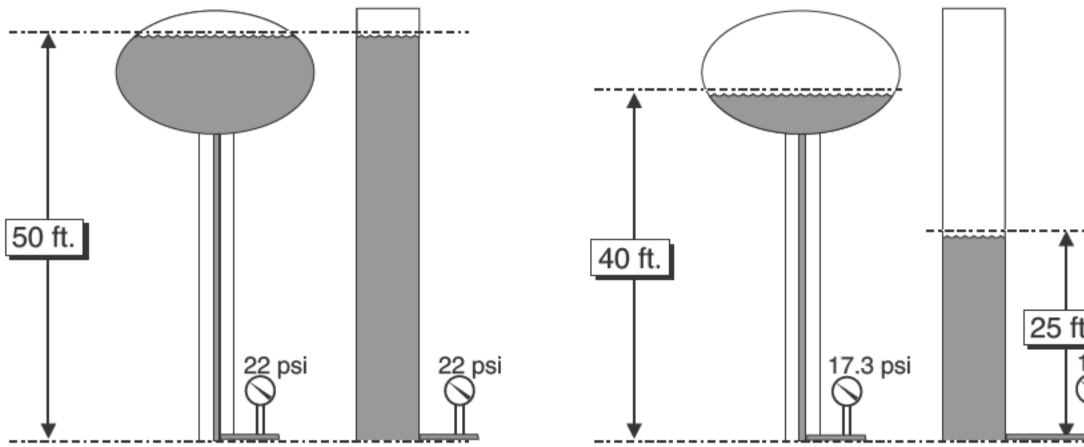
Container Shape or Volume

Pressure Relative to Container Shape The pressure at the bottom of a container is only affected by the height of water in the container and not by the shape of the container. In the drawing below there are four containers, all of different shapes and sizes. The pressure at the bottom of each is the same.



Pressure and Volume

The pressure exerted at the bottom of a tank is relative only to the head on the tank and not the volume of water in the tank. For example, below are two tanks, each containing 5,000 gallons of water. The pressure at the bottom of each is 22 psi. If half of the water were drained from the tanks, the pressure at the bottom of the elevated tank would be 17.3 psi while the pressure at the bottom of the standpipe would be 11 psi.



Depth of Water in a Well

Bubbler Tube

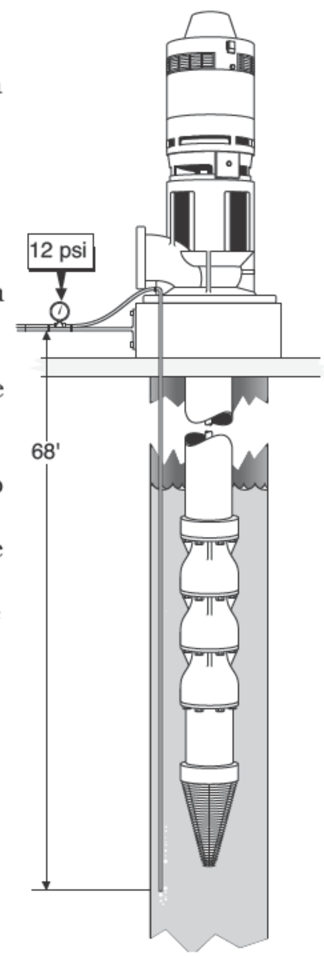
One method of measuring water levels in a well is with a bubbler tube system. The bubbler tube system requires some interpolation and calculations to obtain a reading.

Equipment

A typical bubbler tube system usually consists of a 5/16 inch or 1/4 inch plastic, copper, or stainless steel tube inserted inside the well casing ending below the water level to below the pump intake. Attached to the top of the tube are a pressure gauge and a connection for an air supply. The air supply can be a continuous pump or a bicycle pump.

Process

The process used is to pump air into the bubbler tube, forcing water out. Observe the gauge; when it stops rising, the pressure is read. This pressure is then converted into feet. The value



obtained is the depth of water above the end of the bubbler tube. In order to determine the distance from the top of the well to the water level, the length of the bubbler tube must be known and the calculated depth of water above the end of the tube is then subtracted from the length of the tube.

Application

A 68 foot long bubbler tube is inserted into a well. The back pressure as a result of air being pumped into the bubbler tube stabilized at 12 psi.

The first step is to determine the height of the water above the end of the bubbler tube.

$$\text{Height of water} = \frac{12\,\text{psi}}{0.433\,\text{psi/ft}} = 27.7\,\text{feet}$$

The top of the water in the well is 27.7 feet above the end of the bubbler tube.

Subtract this distance from the length of the bubbler tube to find out the distance from near the top of the well to the top of the water.

68 ft – 27.7 ft = 40.3 ft

Summary of Terms

Liquids are rest are said to be in a static or non-flowing condition. Pressures readings taken in a static condition are called static pressure and expressed as psi or feet of static head.

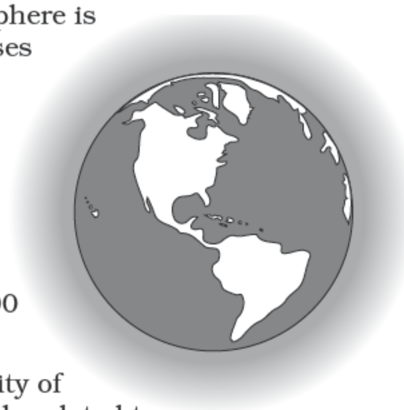
Energy Consideration

The difference in elevation between two water surfaces is typically expressed as feet of head. This difference in head is considered to be a potential energy source. This is the energy available to cause the water to flow between the two elevations.

Atmospheric Pressure

Composition of Air Mass

The earth is surrounded by a mass of air called its atmosphere. The atmosphere is composed of various gases including oxygen, hydrogen, nitrogen and carbon dioxide. The atmosphere is held to the earth by the earth's gravity. Ninety nine percent of the atmosphere is within 100 miles of the earth.

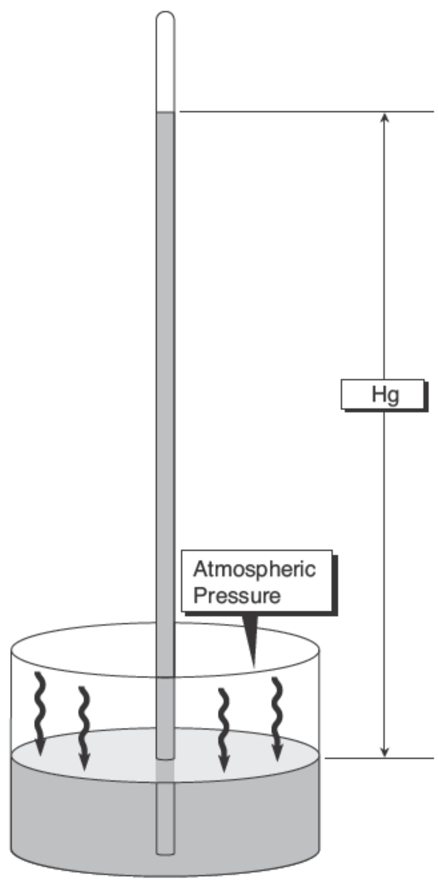


Impact of Gravity

The thickness and density of the atmosphere is directly related to the pull of gravity. Gravity's ability to attract an object is reduced it is moved further away from the earth. This gravitational attraction is reduced to near zero at a point just beyond the atmosphere. Thus the density of the atmosphere is greatest at the surface of the earth and zero at the outer edge of the atmosphere. If the atmosphere is composed of various gases that have a mass, is should be possible to measure the weight of these gases.

An Experiment

If a small diameter glass tube three feet in length were filled with mercury and then inverted into a beaker of mercury. The mercury in the tube would fall and then stop and remain at a specific height. The height of the mercury in the tube is directly relative to the weight of the atmospheric pressure on the surface of the mercury in the beaker. That is, the weight of the column of mercury is equal to the weight of the atmosphere on the surface of the mercury in the beaker.



Elevation and Atmosphere

This can be verified by moving the beaker and column of mercury to a higher elevation. As the elevation is increased, the height of the atmosphere above the beaker is reduced, thus reducing the height of the column of mercury.

Height of Column

While mercury is used in this example, other fluids can be used. The height of the column of any liquid can be calculated using the following formula:

$h = pa/W$

Where:

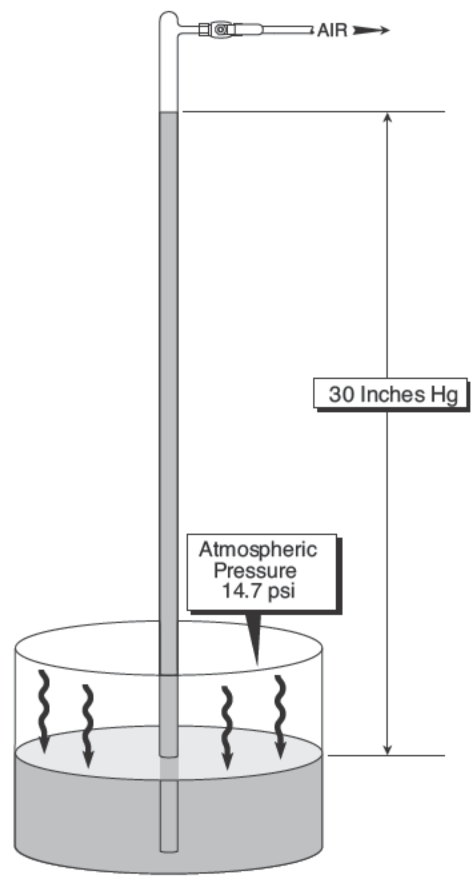
h = height of the liquid in the column

pa = Atmospheric pressure

W = specific weight of the fluid (The units of the specific weight will determine the units of the height of the liquid in the column. For example, if the units are lbs/ft^3 then the height will be in feet.

Weight of the Atmosphere

At sea level, and on a clear sunny day the column of mercury in the beaker would be 30 inches tall. A device that measures the weight of the atmosphere is called a barometer. The barometric pressure at any elevation will change based on atmospheric conditions. During a storm the barometric pressure will drop and it will rise again in clear weather.



Comparison to Water

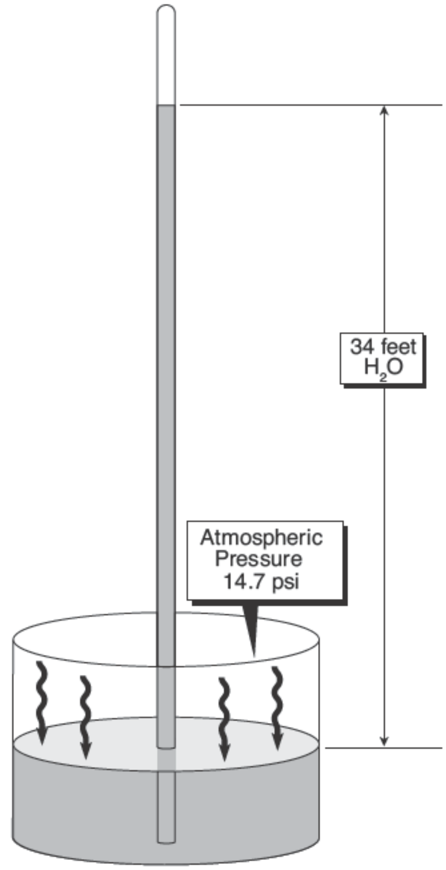
Mercury has a specific gravity of 13.6. If a barometer were made with water rather than mercury, the water column would be:

30 inches of Hg X 13.6 = 408 inches or 34 feet

While this would be more accurate in measuring small changes in barometric pressure, it would be unreasonable to use a barometer that was 34 feet tall.

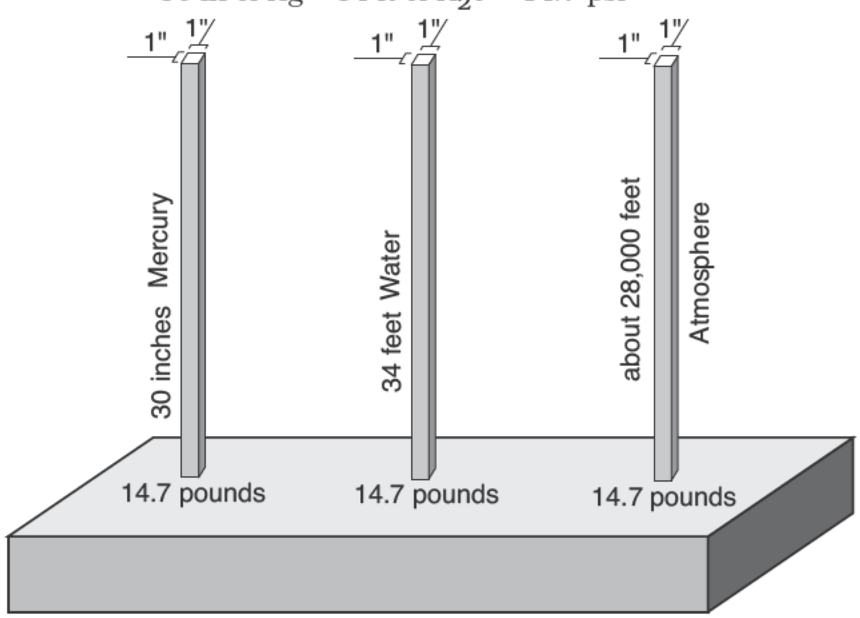
Based on the conversion of feet of head to pressure we can determine the pressure in psi of the atmosphere.

34 ft X 0.433 psi/ft = 14.7 psi



Therefore, the weight of a column of atmosphere is 14.7 psi which is equivalent to a column of water approximately 34 feet tall.

30 in of Hg = 34 ft of H_20 = 14.7 psi



Atmosphere and Elevation

The greater the elevation the less the weight of the atmosphere. The table below shows various atmospheric pressures and corresponding heads at different elevations.

Variations in Atmospheric Pressure with Altitude

Altitude Above sea level (ft)	Pressure (psi)	Head (feet)
- 0 -	14.7	33.9
1,000	14.2	32.8
2,000	13.7	31.6
3,000	13.2	30.5
4,000	12.7	29.3
5,000	12.2	28.2
5,280	12.1	27.9
6,000	11.8	27.3
7,000	11.3	26.1
8,000	10.9	25.2
9,000	10.5	24.2
10,000	10.1	23.3

Types of Pressure Readings

Absolute Pressure

Absolute pressure is a pressure that includes atmospheric pressure. A measurement of absolute pressure is written as psia (pounds per square inch absolute).

Gauge Pressure

The pressure reading taken with a standard pressure gauge does not include the pressure from the atmosphere and is written as psig (pounds per square inch gauge). Since the vast majority of pressure readings are psig it is normally written as just psi, and is assumed to be psig.

Vacuum

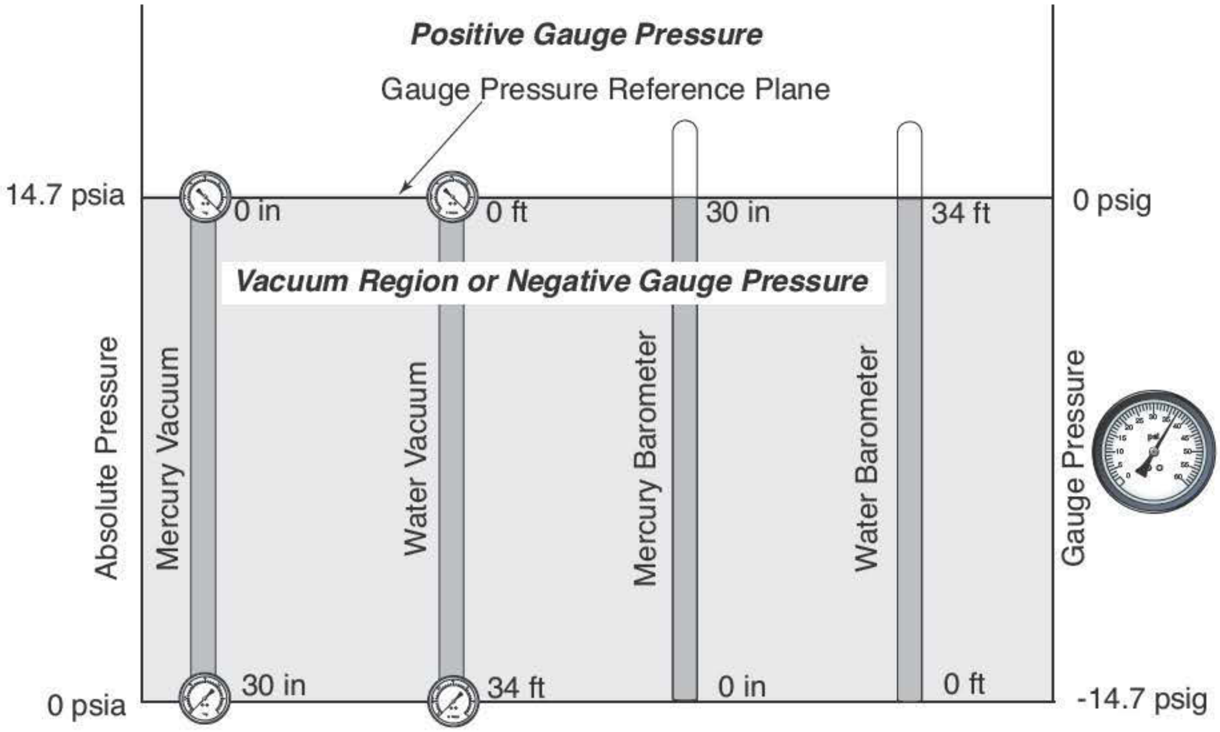
Any gauge pressure of less than zero is considered to be a vacuum. While a vacuum is actually a negative gauge pressure, it is typically measured as inches of mercury. To better understand how the units of vacuum compare with units of pressure, utilize the drawing on the next page.

Gauge Pressure at Zero

At zero gauge pressure the absolute pressure would be the atmospheric pressure. If the atmospheric pressure is 14.7 psi, the mercury barometer would be at 30 inches, a water barometer would be at 34 feet, absolute pressure would be 14.7 psi, gauge pressure would be zero, and water or mercury vacuum would be zero.

Absolute Pressure at Zero

At zero absolute pressure, the gauge pressure would be -14.7 psig, the mercury vacuum would be 30 inches, water vacuum 34 feet, and the mercury and water barometers would both be at zero.



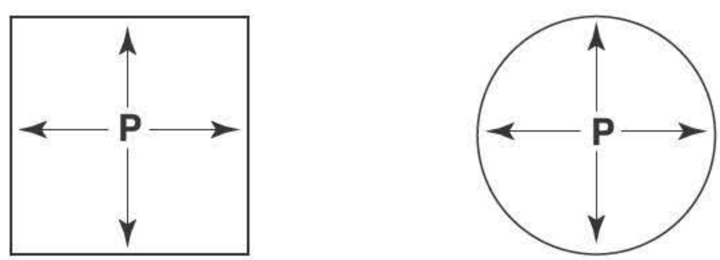
Pascal's Law

Three Rules

Pascal's Law (as it applies to liquids) provides three rules that assist in the understanding of how liquids respond to pressure. The three rules are:

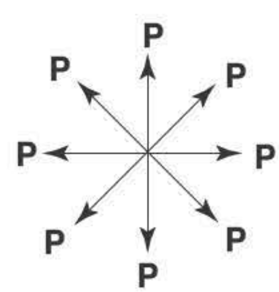
Rule #1

Pressure in a container is exerted on the walls of the container at right angles to the walls.



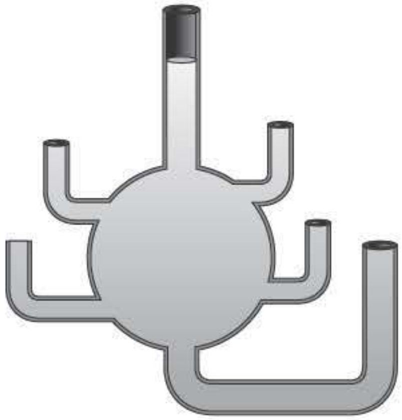
Rule #2

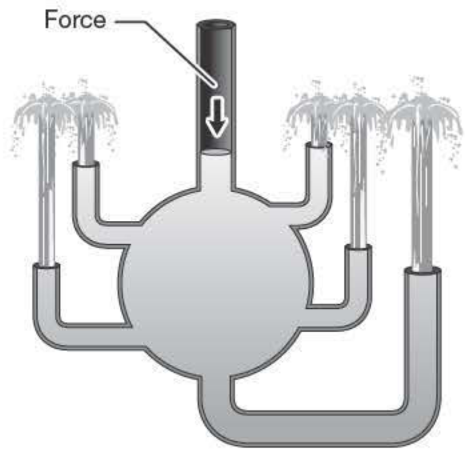
Pressure at any give point in a liquid at rest is the same in all directions. (If this were not true the liquid would be in motion.)



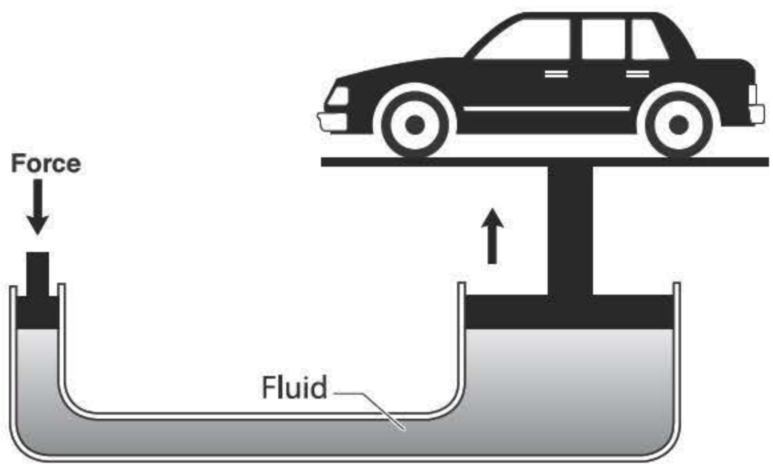
Rule #3

The most stated rule is: When there is an increase in pressure at any point in a confined liquid, there is an equal increase in pressure at all points in the container. Another way to say this is: when an external force is applied to a liquid at rest, the force is distributed equally in all directions.





This is the principle that allows a hydraulic hoist to function.



Pressure Measurements

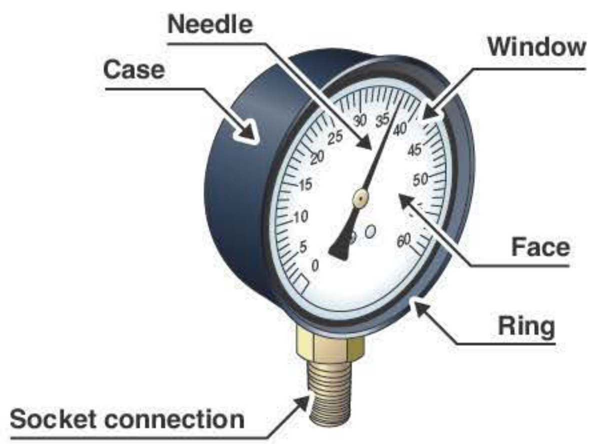
Pressure Measurement Devices

Pressure measurements are made with manometers, solid-state pressure transducers and gauges. While manometers and transducers are used in the water and wastewater industry Bourdon tube-type gauges are the most common and thus will be the device discussed in this text

Pressure Gauges

About Gauges

Gauges are relatively simple mechanical devices made up of a number of specific components. Below is a brief discussion of the key components of a pressure gauge.



Socket Connection

The socket connection is commonly a brass 1/8" or 1/4" NPT. Stainless steel connections can be special ordered.

Case

As noted above, the outside of the gauge is called the case. This is typically made of stainless steel, painted steel, aluminum, or ABS plastic. The case surrounds and protects the gauge working components.

Face

The painted surface displaying the numbers is called the face.

Needle

The needle is the device that moves and indicates the pressure.

Ring

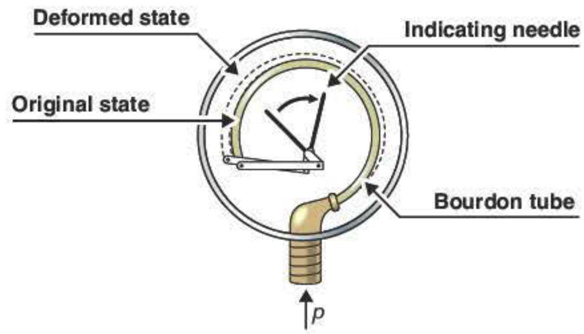
A ring is used to hold the window in place and protect the gauge face. The ring is typically made of the same material as the gauge case.

Window

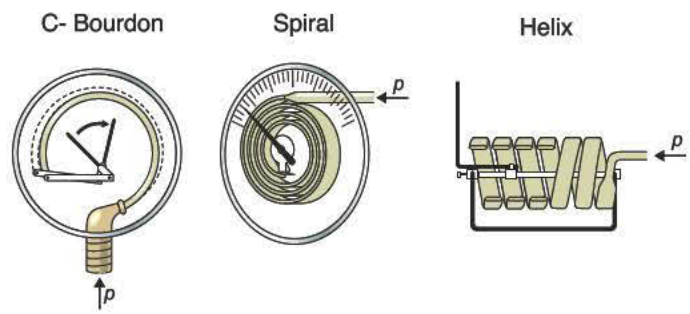
The window can be made of glass, acrylic, or polycarbonate. In recent years, polycarbonate has become the most common. It is strong, resists breakage, resists scratching, and does not fog easily.

Bourdon Tube

The key operating component of a pressure gauge is the Bourdon tube. The Bourdon tube is a hollow metallic tube sealed on one end. It is formed into a "C" helical, or spiral. When pressure is applied to the inside of the tube it attempts to straighten. This straightening movement is transferred through a set of gears to the pointer.



Dry gauges usually use the "C" shaped Bourdon tube. Liquid filled gauges usually use the helical or spiral Bourdon tube.

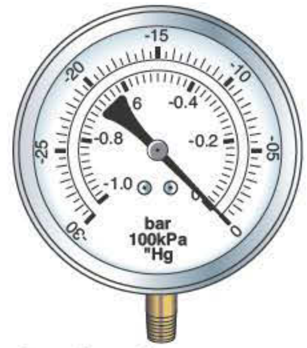


Commercial Gauge Types

The vast majority of gauges used in the water and wastewater industry are classified as commercial gauges. There are three common commercial gauge types:

- Pressure - Usually read left to right. Units of psi are most common.

- Vacuum - The vacuum gauge reads from right to left (counter clockwise). With the example below there are two scales - 0 to 30 inches of mercury (Hg) and zero to -1.0 Bar or kPa (kilopascales). Bar and kilopascales are the metric equivalent to inches of mercury vacuum.



- Altitude - The altitude gauge is typically a dual scale gauge showing pressure in psi and in equivalent feet of water. They are used to estimate the level of water in a tank or the depth of water in a well.

How a Bourdon Tube Gauge Works

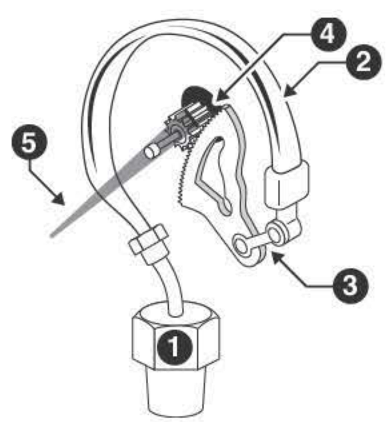
General Description

Gauges using a "C" shaped Bourdon tube are designed for clean, non-clogging liquids and gases. The following is a step-by-step description of how a "C" shaped Bourdon tube gauge works.

Step by Step

1. Inlet

Fluid enters through the inlet (#1) of the gauge and into the Bourdon Tube (#2).



2. Bourdon Tube

The Bourdon tube is a hollow metallic tube sealed at one end, and compressed and bent into an arc. As fluid enters the Bourdon tube, it causes the tube to flex as it attempts to regain its natural shape. Essentially, the arc tries to straighten itself out but cannot because it is secured (#3) to the geared movement.

3. Linkage

As the Bourdon tube moves, the linkage engages the gears (#4).

4. Gearing

Precision built gears control the movement of the pointer (#5). Finer increments or higher accuracy gauges require more complicated gearing than used by "standard gauges."

5. Pointer

The pointer moves with the gearing to indicate the operating pressure within the accuracy rating of the gauge.

How to Read a Pressure Gauge

Determine Function

The first step in accurately reading a gauge is to determine its function. A pressure gauge is read from left to right. A vacuum gauge is read from right to left. Gauges that provide dual readings such as pressure and feet read from left to right.

Two Components of the Face

In order to accurately read a pressure or vacuum gauge there are three elements of the face that must be known.

- Units being measured (psi, feet, bars, etc)
- The figure intervals
- The number of graduation marks

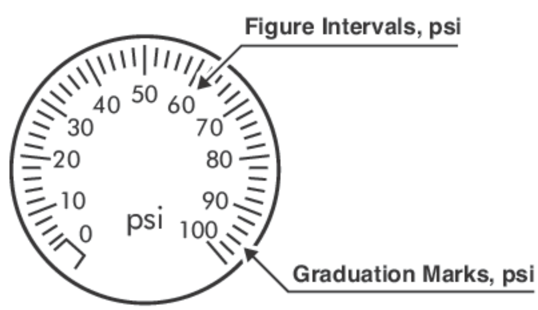


Figure Intervals

Figure intervals refer to the value between numbers on the dial face. Typical value differences are 1, 10, 25, and 100. The most common is 10. The dial face above has a figure interval of 10. That is, it is 10 psi between each number.

Graduation Marks

Graduation marks are the hash marks between the figure intervals. Typical graduation marks are 1, 2, and 5. Before reading a gauge it is critical to determine the number of hash marks between figures and thus the value of each hash mark. For example, the gauge shown above has 4 hash marks between each figure. The 4 hash marks divide the interval into 5 spaces. Since the figure interval is 10 psi and there are five spaces, each space is equivalent to 2 psi (10 ÷5 = 2). This means you'll find a figure (number) every 10 psi and hash marks at every 2 psi on the dial face.

Examples

Example #1

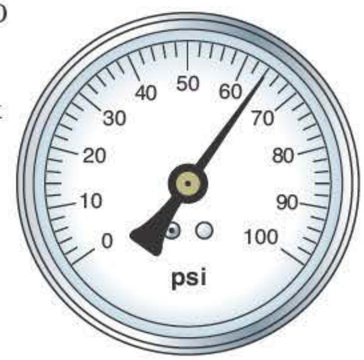
The figure intervals are 5 psi. There are 4 hash marks between intervals and thus each hash mark represents 1 psi. The gauge is reading 37 psi.

Example #2

The figure intervals are 5 inches Hg. There are 9 hash marks between intervals and thus each hash mark represents 0.5 inches Hg. The gauge is reading -16 inches of Hg or -0.52 bar or kPa.

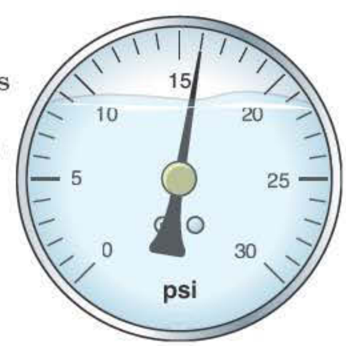
Example #3

The figure intervals are 10 psi. There are 4 hash marks between intervals and thus each hash mark represents 2 psi. The gauge is reading 64 psi.



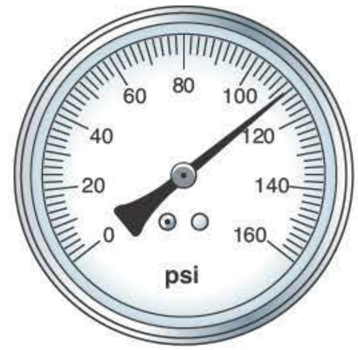
Example #4

The figure intervals are 5 psi. There are 4 hash marks between intervals and thus each hash mark represents 1 psi. The gauge is reading 16 psi.



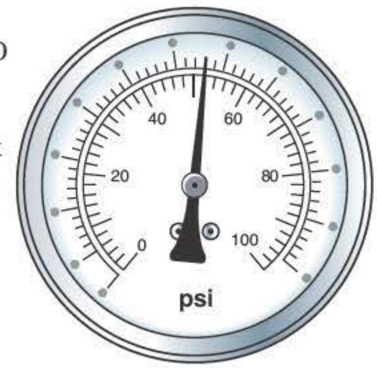
Example #5

The figure intervals are 20 psi. There are 9 hash marks between intervals and thus each hash mark represents 2 psi. The gauge is reading 112 psi.



Example #6

The figure intervals are 20 psi. There are 9 hash marks between intervals and thus each hash mark represents 2 psi. The gauge is reading 52 psi.



Fluids at Rest — Pressure Problems

1. Convert 75 psig to:
   a. Inches of Hg
   b. Feet of water
2. A deep sea diver is at 250 feet below the ocean surface. What is the pressure on the diver in psig?
3. What is the absolute pressure in psia for 12 inches of Hg vacuum?
4. Convert 8 inches of Hg vacuum to gauge pressure.
5. The gauge pressure at the bottom of tall round concert storage tank is 26 psi. A second pressure gauge is located near one of the access ladder landings and reads 14 psi. What is the difference in elevation in feet between the two gauges?
6. A storage tank for a small community is located so that when it is full the surface of the water is at an elevation of 385 feet. What static pressure could be expected at the discharge nozzle of a fire hydrant that is located at an elevation of 210 feet?
7. A 234 foot long, ¼ inch stainless steel sounding tube has been installed in a well. Air is being pumped through this tube with a hand pump. A pressure gauge is installed at the top of the well and reads 42 psi. What is the distance from the top of the well to the top of the water in the well?
8. A mercury barometer reads 26.32 inches.
   a. This corresponds to what equivalent height in a water barometer?
   b. What is the atmospheric pressure in psia?
   c. What is the atmospheric pressure in psig?
9. A storage tank for a small distribution system contains 20 feet of water.
   a. What is the pressure at the bottom of the tank in psig?
   b. What is the pressure at the bottom of the tank in lbs/ft^2?
   c. What is the pressure at the bottom of the tank in psia?
10. The normal low pressure observed in the water distribution system is 72 psi. The minimum allowable pressure at any fixture in this system is 30 psi. How tall a building could be constructed and meet this minimum static pressure requirement?
11. The gauge on the suction side of an end-suction centrifugal pump reads 10 inches of Hg.
   a. What is the suction head in feet of water?
   b. What is the absolute pressure at the eye of the impeller when the barometer reads 28.4 inches of Hg?

Fluids at Rest — Answers to Pressure Problems

1. a. 152.9 inches or 183 in absolute
   b. 173.25 ft or 207 ft absolute

2. 108.3 psi

3. 8.82 psia

4. - 3.92 psig

5. 27.71 feet

6. 75.8 psig

7. 137 ft

8. a. 29.83 ft
   b. 12.90 psia
   c. -1.8 psig

9. a. 8.66 psig
   b. 1,247 lb/ft^2
   c. 23.36 psia

10. 97,0 ft

11. a. 11.3 ft
    b. 13.916 psia

Force Exerted by Liquids

Force in a Container

Liquid in a container results in a force on the floor and inside walls of the container. The total force on any inside surface of the container (floor or walls) is equal to the average pressure on the surface times the area of the surface.

Units

In the English system this force is expressed in pounds. In order to easily calculate total force, the pressure units should be in pounds per square feet or pounds per square inch, depending on the units used to calculate the area (feet or inches). The formula for calculating the force on the walls or floor of a container is:

$F = P_{avg} \text{ X } A$

Where

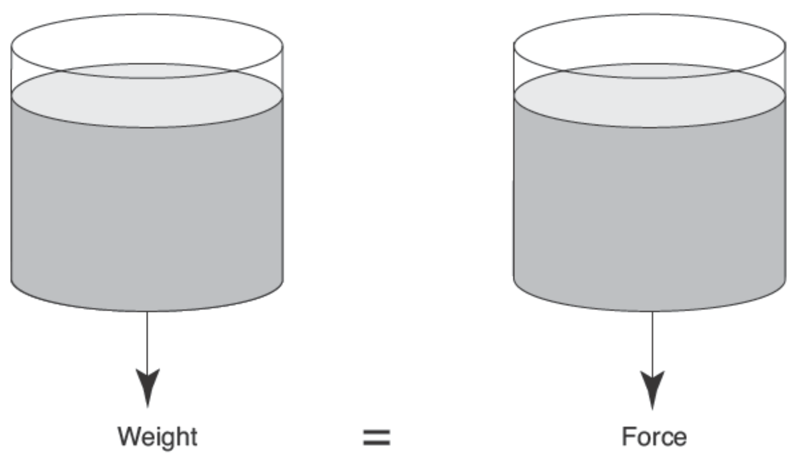
F = Force in pounds

P_{avg} = Average pressure (in lbs/ft^2 or lbs/in^2). The average pressure is computed from Pressure = weight x height. For water the weight is either 62.4 lbs/ft^2 or 0.433 lbs/in^2. In each case this is the weight of one foot of water and is also called the specific weight of water.

A = Area in ft^2 or in^2

Force & Weight

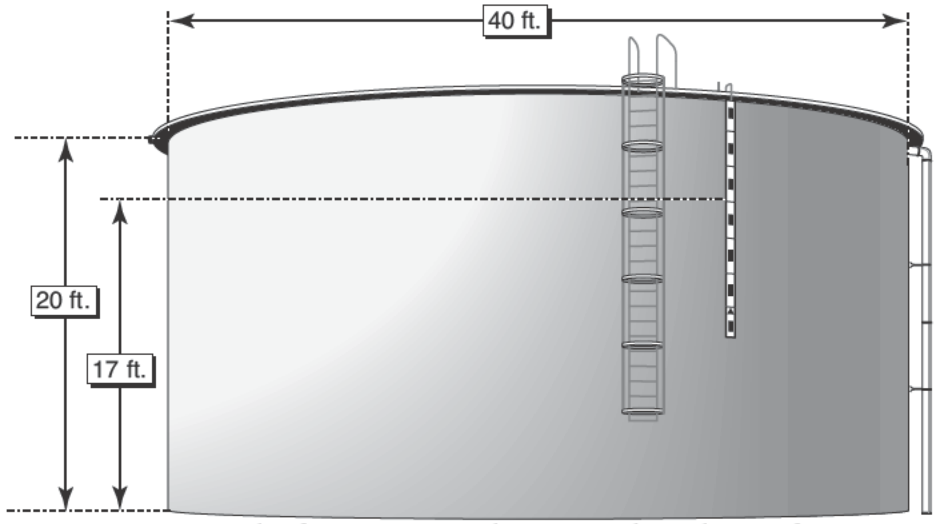
If the bottom of a container is flat, then the force on the bottom of the container is equal to the weight of the liquid in the container.



Force & Weight Application

Storage Tank

A storage tank is 40 feet in diameter and 20 feet tall. The water level in the tank is 17 feet. Determine the force on the bottom of the tank.



Volume of Water

The first step is to determine the volume of water in the tank.

$V = A\ h$

Where:

V = Volume in cubic feet

A = Area of the bottom of the tank in square feet (area of a circle is πr^2)

h = height of the water

$V = \pi (20ft)^2 \text{ X } 17\ ft$

$V = 21{,}363\ ft^3$

Weight of the Water

The force is calculated by multiplying the volume in cubic feet times the weight of a cubic foot of water.

$21{,}363\ ft^3 \text{ X } 62.4\ lbs/ft^3 = 1{,}333{,}041\ lbs$

Force on the Bottom of the Tank

The force can also be calculated based on the pressure. The pressure exerted by one foot of water is 0.433 psi/in^2 or 62.4 lbs/ft^2. By multiplying the pressure per square foot by the depth the total pressure on one square foot can be calculated as:

$F = P_{avg} \text{ X } A$

$P_{avg} = 62.4\ lbs/ft^3 \text{ X } 17\ ft = 1{,}061\ lbs/ft^2$

The pressure per square foot is then multiplied times to total area.

$F = 1{,}061\ lbs/ft^2 \text{ X } \pi (20ft)^2 = 1{,}333{,}292\ lbs$

Summary

Note that the weight of the water is equal to the force the water places on the floor of the tank.

Horizontal Force

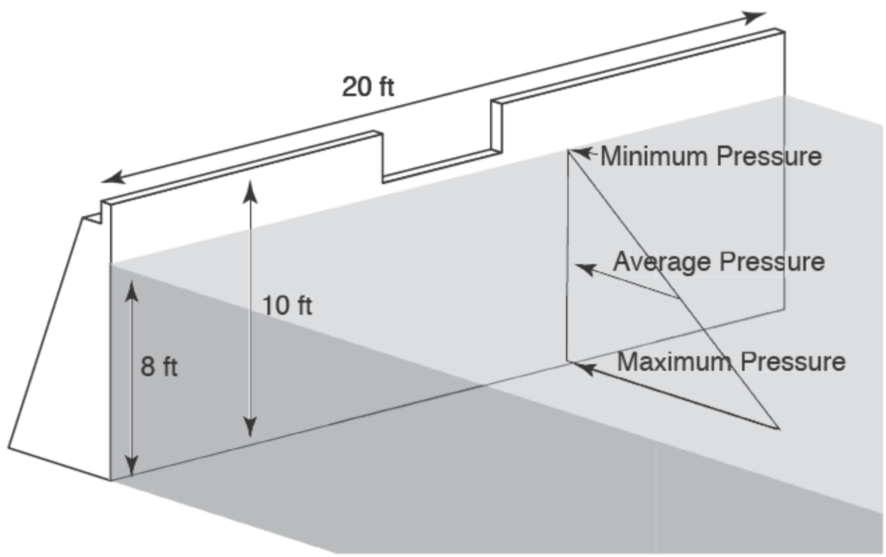
Average Pressure

The force applied to a horizontal surface such as the wall of a tank, is the average pressure between the top and bottom of the water that is against the wall of the tank. The average pressure on the wall of a tank would be equal to the pressure at one-half of the distance between the top and the bottom of the water.

Application

Force Behind a Dam

The force on a gravity dam that is 10 feet tall and 20 feet in length restraining 8 feet of water can be determined by using the force equation: $F = P_{avg} \times A$.



The average pressure is the pressure one-half the depth or 4 feet.

$P_{avg} = 62.4 \text{ lbs/ft}^3 \times 4 \text{ ft} = 249.6 \text{ lbs/ft}^2$

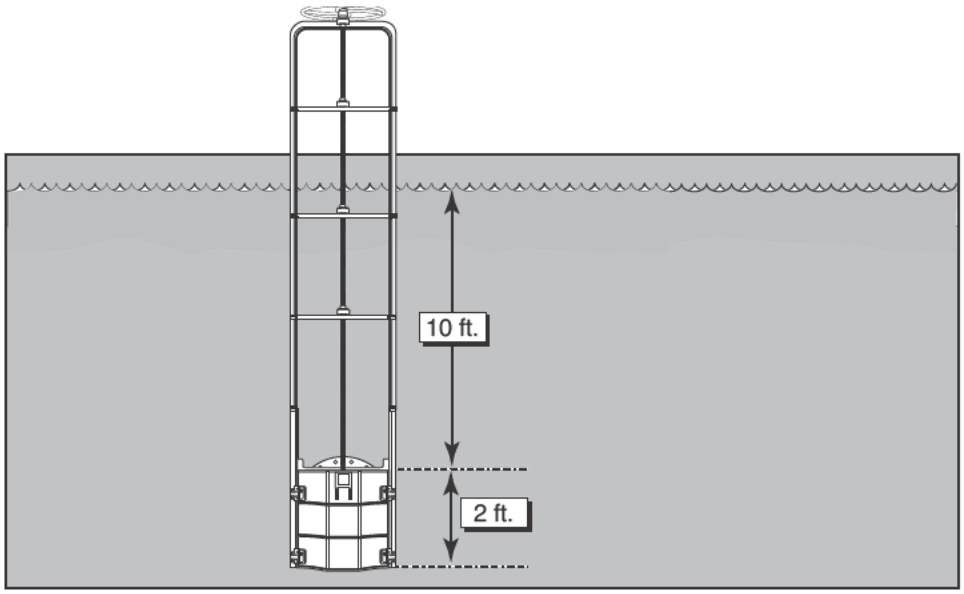
$F = P_{avg} \times A$

$F = 249.6 \text{ lbs/ft}^2 \times 8 \text{ ft} \times 20 \text{ ft} = 39{,}936 \text{ lbs}$

Force on Shear Gate

A two foot square shear gate is located on the backside of a small dam. The top of the shear gate is 10 feet below the water surface.

The average pressure is the pressure at the center of the shear gate, which is 11 feet below the surface of the water. The pressure at 11 feet is:



P_{avg} = 62.4 lbs/ft^3 X 11 ft = 686.4 lbs/ft^2

The force on the shear gate is calculated using the force equation F = P_{avg} X A

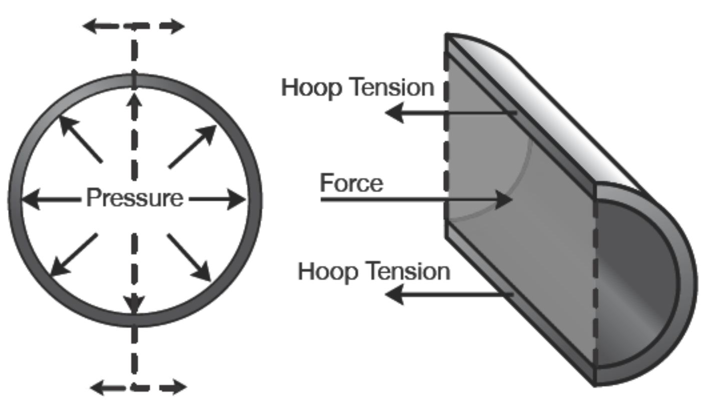
F = P_{avg} X A

F = 686.4 lbs/ft^2 X 2 ft X 2 ft = 2,745.6 lbs

Hoop Tension in Pipes and Tanks

Description

Hoop tension is the force on the walls of a pipe or tank that tends to pull the wall apart. The force is the result of the internal pressure. Hoop tension is determined for each inch of pipe length or inch of tank height, and is calculated using this formula:



$$T = \frac{PD}{2}$$

Where:

T = Hoop Tension in lbs/in

P = Pressure in psi

D = Diameter of pipe or tank in inches

Water Hammer

The pressure inside of a storage tank is primarily static, thus the wall thickness required to prevent failure is based on the static force when the tank is full. However, the walls of a pipe must be able to withstand the internal static force plus the force that results from water hammer. The AWWA Standards for a specific pipe material designates the allowance that must be given for water hammer. When calculating the hoop tension on a pipe the pressure (P) is the internal working pressure plus an allowance for water hammer.

Tensile Stress

The stress on the pipe or tank material caused by the hoop tension is called Tensile Stress and is the force applied per unit of area (pounds per square inch – psi) on the pipe or tank material. Tensile Stress is calculated using this formula.

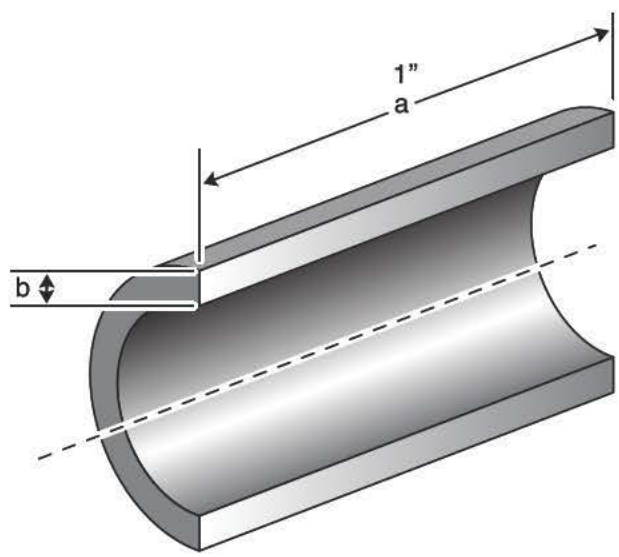
$$f = \frac{T}{A}$$

Where:

f = Tensile Stress in psi per inch of length

T = Hoop tension in Lbs/in

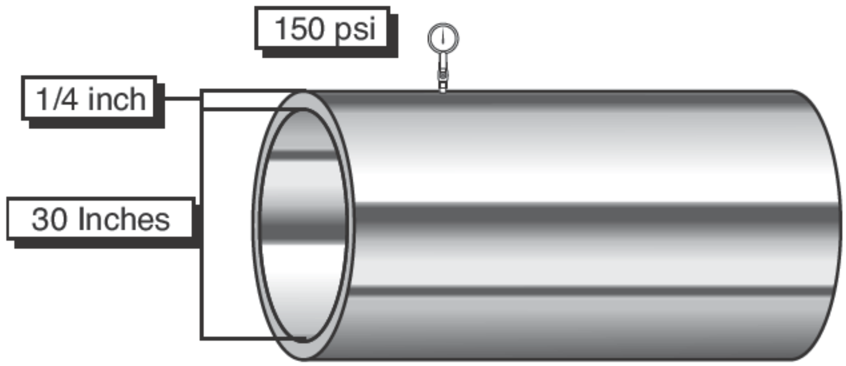
A = Cross-sectional area of the wall of the pipe or tank material in square inches, for each inch of wall length or tank height. (a x b = A)



Hoop Tension Application

Data

Determine the tensile stress on a 30-inch diameter pipe that has an internal working pressure of 150 psi. An allowance of an additional 100 psi is required for water hammer. The wall thickness of the pipe is 0.25 inches.



Hoop Tension

The hoop tension is:

$$T = \frac{PD}{2} = \frac{(\text{Internal Pressure} + \text{Water Hammer}) \text{ X } D}{2}$$

$$T = \frac{(150 \text{ psi} + 100 \text{ psi}) \text{ X } 30 \text{ in}}{2}$$

$$T = \frac{250 \text{ lbs/in}^2 \text{ X } 30 \text{ in}}{2} = 3{,}750 \text{ lbs/in}$$

Tensile Stress

The tensile stress is:

$$f = \frac{T}{A} = \frac{3{,}750 \text{ lbs/in}}{0.25 \text{ in X } 1 \text{ in}} = 15{,}000 \text{ lbs/in}^2 \text{ per inch of length}$$

Will the Pipe Burst?

To determine if the pipe will burst under this condition, the Tensile Stress must be compared with the Tensile Strength of the pipe as determined by either testing or the manufacturer's data. While this is a nice academic exercise and worthwhile for an operator to understand, it is a basic engineering function and is used, typically with tables, to determine the class of pipe selected for a specific situation.

Transmitting Force

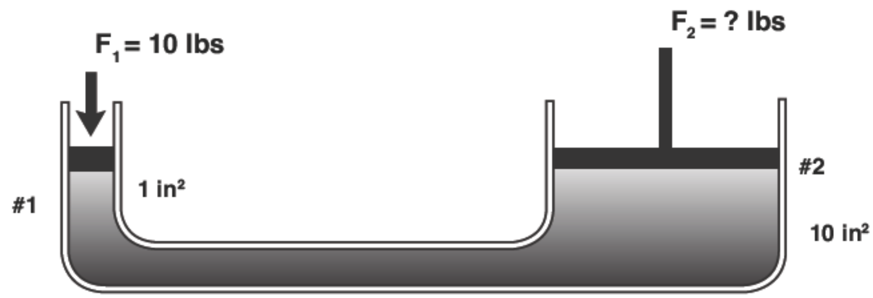
Pascal's Law

The second rule of Pascal's Law states: The pressure at any given point in a liquid at rest is the same in all directions. The third rule states: When an external force is applied to a liquid at rest, the force is distributed equally in all directions.

These two rules are used to design water operated hydraulic valves and hydraulic jacks.

Hydraulic Jack

In the drawing below, a force of 10 pounds is applied to piston number 1. The pressure resulting from this force is applied equally throughout the liquid including on the bottom of piston number 2. Since force is pressure times the area over which it is applied, the upward force on piston number 2 is greater than the downward force on piston number 1. The relationship between the force on piston one and the force on piston two is directly related to the diameter of the two pistons.



Application

Data

In the drawing above, piston number 1 has a surface area of one square inch. Piston number 2 has a surface area of 10 square inches. With a force (weight) of 10 pounds applied to piston number 1, determine the upward force on piston number 2.

Pressure

The pressure in the liquid in the hydraulic jack can be computed from the force formula.

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

$$P_1 = \frac{F_1}{A_1} = \frac{10 \text{ lbs}}{1 \text{ in}^2} = 10 \text{ lbs/in}^2$$

Force at Piston #2

Based on Pascal's Law the pressure at Pistons number 2 is equal to the pressure at Piston number1. Thus, using the force formula the upward force on piston number 2 can be calculated as follows:

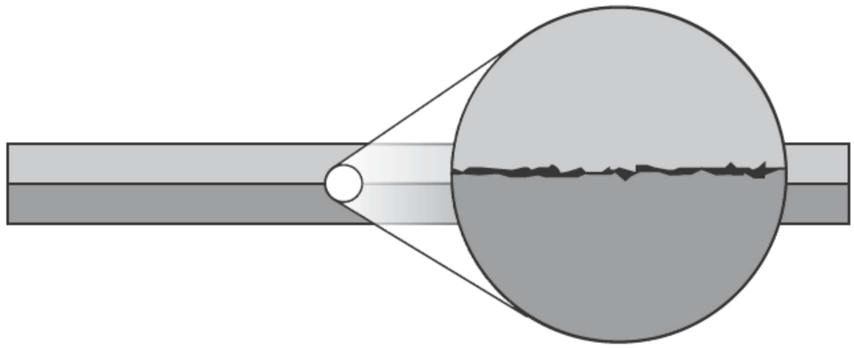
$$F_2 = P_2 \text{ X } A_2$$

$$F_2 = 10 \text{ lbs/in}^2 \text{ X } 10 \text{ in}^2 = 100 \text{ lbs}$$

Sliding Friction

Description

The force necessary to cause one object to slide along another object at a constant velocity is the force required to overcome the friction between the two objects. The friction between two objects is directly related to the roughness of the surfaces that are in contact and the force holding the objects together. In a practical sense, the force necessary to overcome friction is independent of the area of the two surfaces.



Inertia

The force required to start the object to move - that is, to overcome inertia - is not included in this calculation.

Formula

The force required to overcome friction is calculated using the following formula.

$f = \mu F$

Where:

f = Force in pounds required to overcome friction

μ = The coefficient of friction

F = Pounds of force between the two surfaces

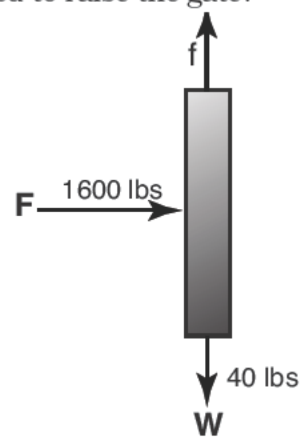
Coefficient of Friction Examples

Material 1	Material 2	Dry Sliding
Aluminum	Aluminum	1.4
Brass	Cast Iron	0.3
Cast Iron	Cast Iron	0.15
Copper	Cast Iron	0.29
Mild Steel	Brass	0.44
Mild Steel	Mild Steel	0.57

Sliding Friction Application

Shear Gate

The calculated horizontal force on a cast iron shear gate is 1,600 pounds. The gate weights 40 pounds and is contained inside of cast iron rails. Not including the force required to overcome inertia, what upward force is required to raise the gate?



Lifting Force

The total force required to lift the shear gate is the force required to overcome friction plus the weight of the gate.

Sliding Friction

The force required to overcome the sliding friction is:

$f = \mu F$

$f = 0.15 \times 1{,}600$ pounds $= 240$ pounds

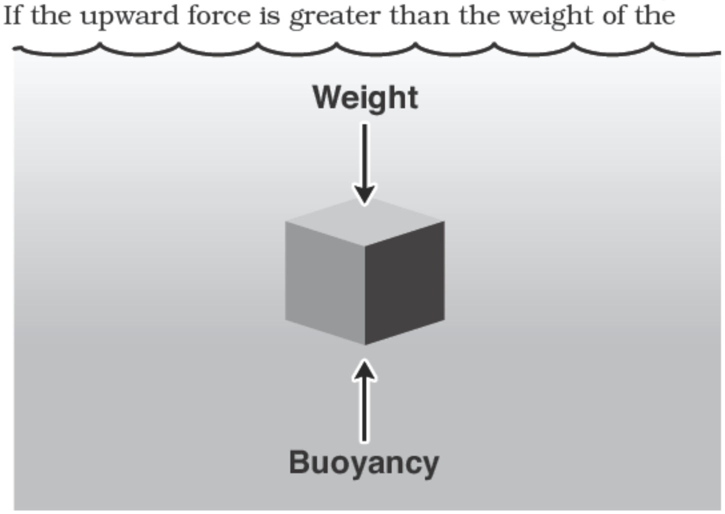
The shear gate weighs 40 pounds. Therefore the total lifting force required is:

240 lbs + 40 lbs = 280 pounds

Buoyancy

Archimedes Principle

The Archimedes Principle states: Any body immersed in a liquid is subject to a buoyant force equal to the weight of the liquid displaced. This buoyant force is an upward force that counteracts the weight of the object. If the upward force is greater than the weight of the



object, it will float. If the upward force is less than the weight of the object, it will sink.

Floating Depth

The percentage of a floating object that extends above the surface of the liquid is directly proportional to the weight of the volume of displaced, liquid to the weight of the object. For example, if an object has a weight of 20 pounds and the volume of liquid that weighs 20 pounds is equal to 75% of the volume of the object, the object will float with 25% of its volume above the surface of the liquid.

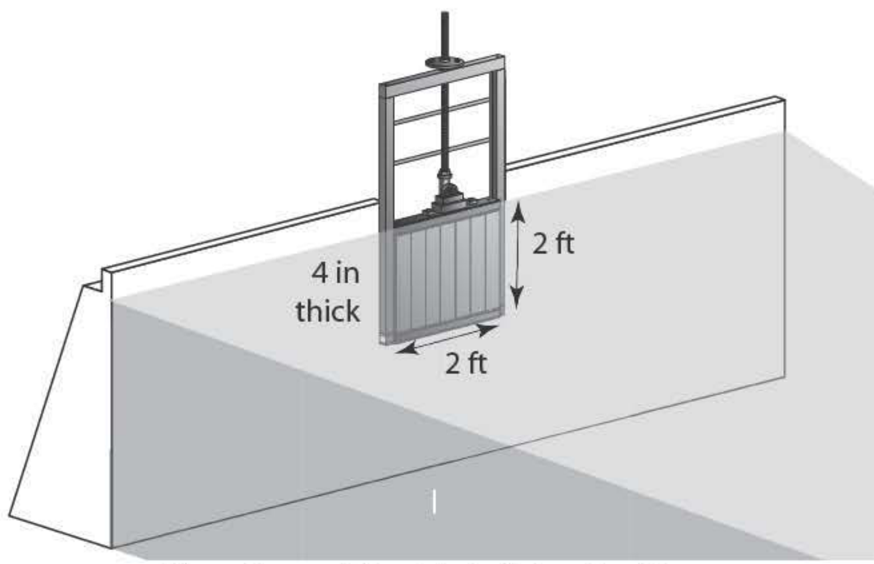
Impact of Specific Gravity

Since the buoyancy force is directly related to the weight of volume of liquid that is displaced the specific gravity of the liquid becomes important. The greater the specific gravity of the liquid the greater the buoyancy force. For example, SAE 30W motor oil has a specific gravity of 0.9 and water is 1.0, thus an object would float at a lower level in oil than in water.

Buoyancy Application

Data

A wooden sluice gate is 2 feet square and 4 inches thick. The sluice gate is made of redwood which has a specific gravity of 0.45. The buoyance force lifting the gate can be determined as follows:



Volume of Gate

The volume of the gate is determined by:

V = L x W x T

Where:

V = Volume in cubic feet

L = Length in feet

W = Width in feet

T = Thickness in feet

V = 2 ft x 2 ft x (4 in ÷ 12 in/ft) = 1.3 ft^3

Weight of Water

The weight of a volume of water equal to 1.3 ft^3 is:

1.3 ft^3 x 62.4 lbs/ft^3 = 81.12 lbs

Weight of Gate

The weight of the gate can be determined by its specific gravity as follows:

$$SG = \frac{\text{Weight of substance}}{\text{Weight of equal volume of water}}$$

SG x Weight of an equal volume of water = Weight of gate

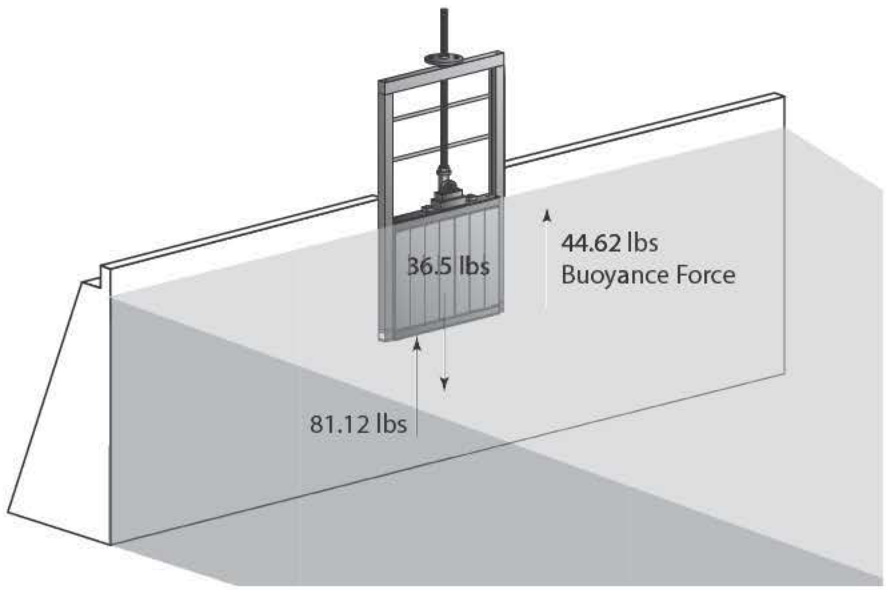
0.45 x 81.12 lbs = 36.5 pounds

This is the downward force due to gravity

Buoyance Force

The buoyance force is determined by subtracting the downward force from the upward force.

81.12 lbs – 36.5 lbs = 44.62 lbs



Buoyance Caveat

A floating object displaces a volume of liquid equal to the weight of the object. However, if the item is totally submerged, the volume of liquid that is displaced is equal to the volume of the object. For example a bottle that is empty will float and displace a volume of liquid equal to its weight. If the bottle were filled with the same liquid and placed on the bottom of the liquid vessel, it would displace less liquid. This is because the glass walls of the tank are denser (weighs more per cubic volume) than the water.

Thrust Blocks

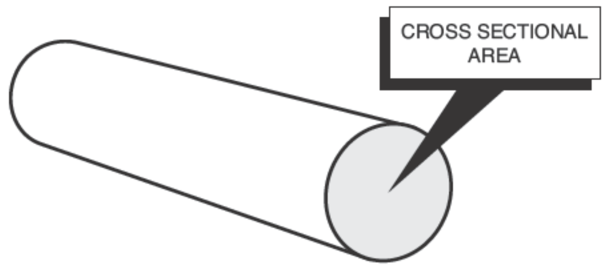
The Forces at Work

Distribution of Force

The pressure inside a pipe is evenly distributed in all directions. As long as the pipe is in a relative straight line the system is stable. However, when the pipe changes direction or comes to a dead end, the internal force caused by the pressure can create a problem. The quantity of this force can be calculated as follows.

Force on Dead End Line

The force at the end of a dead end line is the result of the internal pressure and the area over which that pressure is applied. The area on the end of a pipe is called the cross-sectional area of the pipe and is determined using the following equation $A = \pi r^2$.



Example – 6 Inch Pipe

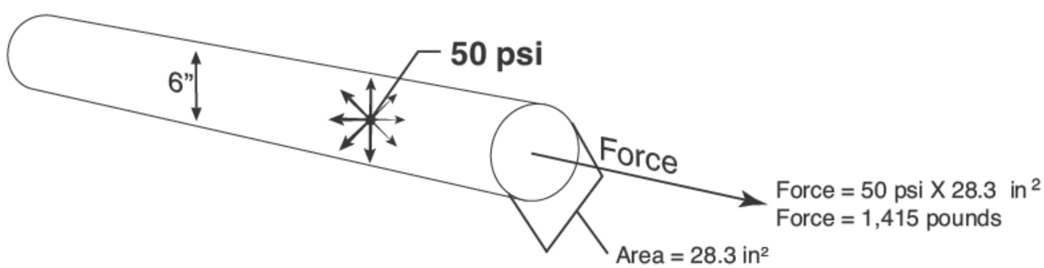
The cross sectional area of a six inch pipe is:

$A = \pi \times 3 \text{ inches}^2 = 28.3 \text{ in}^2$

Force at 50 psi

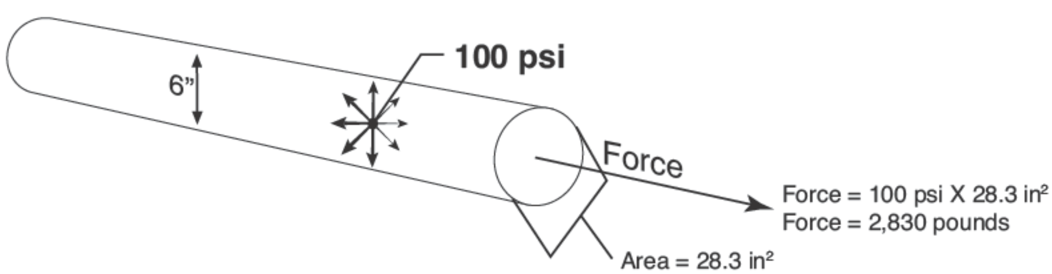
The force exerted on the end of a six inch pipe as a result of a 50 psi internal pressure is:

$50 \text{ psi} \times 28.3 \text{ in}^2 = 1{,}415 \text{ pounds}$



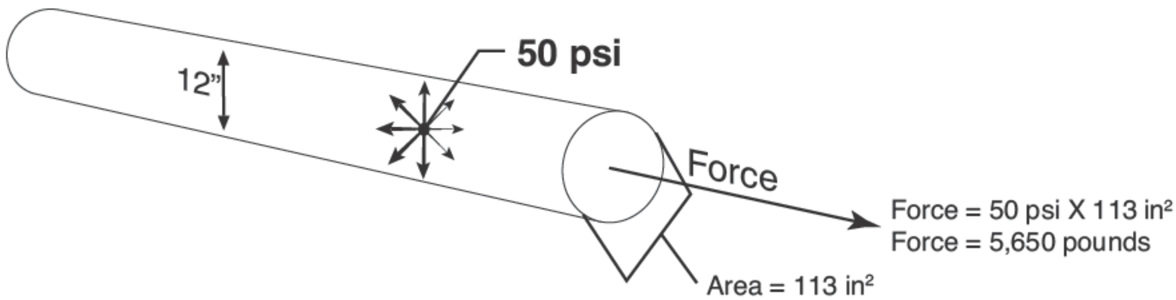
Double the Pressure

If the pressure were doubled from 50 psi to 100 psi, the total force will also double.



Double the Pipe Size

If the pipe size were doubled from 6 inch to 12 inch, the cross sectional area is increased by a factor of four. Thus the resulting force on the end of the pipe is also increased by a factor of four. 1,415 pounds for a six inch pipe at 50 psi becomes 5,650 pounds on the end of a 12 inch pipe with 50 psi of internal pressure.

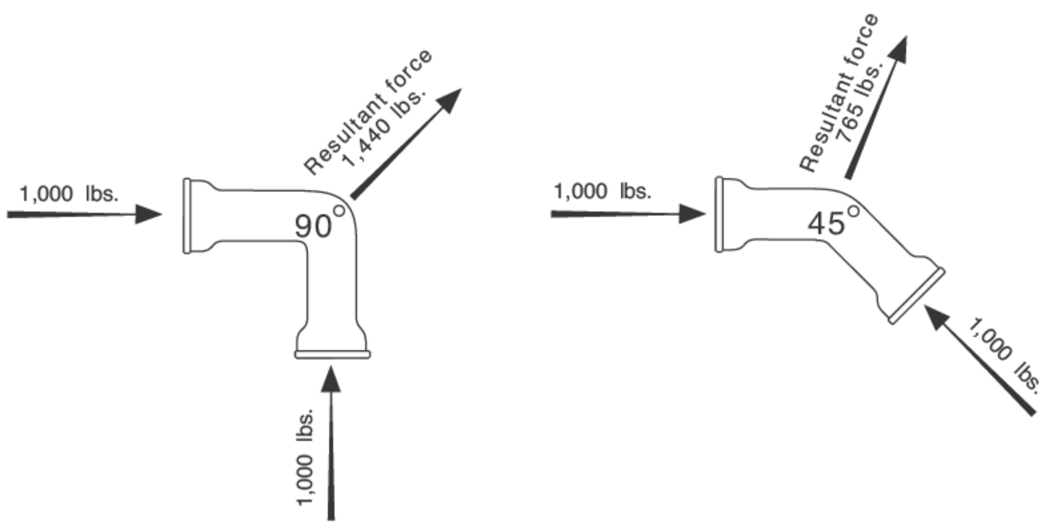


Changing Directions

When the pipe changes direction, the resulting force is a function of two internal forces.

Results with Bends

For bends of less than 60 degrees, the resulting force is less than the force on one end of the pipe, because the two forces have a tendency to counteract one another. For example, a 45° elbow with an internal force of 1,000 pounds causes a resulting force on the elbow of 765 pounds. At bends of 90 degrees and greater, the resulting force is greater than that observed on a dead end line. For example, a 90° elbow with the 1,000 pounds of internal force will result in a force on the elbow of 1,440 pounds.



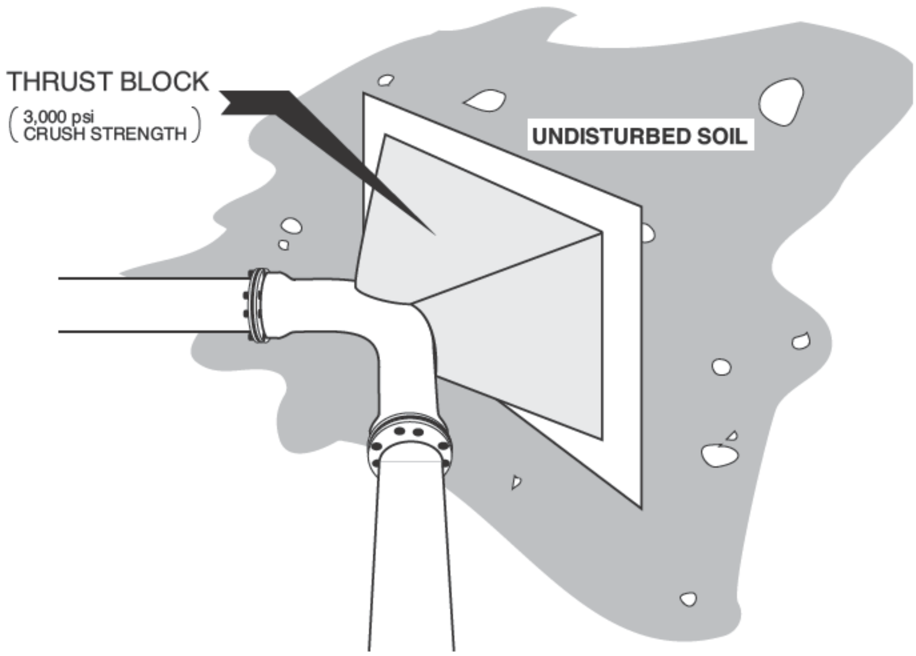
To Counter The Force

These resulting forces could push the elbow or other ,fittings off of the pipe. To counteract the resulting force a concrete block, called a thrust block, is placed between the pipe fitting and the wall of the trench, transferring the force from the fitting to the wall of the trench. (This type of thrust block is also called a “concert thrust reaction block.”)

How Thrust Blocks Work

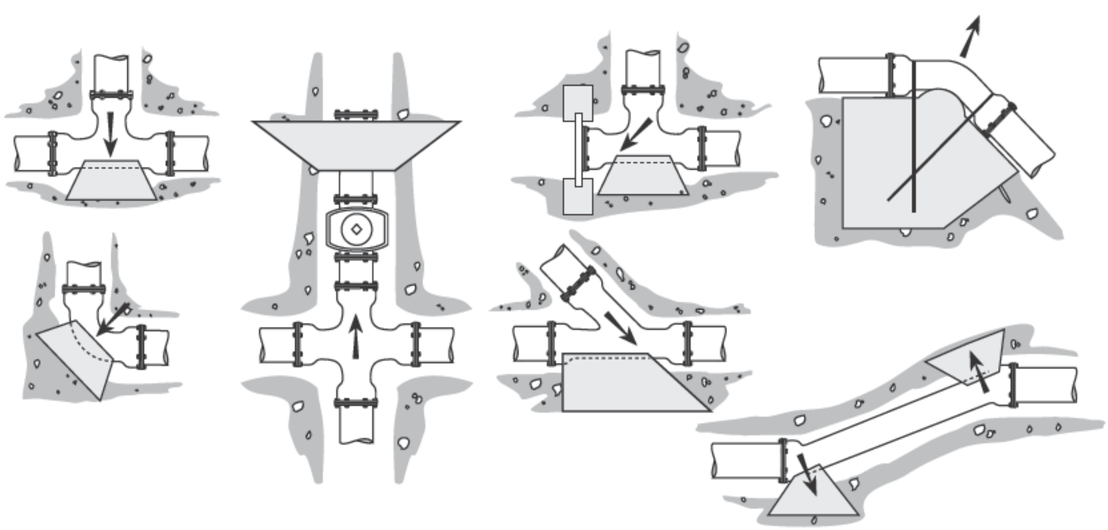
Transfer of Force

A thrust block is a wedge of concrete placed between the fitting and the wall of a trench. In most cases, it is the trench wall, not the thrust block, that holds the fitting in place. Concrete thrust blocks are designed and installed using concrete with a compression strength of 3,000lbs/in^2. Wooden blocks, rocks, or other material will not serve the same function.



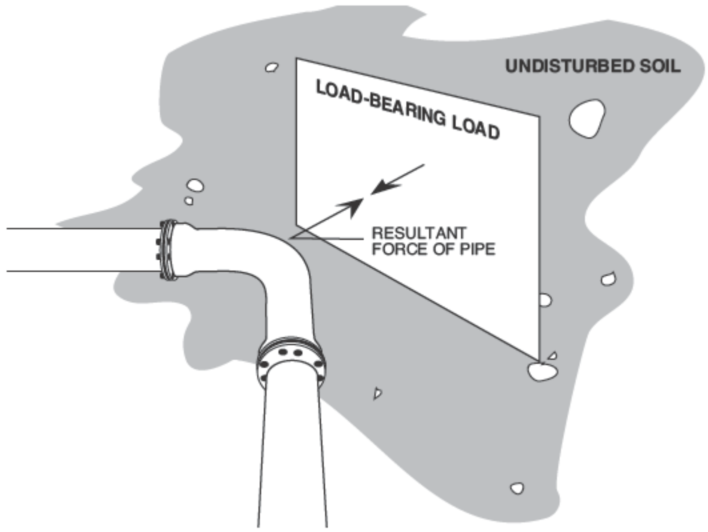
Examples

Below, are some examples of common locations of thrust blocks. Note that with the thrust block in the upper right of the drawing the fitting is tied back to the thrust block rather than the thrust block being placed between the fitting and the trench wall. In this case the weight of the concrete is used to hold the fitting in place.



What Determines Size

In summary; the size and shape of the thrust block needed is dependent upon the strength of the soil and not the size or weight of the thrust block. The key element is the surface area required to support the force from the pipe. The surface area is dependent upon the soil load bearing strength and the pressure in the pipe. The calculations used to determine the size of a thrust block are based on the load bearing strength of undisturbed soil and the resultant force from the pipe or fitting.



Soil Type and Load Bearing Strength

Below is a table of typical load bearing strengths of various soil types.

SOIL TYPE	LOAD BEARING STRENGTH lbs/ft ^{2}
MUCK	0
SOFT CLAY	1,000
SILT	1,500
SANDY SILT	3,000
SAND	4,000
SANDY CLAY	6,000
HARD CLAY	9,000

Thrust Block Design

Two Forces to Calculate

There are two separate forces that must be calculated in order to determine the size and shape of a thrust block. The first force is the one that tends to remove the fitting from the pipe, called the resultant force. The second is the ability of the soil to withstand this force.

Force from Pipe

The resultant force that tends to remove a pipe fitting from the pipe is calculated using the formula:

$$F = 2pA\ (\text{sine } 1/2\ Ø)$$

Where: F = the force in pounds

p = the line pressure in psi

A = the cross sectional area of the pipe

Ø = the angle of the bend

The Angle

The component (sine 1/2 Ø) is read as the sine of one half of theta. Theta is the Greek symbol for angle. So the component could be read as the sine of one-half the angle theta. This angle is the inside angle of the bend, 90°, 45° , etc. The computation is made using one-half the angle to reflect the true direction of the force driving the fitting away from the pipe. This number can be determined from tables or from most scientific calculators. However, for convenience, a table for common elbows is included below.

Angle Ø	1/2 of Ø	Sine of 1/2 of Ø
90	45	0.707107
45	22 1/2	0.382683
22 1/2	11 1/4	0.199368
11 1/4	5 5/8	0.098017

Line Plus Test Pressure

A thrust block must be sized to accommodate the static line pressure plus the pressure during line testing. Test pressure is typically 1.5 times the line pressure for Ductile iron pipe. However, the design engineer may select a pressure greater than 1.5 times the line pressure.

Force of Soil

The final key to determining the size of the thrust block is the load bearing strength of the soil. This is the ability of the soil to withstand a load. This is not the same as the unconfined compressive strength of the soil that is used in the design of a shoring system. The best way to determine the load bearing strength of the soil is through a soil test. However, when such a test is not available a table of common load bearing strength based on soil type is used.

Three Steps

There are three steps required in determining the size of a thrust block. They are:

Resultant Force

1. Calculate the resultant force exerted by the line. This is done by using either the equation F = pA for dead end lines or the equation F= 2pA (sine 1/2Ø) for elbows.

Load Bearing Strength 2. Determine the load bearing strength of the soil.

Thrust Block Size 3. Calculate the size of the thrust block.

Application – Thrust Block Size for a Dead End Line

Data

Determine the size of a thrust block for a dead end line with the following conditions:

- Internal pressure of 85 psi
- 6 inch line
- Soil is sandy silt

Step 1 - Force

Calculate the force on the end of the line using the formula:

$F = pA$

p = working pressure plus test pressure. A pressure of 1.5 times the line pressure is used or:

85 psi x 1.5 = 127.5 psi

A = the cross sectional area in square inches. The area of a circle is calculated using the formula:

$A = \pi \times r^2$ ($\pi = 3.14$)

$A = \pi \times (3 \text{ in})^2$

$A = 28.3 \text{ in}^2$

The force can now be calculated.

$F = pA$

$F = 127.5 \text{ psi} \times 28.3 \text{ in}^2$

F = 3,608 pounds

Step 2 - Soil Strength

Using the table, select the load bearing strength for sandy silt soil, which is 3,000 lbs/ft^2. *Many utilities use a load bearing strength of 1,500 lbs/ft^2 as a standard. This is on the low end of the spectrum of soil bearing loads and thus gives a considerable safety factor.*

Step 3 - Thrust Block Size

The last step is the calculation of the size of the thrust block. This is accomplished by dividing the resultant force by the load bearing strength of the soil.

$$\text{Size}_{ft^2} = \frac{\text{Force}_{lbs}}{\text{Load Bearing Strength of the soil}_{lbs/ft^2}}$$

$$\frac{3{,}608 \text{lbs}}{3{,}000 \text{lbs/ft}^2} = 1.2 \text{ft}^2$$

A thrust block with a surface area of 1.2 ft^2 placed against undisturbed soil is required. It is always best with thrust blocks to provide a little extra size. Therefore, it is recommended that this thrust block be built at least 1 foot high and 1.5 feet long or 1.5 ft^2.

Application – Thrust Block Size 90 Degree Elbow

Data

Determine the size of a thrust block for a line with the following conditions:

Internal pressure of 85 psi

6 inch line

90 degree elbow

The soil is silt

Step 1 - Force

Calculate the force exerted by the line.

F = 2pA (sine 1/2 Ø)

p = The internal pressure plus the allowance for test pressure.

p = 85 psi x 1.5 = 127.5 psi

A = the cross sectional area in square inches. The area of a circle is calculated using the formula $A = \pi \times r^2$

$A = \pi \times (3 \text{ inches})^2 = 28.3 \text{ in}^2$

$F = 2 \text{ X } 127.5 \text{ psi X } 28.3 \text{ in}^2 \text{ X } 0.707 = 5{,}102 \text{ lbs}$

Step 2 - Soil Strength

Determine the load bearing strength of the soil. From the table, silt has a load bearing strength of 1,500 lbs/ft^2.

Step 3 - Thrust Block Size

Calculate the size of the thrust block by dividing the resultant force by the load bearing strength of the soil.

$$\text{Size}_{ft^2} = \frac{\text{Force}_{lbs}}{\text{Load Bearing Strength of the soil}_{lbs/ft^2}}$$

$$\frac{5{,}102 \text{ lbs}}{1{,}500 \text{ lbs/ft}^2} = 3.4 \text{ ft}^2$$

This means that a square thrust block would be 1.8 feet on the side against the undisturbed soil. However, it is always best to error with thrust block size in the direction of increased size. Therefore, it is recommended that the thrust block actually be poured 2 ft X 2 ft or 4 ft^2, against the undisturbed soil.

PIPE SIZE	Steel & PVC Scheduled Pipe				PVC Pressure Pipe					
inches	40		80		125		160		200	
	ID	OD	ID	OD	ID	OD	ID	OD	ID	OD
1/2	0.612	0.840	0.546	0.840					0.716	0.84
1	1.049	1.315	0.957	1.315	1.211	1.315	1.195	1.315	1.189	1.315
2	2.067	2.375	1.939	2.375	2.229	2.375	2.193	2.375	2.149	2.375
4	4.062	4.5	3.826	4.5	4.224	4.5	4.154	4.5	4.072	4.5
6	6.065	6.625	5.76	6.625	6.217	6.625	6.115	6.625	5.993	6.625
8	7.981	8.625	7.625	8.625	8.095	8.625	7.961	8.625	7.803	8.625
10	10.02	10.75	9.56	10.75	10.08	10.75	9.924	10.75	9.73	10.75
12	11.93	12.75	11.374	12.75	11.966	12.75	11.77	12.75	11.43	12.75
16	15.0	16.0	14.31	16			16.01	17.4		
20	18.81	20.0	17.938	20			19.87	21.6		
24	22.62	24.0	23.0	24			23.74	25.8		
36										
48										

PIPE SIZE	PVC Class Pipe						AC						DIP Thickness Class			
inches	100		150		200		100		150		200		51		52	
	ID	OD	ID	OD	ID	OD	ID	OD	ID	OD	ID	OD	ID	OD	ID	OD
1/2																
1																
2																
4	4.39	4.80	4.23	4.80	4.07	4.80							4.28	4.80	4.22	4.80
6	6.30	6.90	6.09	6.90	5.86	6.90	6.0	7.16	5.80	7.12	5.70	7.36	6.34	6.90	6.28	6.90
8	8.28	9.05	7.98	9.05	7.68	9.05	8.0	9.32	7.80	9.44	7.60	9.68	8.45	9.05	8.39	9.05
10	10.16	11.10	9.79	11.10	9.42	11.10	10.0	11.46	10.0	11.85	9.60	11.88	10.46	11.10	10.40	11.10
12	12.08	13.20	11.65	13.20	11.20	13.20	12.0	13.70	12.0	14..11	11.44	14.11	12.52	13.20	12.46	13.20
16			*16.01	*17.40			15.5	17.50	16.0	18.65	15.50	18.74	16.66	17.40	16.6	17.40
20			*19.87	*21.60			20.0	22.5	20.0	23.54			20.82	21.60	20.76	21.60
24			*23.74	*25.83			24.0	27.17	24.0	28.22			24.98	25.80	24.92	25.80
36													37.34	38.30	37.24	38.30
48													49.64	50.80	49.5	50.80

* For Class 165

PIPE SIZE	HDPE IPS				DIP Thickness Class					
inches	DR-11		DR-9		250		300		350	
	ID	OD	ID	OD	ID	OD	ID	OD	ID	OD
3/4	0.839	0.906	0.797	0.906						
1	1.056	1.140	1.003	1.140						
2	1.917	2.375	1.815	2.375						
4	3.633	4.5	3.440	4.5					4.30	4.80
6	5.349	6.625	5.065	6.625					6.4	6.90
8	6.963	8.625	6.594	8.625					8.55	9.05
10	8.679	10.75	8.219	10.75					10.58	11.10
12	10.293	12.75	9.746	12.75					12.64	13.20
16	12.915	16.0	12.231	16.00	16.80	17.40	16.76	17.40	16.72	17.40
20	16.149	20.0	15.289	20.00	20.94	21.60	20.88	21.60	20.84	21.60
24	19.374	24.0	18.346	24.00	25.14	25.80	25.00	25.80	24.94	25.80
30	24.219	30.0	22.934	30.00	31.32	32.00	31.10	32.00	31.02	32.00
48					49.64	50.80	49.52	50.80	49.40	50.80

Fluids at Rest Force Practice Problems

1. The depth of water in a 12 inch well is 125 feet. Calculate the force at the bottom of the well.
2. A round storage tank is 140 feet in diameter and contains 14 feet of water. Calculate the pressure in psig at the bottom of the tank. Calculate the total force on the sidewalls of the tank.
3. A circular steel storage tank contains 20 feet of water. A 16-inch gate valve has been installed on the side of the tank, with the center of the valve 1.4 feet from the tank floor. Determine the pressure in psig at the center of the valve and the total force on the valve. (Assume the valve gate is 16 inches in diameter.)
4. A two foot square shear gate is installed behind a small gravity dam. The center of the gate is 6 feet below the normal water level. Find the total force in pounds on the gate.
5. A 2 foot square wooden shear gate is 4 inches thick. The gate is installed so that its top is 4 feet below a small gravity dam. The sides of the gate are enclosed in mild steel and the runners are also mild steel. The specific gravity of the gate has been determined to be 0.85 and the coefficient of friction between the gate and the runners is 0.57. Find the force necessary to lift the gate.
6. A 4 inch diameter water operated hydraulic cylinder is used to operate a gate valve in a older water treatment plant. The water supply line and supply valve are both ½ inch inside diameter. The force required to move the gate valve has been determined to be 40 pounds. a) What pressure in psi is required in the supply line? b) What is the force in pounds on the supply line?
7. A section of older 6 inch gray cast iron pipe (6.42 in ID) has a wall thickness of 0.42 inches and a tensile strength of 18,000 psi. What internal pressure in psig is necessary to burst the pipe?
8. What is the total force in pounds on the end cap of a 8-inch Class 200 PVC dead-end line with an internal pressure of 75 psi?
9. A concert storage tank is located so that the normal water level in the tank is at an elevation of 385 feet. A fire hydrant located in the distribution system that is connected to this storage tank is at an elevation of 132 feet. Under a static condition, what pressure in psig would be expected at the discharge nozzle of the fire hydrant? At this pressure, what would be the total force on the inside of a 2-1/2 inch nozzle cap?
10. Determine the size in square feet of a thrust block for a 90-degree bend on a 8 inch cast iron pipe that has an internal working pressure of 85 psi. The pipe is to be installed in sandy silt soil.
11. A four-foot square mild steel shear gate is one-inch thick. If its specific gravity is 2.65, what will it weigh when immersed in water?
12. Class 350 six-inch diameter ductile cast iron pipe (6.4 inches ID) has a calculated wall thickness of 0.25 inches. What is the tensile stress applied when the internal pressure is 65 psi?

Fluids at Rest

Force Practice Problems Answers

1. 6,121 lbs
2. 6.1 psi & 2,687,537 pounds of force
3. 8.05 psi & 1,619 lbs
4. 1,498 lbs
5. 171 lbs
6. a) 3.18 psi b. 0.63 lbs
7. 2,355 lbs/in^2
8. 3,474 lbs
9. a. 109.5 psi

   b. 539 lbs
10. Total force of 9,062 lbs, thrust block of 3 square feet about 1,74 feet on a side
11. 137 lbs
12. 832 lbs/in^2 per inch