Gears
Educational Systems, LLC

Pressure in Pneumatic Systems
Using Pneumatic Systems to Perform Work and Power Mechanisms

Pressure in Pneumatic Systems
The science of compressed air

We live at the bottom of a sea of air. The upper limit of the earth's atmosphere is not clearly defined, but it is safe to say that most of the earth's atmospheric mass lies within 100km or about 60 miles above the surface.

Air has mass, and therefore it is affected by gravity. Gravity acts on the particles of air and gives them weight. The weight of the air above us creates a pressure around us. When you push down on the handle of a bicycle pump, you are putting a force equal to some of your weight on the handle.

The handle is attached to a rod and piston within the pump. The force of your weight pushing down on the piston reduces the volume of air in the pump, and raises the pressure. The weight of the air above us does the same thing to the air around us.

We are not aware of the weight of the ocean of air above us, because we were born into it. We have never been without it. Without the pressure of this ocean of air around us, we would not be able to breathe.

Hold your hand on your chest and inhale deeply. Can you feel your chest expand? As you expand your chest muscles, your lungs increase in volume and the pressure of the ocean of air around us forces air into your lungs! Without the pressure of the ocean of air, you would not be able to breathe.

Climbing higher into the atmosphere reduces the depth of air above you and thus reduces the mass and weight of the air above you. This results in a lower air pressure and makes it hard to breathe. Climbers on the world's highest peaks bring bottles of oxygen with them in order to survive at high altitudes.

Air Pressure at Sea Level

Air pressure varies across the face of the earth. The most significant factors that affect air pressure are temperature, wind and altitude.

For our purposes we will consider standard atmospheric air pressure to be 14.7 pounds per square inch.

There are many units of measurement for pressure. We will consider only 2.

Standard Pressure = 14.7 psi (Pounds per square inch) or 1.5 mega Pascal

Note: a Pascal is a very small unit of pressure equal to the force exerted by 1 Newton acting over an area of 1 square meter. Therefore we use units of mega or millions of Pascals to describe standard air pressure or multiples of standard air pressure.

Pressure is a Force Acting Over an Area

Pressure is described as the amount of **F**orce acting on a specified **A**rea. Mathematically pressure looks like this.

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

Pressure is a force exerted by a fluid or a gas and it is transmitted in all directions equally throughout the fluid/gas. Pressure acts on the surface area of the vessels or chambers in which it is confined.

Figure 7

Consider the reservoir in the GEARS-IDS™ pneumatic circuit you are using. The reservoir is a hollow cylinder with internal dimensions that are approximately 1-1/2" in diameter x 5-1/2" long. The end caps are circular with an internal diameter of approximately 1-1/2".

Study the cross section drawing of the reservoir below:

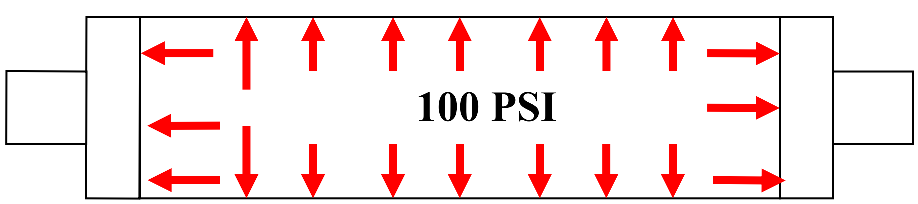


Figure 8

The drawing above illustrates a GEARS-IDS™ reservoir filled to 100 psi or 100 pounds per square inch of pressure.

This is an example of a fixed volume (The interior space of the reservoir) with a fixed amount of air contained within it.

The Nature of Air Pressure

One way of visualizing pressure is to think about the atomic model. The air within the cylinder is made up of highly energized (Rapidly moving) particles called molecules. The air is made up of different gases that can be visualized as a mixture or "Soup" of different gas molecules.

Each one of these molecules are surrounded by a negatively charged cloud we call electrons. The example below provides a means of visualizing two gas particles or molecules, each surrounded by a negatively charged cloud of electrons.

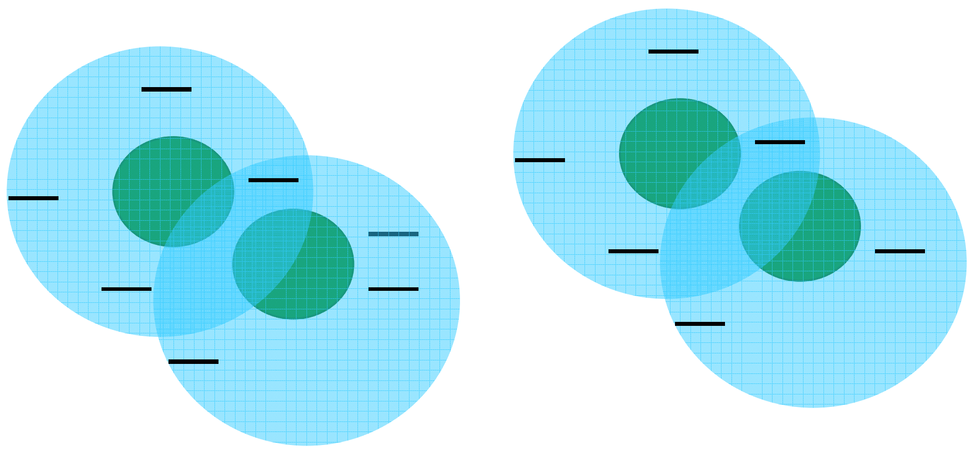
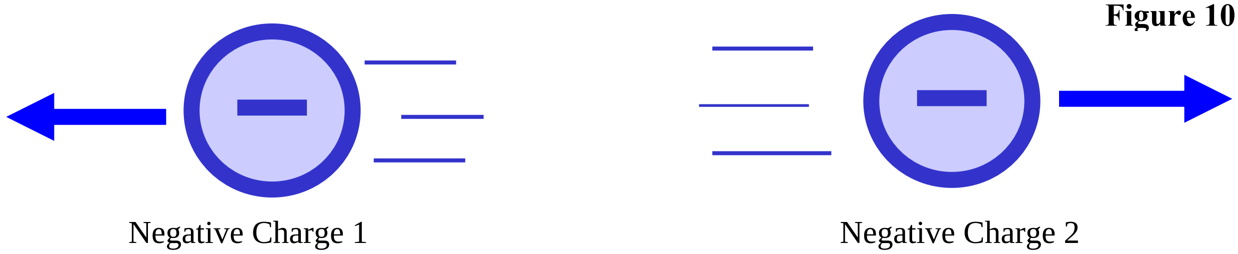


Figure 9

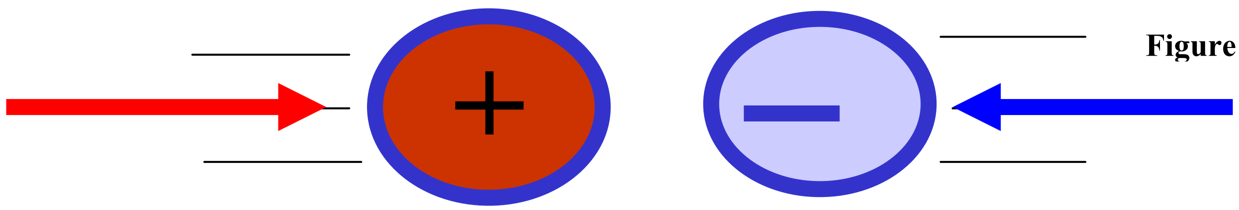
We recognize that like charges repel each other.

Figure 10



We also recognize that unlike charges attract each other:

Figure 11



Thinking of a gas as being made up of particles surrounded by a negatively charged cloud, it's easy to see that the gas particles are going to resist being pushed together. This is similar to what happens when you bring (2) similar magnetic poles into contact. The closer they are pushed together, the more they resist being pushed together….try it!

This is what happens to air molecules. They can be pushed together, but the more you try to push them closer together, the harder they resist. The amount or force of this resistance is what causes pressure!

Air Pressure Activity Example

This is an activity that can help you visualize what is happening as you pump more and more air into the reservoir.

Materials: Pringles potato chip can or tennis ball can. Foam mattress pad (Available from Wal Mart etc) Rounded length (12"-14") of broomstick or 1" PVC pipe.

Cut or tear the foam pad into circular hockey puck like sections (molecules), that are nearly the size of the interior diameter of the can, but small enough in diameter to just drop into the can without being pushed very hard.

Fill the can with as many "Pucks" as it takes to come nearly level with the can. Don't force them in, lay them in with only their own weight forcing them down.

Count how many pucks you have. Record this number.

This can full of pucks represents air in a reservoir at standard temperature and pressure. This is how much air is inside the reservoir when the gage reads 0 (zero) pressure!

Now start to fill the Pringles can with more pucks….what happens?

This is similar in some ways to what happens when you pump air into the reservoir with the bicycle pump. Each pump or stroke of the handle is like one more "Puck" of foam.

Molecular Motion Causes Pressure
Air Particles are very different from foam pucks. Air particles are always in Motion. They are constantly colliding with each other and with the interior surfaces of whatever contains them. It is the force of these impacts and rate at which they occur, that produce the effect we call pressure.

The relationships between pressure, volume and temperature when considering a fixed amount of gas or air can be more easily understood if we understand that gas particles are always in motion, and that the things that cause changes in the motion of gas particles, also cause changes in the temperature, pressure and/or volume of a gas.

Heat and Pressure
Heat causes molecular motion. If we heat a container of air, the motion of the air particles within the container is increased. As the motion increases, the number and severity of the internal collisions increases. These collisions cause "Pressure". Heat causes more rapid molecular motion of gasses, thus resulting in increased pressure.

Heated Gases in closed Containers is Very Dangerous!

Increases in pressure due to heating can result in a very dangerous condition. If the heated gas cannot be vented the pressure within the container will continue to rise. Heating can increase pressure to the point that the forces developed within the container exceed the strength of the bonds that hold the container materials together….and the gas container will explode.

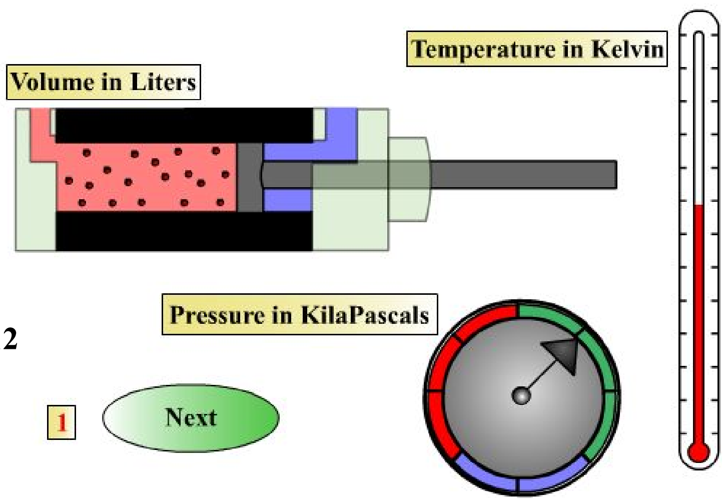


Figure 12

The physical laws that govern gasses are predicated on the understanding that gas particles, or molecules are in constant motion. By increasing or decreasing the relative motion of molecules in gasses it is possible to effect changes in either the temperature, pressure or volume of a fixed amount of gas.

Click on the image to view an animation that graphically illustrates the relationship between the temperature, pressure and volume of a fixed amount of gas.

3.1 - Air Pressure in the Reservoir

Use the bicycle pump and the pneumatic circuit you constructed and tested at the start of this unit. Fill the reservoir with air to a pressure of 100 psi.

On a separate sheet of paper draw a picture diagram of the reservoir. The reservoir is made up of three parts, the stainless steel cylinder and two aluminum end caps. Using what you have learned from the examples in this unit, sketch an illustration of the pressurized reservoir.

Label the pressure inside the reservoir at 100psi, and label the pressure outside the reservoir as standard atmospheric pressure of 14.7psi.

Consider the force acting on the end cap.

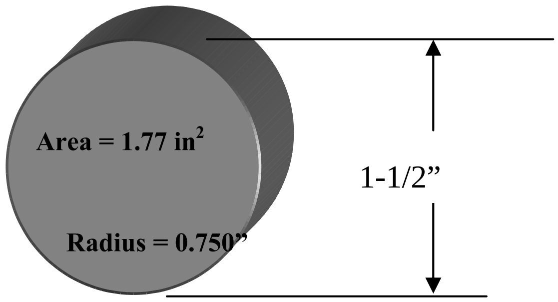


Figure 13

The end cap can be represented by a cylinder having a cross sectional diameter of 1-1/2".

The surface area of the circular surface can be found using the formula;

$$\mathbf{Area_{circle} = \pi * R^2}$$

Thus the approximate (internal) area of the end cap is equal to:

$$A_{circle} = \pi * R^2$$
$$A_{circle} = 3.142 * (\frac{Dia}{2})^2$$
$$A_{circle} = 3.142 * 0.750^2$$
$$A_{circle} = 3.142 * 0.5625$$
$$A_{circle} = 1.77 in^2$$

The pressurized air contained in the reservoir acts on the interior surface of the end cap, which has been calculated to be: 1.77 in^2

The force of pressurized gas acting on a given area can be described with this formula:

F=P*A

Using this formula it is a simple matter to calculate the force acting on the end cap.

F = 100psi * 1.77in^2
F = 177 pounds-force or 177 lbsf

This suggests that the end cap is resisting a force of 177 pounds-force when the reservoir is pressurized to 100psi.

Can you estimate what the force on the end cap would be if the internal pressure of the reservoir were 50psi?

If your guess was around 88.5 lbsf you are correct. This implies that force is proportional to pressure

A Word about Gauge Pressure

Pressure is most often measured using a pressure gauge like the one on the regulator supplied in the GEARS-IDS™ kit, or the one on your bicycle pump.

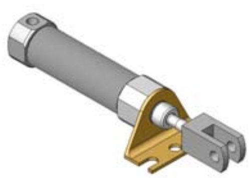
When the pneumatic circuit is not pressurized, or the bicycle pump is not in use, the gauge reads zero. That might strike you as strange since we've accepted that the atmospheric pressure around us is roughly 14.7psi.. Why then does the gauge read zero?

The answer lies in the fact that the gauges are used to show the **difference** between atmospheric pressure and the pressure they are reading. These gauges are calibrated to ignore the effect of atmospheric pressure by reading zero when they are exposed to atmospheric pressure. When the bicycle pump or pneumatic circuit gauges read 100psi, they are showing that there is a pressure difference of 100psi between the air in the system they are monitoring, and the atmospheric air pressure around us.

3.2 - Air Pressure in the Cylinder

The pneumatic cylinder is a machine that changes and directs the force created by the pressurized air in the system. The cylinder also uses that force to accomplish useful work. Work is accomplished when the piston and rod are extended or retracted by the pressurized air acting on the surface of the piston.

The Relationship Between Area, Pressure and Force in a Pneumatic Cylinder



The force created by the pneumatic cylinder is adjustable. By adjusting the pneumatic circuit pressure using the regulator, it is possible to increase or decrease the pressure in the pneumatic cylinder. This change in pressure results in a proportional change in the force developed by the pneumatic cylinder.

Another way to increase or decrease the forces generated by the cylinder is to choose a cylinder with either a larger *(Greater force)* or smaller *(Less force)* diameter. Remember the larger the diameter, the greater the surface area of the piston. The same pressure acting on a larger surface area results in a greater force generated at the cylinder rod and piston.

The relationship between pressure, area and force can be described by this simple algebraic statement;

Force = Pressure x **Area**

It is easy to see that increasing the cylinder diameter or pressure will increase the force produced by the cylinder and piston.

This is important information to an engineer who is trying to design a system that will accomplish a task, but not use too much air in the process.

Here is an example problem;

An engineer is designing a pneumatic latching system for a highly automated material handling system. She needs to create a force of 20lb or (89N) to operate the latching system. The air pressure supplied throughout the manufacturing plant is 100psi or 0.67 MPa.

What is the *(approximate)* minimum size *(diameter)* cylinder necessary to accomplish this task?

In order to solve this problem the engineer needs to consider the relationship between force, pressure and area described by the formula shown above. She begins by taking into account the existing parameters or limitations imposed by this design problem.

These limitations are:

Expected air pressure = 100psi or 0.67 MPa.
Necessary force = 20 pounds or 89 Newtons

In order to arrive at an initial estimate for the size (diameter) of the cylinder, the engineer uses the formula that describes the relationship between force, pressure and area.

Force = Pressure x Area

Since the area is the unknown variable, the formula can be rewritten in terms of the area.

Area = Force/Pressure
Area = 20lbs/100psi
Area = 0.2 in^2

The engineer now knows that the area of the piston must be at least 0.2 in^2. She must use this information to determine the cylinder diameter. To do this she chooses the formula for the area of a circle. She then substitutes the information she has and re-orders the equation to solve for the single unknown variable. The example follows:

$$Area_{circle} = \pi * R^2$$

$$Radius = \sqrt{\frac{Area}{\pi}}$$

$$Radius = \sqrt{\frac{0.2 sq.in.}{3.142}}$$

$$Radius = 0.255''$$

The radius of the cylinder needs to be at least 0.255”. since the radius of a circle is half of the diameter, the minimum cylinder diameter needs to be approximately ½”.

By using the value for the necessary area (0.2 in^2), and plugging that value into the formula for the area of a circle, the engineer was able to re write the formula in terms of the radius. The diameter is equal to 2 x radius, so the diameter would equal 2 x 0.255” or 0.51.

Pneumatic cylinders are typically sized in ½” increments. The best choice in this case would be ½” diameter cylinder.

A Pneumatic Engineering Problem

Refer to the previous example and solve this (similar) problem.

Specify a pneumatic cylinder diameter that will produce 40lbs (178 Newtons) of force when pressurized to 50 psi (0.34 MPa).

Piston Area = _______ in^2 __________ cm^2
Piston Diameter = _______ inches __________ cm

Gears Educational Systems, LLC

Pneumatic Systems; Force, Pressure and Flow
Using Pneumatic Systems to Perform Work and Power Mechanisms

Force in Pneumatic Systems

Force
A force can be thought of as a push or a pull. Sometimes forces are great enough to make things move. Sometimes they are not. A force does not always cause a (Noticeable) motion, or a change in motion. **A change in motion only occurs when forces become unbalanced.** Additionally, forces act in specific directions.

Consider the linear (Straight line) force generated by a linear pneumatic actuator like the one pictured below. In this case the pneumatic actuator to be considered is called a pneumatic cylinder or cylinder for short. A pneumatic cylinder is comprised of a cylindrical body, a movable piston and rod and ports to allow the air to enter and exit the cylinder.

The force exerted by pressurized air acts on the surface area of the piston causing it to move. The (Cylindrical) side of the piston contains a seal that prevents air from moving past the piston. The piston is attached to the rod and the motion and force of the piston is transmitted to the rod. The cylinder in the GEARS-IDS™ kit (pictured below) is a **single acting cylinder**. The force needed to retract the rod after the air pressure has caused it to extend, is provided by the internal spring acting against the piston. See the illustration below (Figure 2).

Figure 2

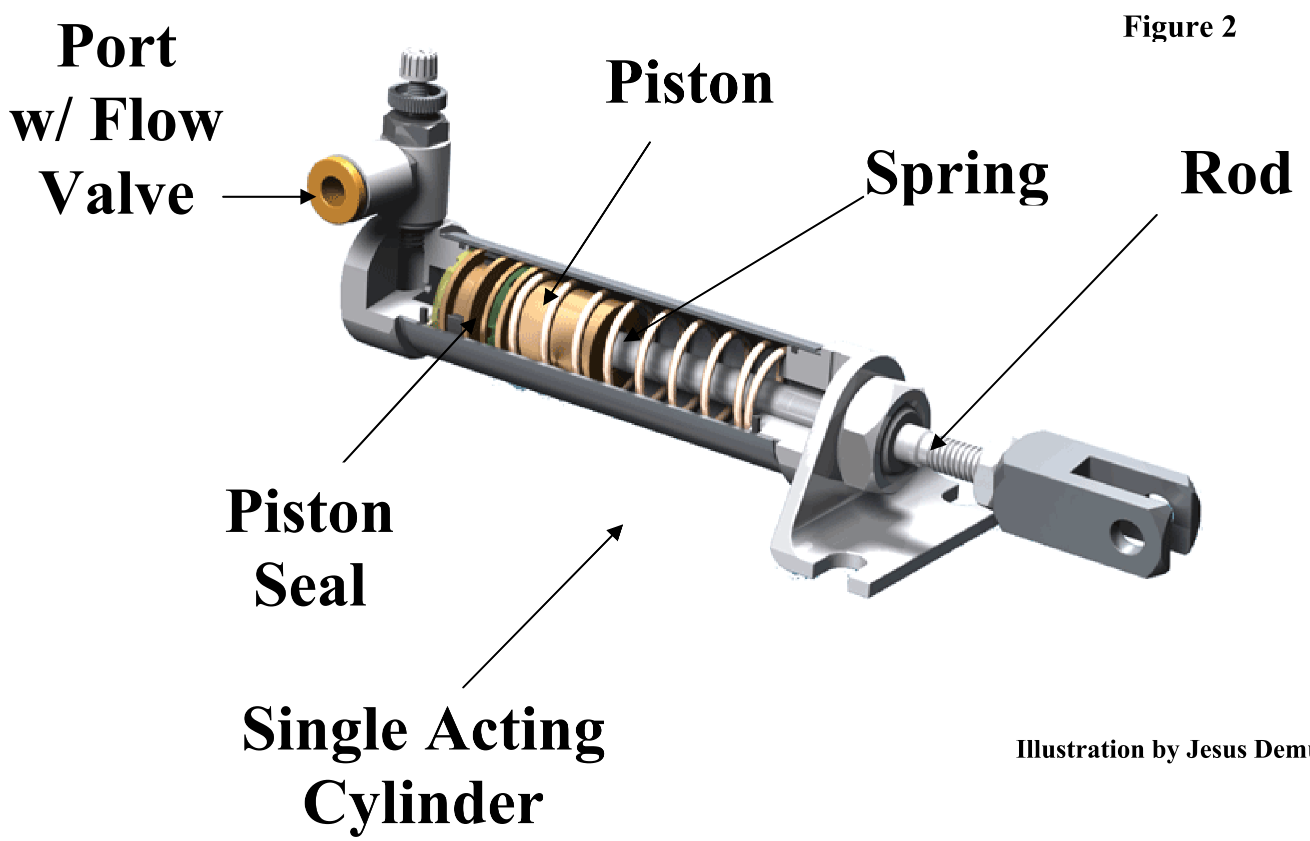


Illustration by Jesus Demula

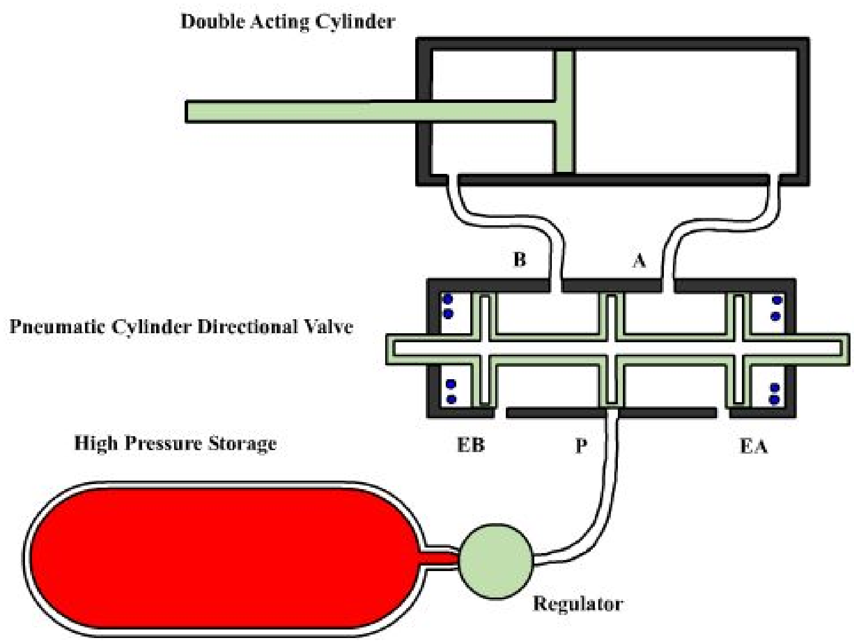


Figure 3

Forces Can Act on Both Sides of the Piston

A double acting cylinder piston and rod are extended and retracted by pressurized air that acts on either side of the piston. (See the figure 3 illustration above) A directional valve controls the direction through which the air enters and exits the cylinder. The directional valve in this example is referred to as a 5/2 valve. *(View the accompanying slide show for more details on specifying directional valves)*

Visit our Flash Points for Educators to see an animation that illustrates how a 5/2 valve is used to control a double acting cylinder.

The advantage of using a double acting cylinder is that the force of the pressurized air can be used to create both a pushing and pulling force. The disadvantage is that the double acting cylinder consumes almost twice the volume of air per cycle (extension and retraction) as does the single acting cylinder. *A double acting cylinder is necessary only when nearly equal forces acting in opposite directions are necessary.*

Construction equipment like backhoes and excavators use double acting cylinders and oil filled systems. Oil filled systems are called hydraulic systems, air filled systems are called pneumatic systems.

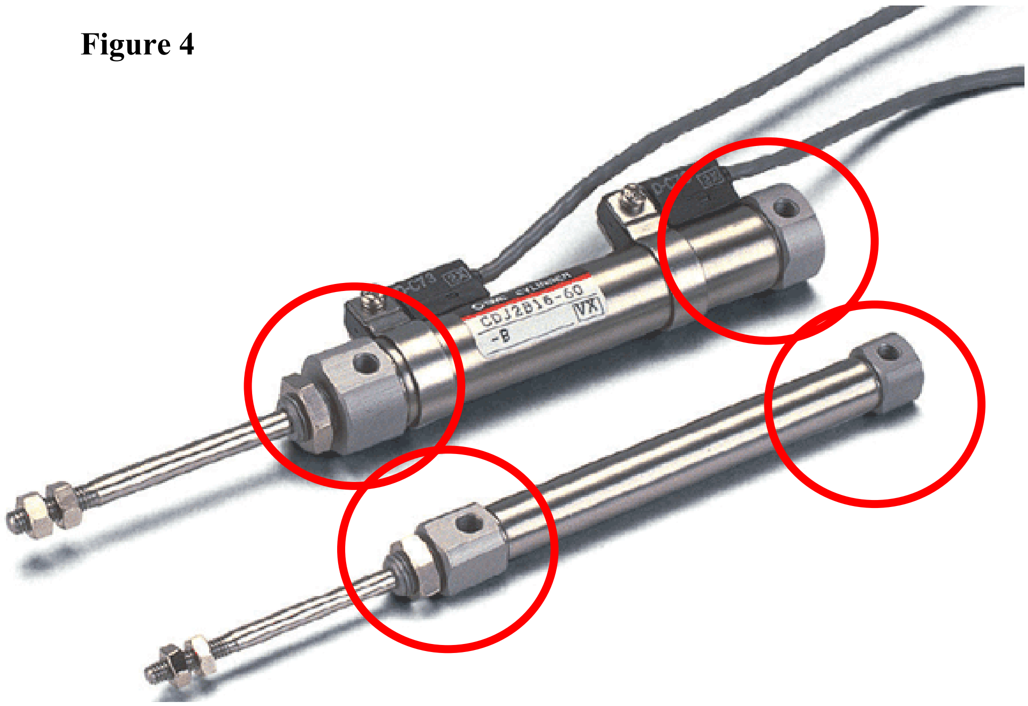
Pneumatic and hydraulic components are very similar, but because of the differences in fluids (air and oil) they perform differently. Both are useful in specific applications.

Can you research and report on the advantages and applications of both pneumatic and hydraulic systems?

Single Acting Cylinder
The pneumatic cylinder pictured in figure 2 is a single acting cylinder. Single acting cylinders can be normally retracted, or normally extended. The cylinder pictured in figure 2 is normally retracted. Air pressure is used to drive the piston in only one direction (extended).

It is interesting to note that there are always "Trade offs" in the world of engineering. The spring used in this single acting cylinder produces a force of about 2lbs. The pressurized air must overcome this force before the piston and rod can begin moving. Overcoming this force requires work, and thus some air is consumed by the work necessary to compress the spring.

Figure 4

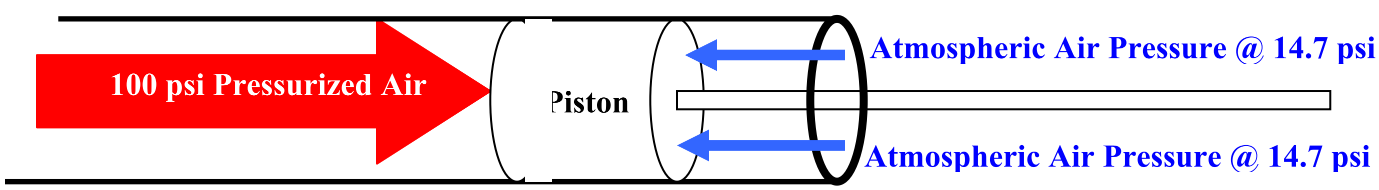


Double Acting Cylinder(s)
The pneumatic cylinders pictured on the left (Figure 4) are double acting cylinders. Air pressure is used to both extend and retract the piston and rod. Note the (2) ports; one on each end of the cylinder body. Pressurized air enters and exits these ports and acts on either or both sides of the piston. Double acting cylinders are the best choice when significant force must be applied during both the extension and retraction of the piston and rod.

Force (*Pushing and Pulling)*
Unbalanced forces create motion. If the force acting to push or pull the object is greater then the force(s) acting to keep it from moving, then the object will move. The greater the difference (Δ Delta) between the two forces, the faster the object will move.

In order for the piston and rod to move, there must be an imbalance of forces acting on either side of the piston. Directing pressurized air to one side of the piston, and allowing air to escape to atmosphere on the other side of the piston provides this imbalance of forces.

Figure 4a



Volume of a Cylinder

When the cylinder is pressurized and the piston and rod are extended , the interior volume of the cylinder increases. The interior volume is at maximum when the piston and rod are fully extended. See fig 5.

In order to calculate the amount of air consumed it is necessary to determine both the maximum volume and pressure inside the cylinder.

Maximum Volume

The graphic below shows a single acting cylinder in both the retracted *(Minimum Volume)* position, and fully extended *(Maximum volume)* position.

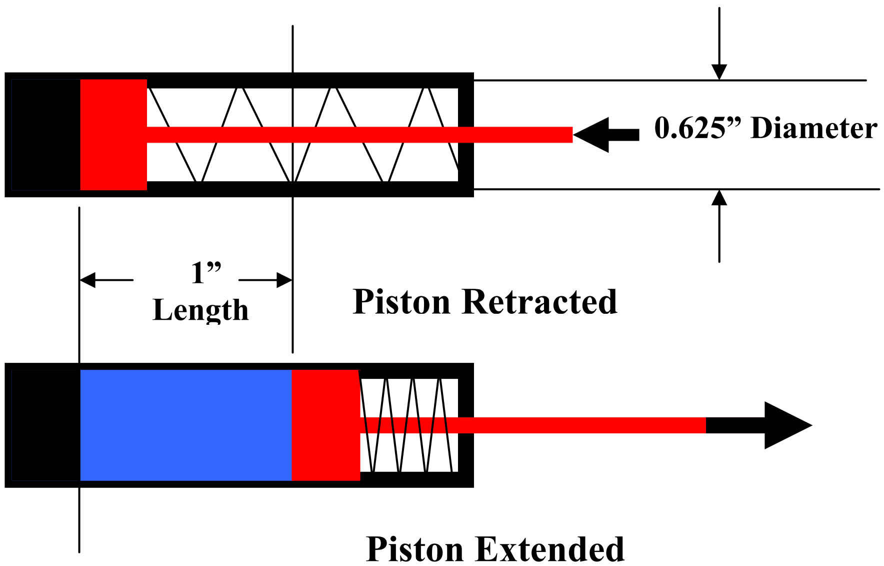


Figure 5

The maximum extension length is called the **stroke**. The stroke of the cylinder pictured above is 1". The internal diameter of the cylinder pictured above is 0.625"

The change *(Increase)* in volume is found using the formula for the volume of a cylinder.

$$Volume = \pi * R^2 * Length$$
$$Volume = 3.14 * 0.312^2 * 1"$$
$$Volume = 3.14 * 0.097 in^2 * 1"$$
$$Volume = 0.305 in^3$$

The change in volume *(Δ volume)* between the retracted (minimum volume) and extended (Maximum volume) of the cylinder pictured above is 0.305in^3 (cubic inches).

Practice Problem:

Calculate the change in volume for a pneumatic cylinder with the following specifications:

Bore:	1" or 2.5 cm	Max Volume (in^3)	________
Stroke:	2" or 5 cm	Max Volume (cm^3)	________

Pneumatic Actuators Apply Forces

In order to analyze and describe forces it is necessary to quantify them. That is, talk about "How much" force or how great is the difference in forces. To accomplish this, it is necessary to develop an appreciation and understanding of the units used to describe and measure forces.

Two common units of force are:

Pounds-force and **Newtons**

Force is commonly measured in **pounds force** (Imperial system), and **Newtons** (SI units). Both units are in common use and it is therefore wise to understand and use them both. A pound of force is greater than a Newton of force.

1 Pound-Force = 4.448 Newtons and conversely **1 Newton = 0.224 pound-force**

Engineering estimates involving work problems are often "rough estimated" during conversations: When making rough estimates that deal with forces it is common to use "round" figures, so that:

1 Pound-Force = 4.5 Newtons and conversely **1 Newton =** ***about*** **a 1/4 pound-force**

When using paper and pencil or electronic calculators to solve equations dealing with forces, it is necessary to respect the decimal places!

Estimates and Approximations

Designers and innovators make extensive use of estimates and approximations in order to make informed guesses about how and where to begin the problem solving process. Approximations often involve the estimation of forces. For this reason, it is wise practice to develop a personal scale that provides a means or "Feel" from which it is possible to make accurate approximations.

Here is an example of a personal scale used to get a "Feel" for relatively low forces that may be involved in an engineering decision or approximation.

A Newton is approximately equal to the force felt by a McDonald's quarter pound hamburger resting on your nose……think about it. No bun, no lettuce….just the burger. Not much force is it?

A Pound-force is approximately equal to 4 of those same hamburgers with a slice of tomato and lettuce, piled on your nose….. sounds silly…but it helps you "Feel" the force.

Now, if you calculate the force of the piston as being 50 Newtons….it might mean something more than just a number. It might mean that you suddenly realize that 50 Newtons won't be able to lift a car….or at least not lift it very fast!

Think about it, and then develop personal scales for every unit of measurement that you encounter. This is a great way to learn how to make accurate and meaningful engineering approximations.