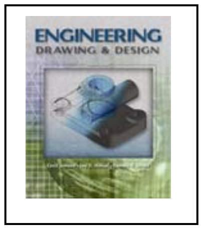
Chapter 30
Fluid Power



Unit 30-1

Hydraulics

The more complex industry becomes, the more vital becomes the role-played by fluids in the industrial machine. One hundred years ago, water was the only important fluid which was conveyed from one point to another by pipe. Today, almost every conceivable fluid is handled in pipes during its production, processing, transportation, or utilization. The age of atomic energy and rocket power has added fluids such as liquid metals — for example, sodium, potassium, and bismuth — as well as liquid oxygen, nitrogen, etc., to the list of more common fluids such as oil, water, acids, and liquors that are being transported in pipes today. Nor is the transportation of fluids the only phase of hydraulics that warrants attention now. Hydraulic and pneumatic mechanisms are used extensively for the controls of modern aircraft, seagoing vessels, automotive equipment, machine tools, earthmoving and road-building machines, and even in scientific laboratory equipment where precise control of fluid flow is required.

So extensive are the applications of hydraulics and pneumatics that almost every designer has found it necessary to be familiar with at least the elementary laws of fluid flow.

BASIC PRINCIPLES

The science of hydraulics dates back several thousand years when water wheels, dams, and sluice gates were used to control the flow of water for irrigation and domestic use. Today, however, the term *hydraulics* is commonly used to refer to *power hydraulics.* In power hydraulics, fluid is used under controlled pressure to do work.

A fluid is infinitely flexible, yet as unyielding as steel. It can readily change its shape; it can be divided into parts to do work in different locations; it can move rapidly in one place and slowly in another; and it can transmit a force in any or all directions. No other medium except fluid combines the same degree of positiveness, accuracy, force, and pressure.

It is interesting and important to note that a hydraulic pump does not pump pressure. The pump merely produces flow. Pressure is generated only when a cylinder, motor, valve, or constriction tends to resist fluid flow. If the flow were to encounter only negligible resistance, the developed pressure would be slight.

Both force and pressure are primarily measures of effort. Work, however, is a measure of accomplishment. It describes the application of a force through a distance and flexibility of control, with the ability to transmit a maximum of power in a minimum of mass.

Although this unit does not aim at an in-depth treatment of hydraulic components and circuits, it will nevertheless be helpful to start by considering some of the fundamental principles involved.

Force, Pressure, Work, and Power

Force is defined as any cause that tends to produce or modify motion. To move an object, such as a machine tool head, force must be applied to it. The amount of force required depends on the object's inertia. In the foot-pound or U.S. Customary system, force can be expressed in any of the units of weight, but it is commonly expressed in pounds. In the metric system force is measured in Newton's (N) for light forces, kilonewtons (kN) for intermediate forces, and meganewtons (MN) for strong forces. (A Newton is approximately one-quarter of a pound-force.)

In the U.S. Customary system, pressure is usually expressed in terms of pounds per square inch ($lb./in.^2$). In the metric system, pressure is measured in pascals. A pascal (Pa) is the pressure produced when a force of one newton is applied to an area of one square meter ($Pa = N/m^2$).

The pascal is a very small unit of measure, equivalent to approximately 0.001 pounds per square inch ($lb/in.^2$). It is used for very low-pressure applications. In most instances the kilopascal (kPa) and megapascal (MPa) are used. In fluid power applications the kilopascal is the recommended unit of pressure. A 1-kPa pressure is equal to approximately 20.9 lb/ft^2, or 6.895 $lb/in.^2$

The earth's atmosphere provides an example of the relationship between force and pressure. The blanket of air enveloping the earth's surface is of such volume that its total mass could be measured in U.S. Customary tons (2000 lb), or metric tons (megagrams). However, the force exerted by the mass of a column of air 1 in^2 in cross-sectional area is only 14.7 lb/in^2 (1 m^2 in cross-sectional area is only 101.325 kPa) at sea level. Thus, atmospheric pressure at sea level is 14.7 $lb/in.^2$ (101.325 kPa), but for low-accuracy work 15 lb/in^2 (100 kPa) is used. The relationship between force, pressure and area is expressed mathematically as

Force = pressure x area

(U.S. Customary) Force in lb = $lb/in.^2 \times in.^2$

(Metric) Newtons = pascals x $meters^2$

$N = Pa \times m^2$

As mentioned previously, work is a measure of accomplishment, describing the application of a force moving through a distance. In the U.S. Customary system, work is expressed in terms of in-lb or ft-lb. Thus, if a force of 1200 lb moves a ram 4 in., the work accomplished equals 4800 in-lb, or 400 ft-lb. In the metric system, work is expressed in joules. A joule (J) is the energy required or expended to move a force of one-newton a distance of one meter. The joule is the special name given the derived unit newton-meter (N-m). The kilojoule (kJ) is the preferred unit. The joule (J) is used to express small quantities of energy; megajoules (MJ) are used for large quantities. Thus, if a force of 500 N moves a ram 3m, the work accomplished equals 1500 J, or 1.5 kJ. The formula is

Work = force x distance

ft-lb = lb x ft

J = N x m

The concept of work makes no allowance for the time factor. *Power* is work per unit of time. In the U.S. Customary system, *horsepower* (hp) is the standard unit of power measurement. One horsepower is that amount of power necessary to raise 33 000 lb one ft in one minute or 550-lb one ft in one second. In the metric system the watt (W) is the standard unit for all forms of power: heat, electric, mechanical, etc. A *watt* is energy per unit of time measured in joules per second (J/s). The preferred units are watt (W) for small values, *kilowatt* (kW) for intermediate values, and *megawatt* (MW) for large values. One watt is that amount of power necessary to move one newton, one meter, in one second.

Behaviors and Mechanics of Fluids

In the 17th century, Pascal formulated the fundamental law that forms the basics of modern hydraulics. Pascal's law states: Pressure at any point in a static liquid is the same in every direction and exerts equal force on equal areas. Figure 30-1-1 illustrates this principle.

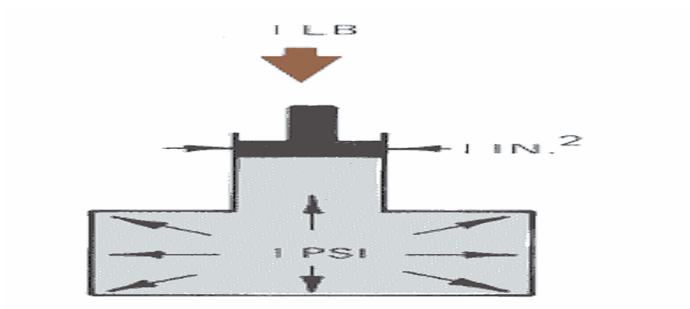


Fig. 30-1-1 Pascal's law.

Since fluids are practically incompressible, mechanical forces may be transmitted, multiplied, or controlled by means of hydraulic fluids under pressure. This is demonstrated in Fig. 30-1-2. Assume that the masses of pistons *P* and *W* are equal. Assume also that the face of piston P has an area of 1 in.^{2}, that the face of piston *W* has an area of 50 in.^{2}, and that the two communicating containers are filled with liquid.

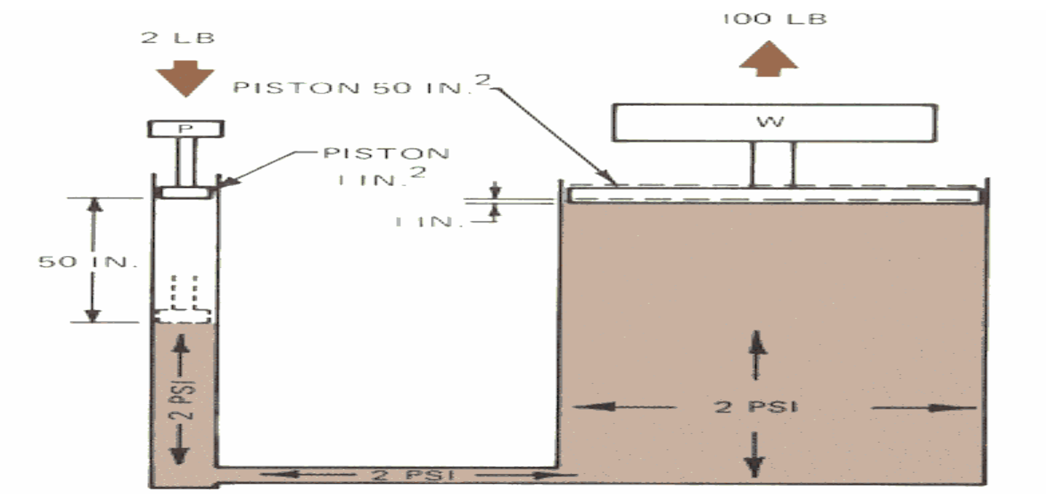


Fig. 30-1-2 Transmission of mechanical forces.

If we were to exert a downward force of 2 lb on piston *P*, this force would be transmitted undiminished in every direction, acting with equal force on equal areas. Since the area of piston *P* is 1 in^2, the pressure at every point in the system is 2 psi. When a pressure of 2 psi is applied to the lower surface of piston *W*, the resultant upward force is 2 x 50, or 100 lb, because the area of piston *W* is 50 $in.^2$ and force equals pressure times area.

In either case, we can multiply force only by sacrificing distance proportionally. If we move piston *P* downward a distance of 50 in., we have forced 50 in^3 of liquid to the underside of piston *W*. Since piston *W* has an area of 50 $in.^2$, 50 in^3 of liquid can raise piston *W* only 1 in.

Characteristics of Flow

Pascal's law neglects the factor of friction because it deals with static fluids. When a fluid flows in a hydraulic circuit, friction results and heat is produced. Thus some of the energy being transferred is lost in the form of heat energy.

Although friction can never be eliminated entirely, it can be controlled to some extent. The four main causes of excess friction in hydraulic lines are excessive length of lines, excessive number of bends and fittings or improper (too sharp) bends, excessive fluid velocity caused by undersized lines, and excessive viscosity of fluid.

Figure 30-1-3 illustrates the effect of friction upon pressure. Since pressure is a result of resistance to flow, the pressure at point *B* is zero. Assume that the mass of the fluid and the diameter of tube *A* are such that a static pressure of 10 lb/ $in.^2$ is created at point *C*. Then the flow from point *C* to point *B* has resulted in a pressure drop of 10 $lb/in.^2$

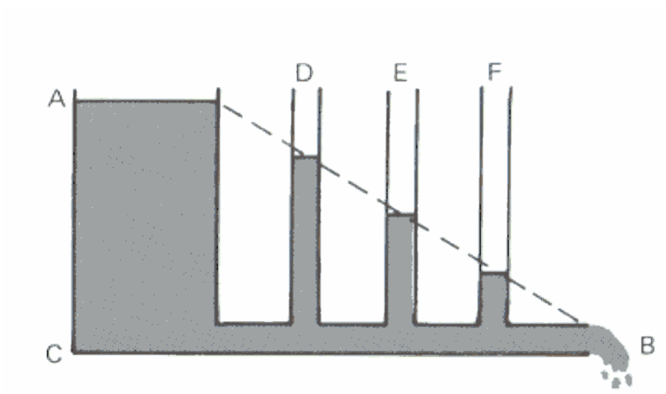


Fig. 30-1-3 Illustrating the effect of friction upon pressure.

The potential energy at point C is completely dissipated in moving the fluid to point *B*. This potential energy has been converted into the heat energy produced by the friction of the fluid moving through the tubes.

The height of the fluid in tubes *D*, *E*, and *F* illustrates the action of friction in producing a pressure drop. In a moving fluid, pressure drop tends to increase and pressure tends to decrease as the distance from the source of pressure increases.

Helpful Information

Some of the points already mentioned are repeated below, along with several additional facts that may help in understanding machinery hydraulics.

1. Oil is the most commonly used hydraulic fluid because it serves as a lubricant for hydraulic components and is practically incompressible.
2. The mass of oil varies considerably with change in viscosity. However, 55 to 58 lb/ft^3 (2.6 to 2.8 kPa) covers the viscosity range of common hydraulic fluids.
3. Pressure at the bottom of a 1-ft column of oil will be approximately 0.4 psi. To find the approximate pressure at the bottom of any oil column, multiply the height in feet by 0.4.
4. There must be a pressure drop (pressure difference) across an orifice or constriction to cause flow through it. Conversely, if there is no flow, there will be no pressure drop.
5. A fluid is pushed into a pump. Atmospheric pressure supplies this push (in an unsupercharged pump) at 14.7 lb/in.^{2} (101.3 kPa) at sea level.
6. The force exerted by a cylinder is dependent on the pressure applied and the piston area.
7. The speed of a cylinder is dependent on its piston area and the rate of fluid flow into it.
8. The flow velocity through a pipe varies inversely with the square of the inside diameter (ID). Doubling the ID increases the area 4 times.

HYDRAULIC CIRCUITS

All *hydraulic circuits* are essentially the same regardless of the application (machine tools, airplanes, farm equipment, boats, etc.). There are four basic components required: a tank (reservoir) to hold the fluid, a pump to force the fluid through the system (the pump is driven by an electric motor or other power source), valves to control fluid pressure and flow, and an actuator (a cylinder for linear or a motor for rotary motion) to convert the energy of fluid movement into mechanical force to do the work.

The complexity of hydraulic systems will vary, of course, depending on the application.

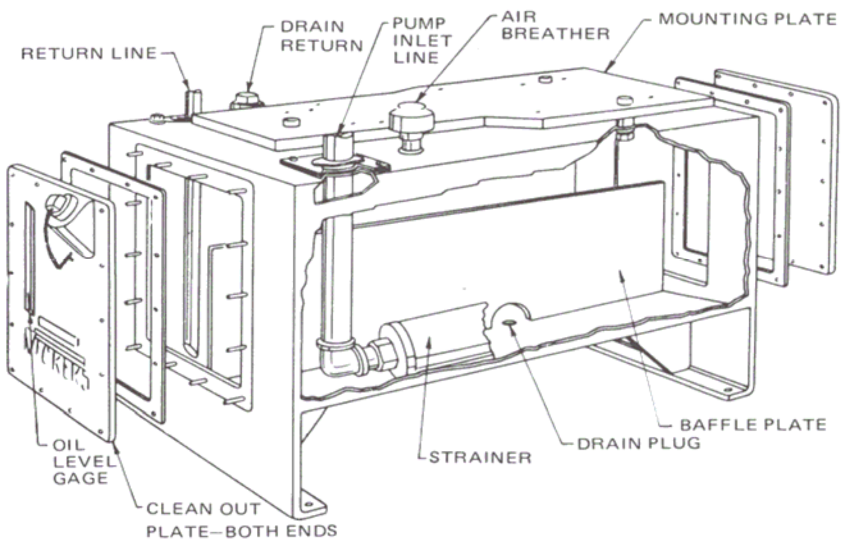
HYDRAULIC EQUIPMENT

Reservoirs

Although it primarily serves as a supply source for hydraulic system fluid, a well-designed reservoir serves other useful purposes. Its construction assists in the separation of air and contaminants from the fluid and helps to dissipate heat generated within the system.

A reservoir that conforms to Joint Industry Conference (JIC) specifications is illustrated in Fig. 30-1-4. The tank is constructed of hot-rolled steel plates with welded joints. Extension of the tank ends support the tank and may be bolted to the floor. The tank bottom is concave and has a drain plug in the middle.

Fig. 30-1-4 Reservoir. (Vickers Incorporated)

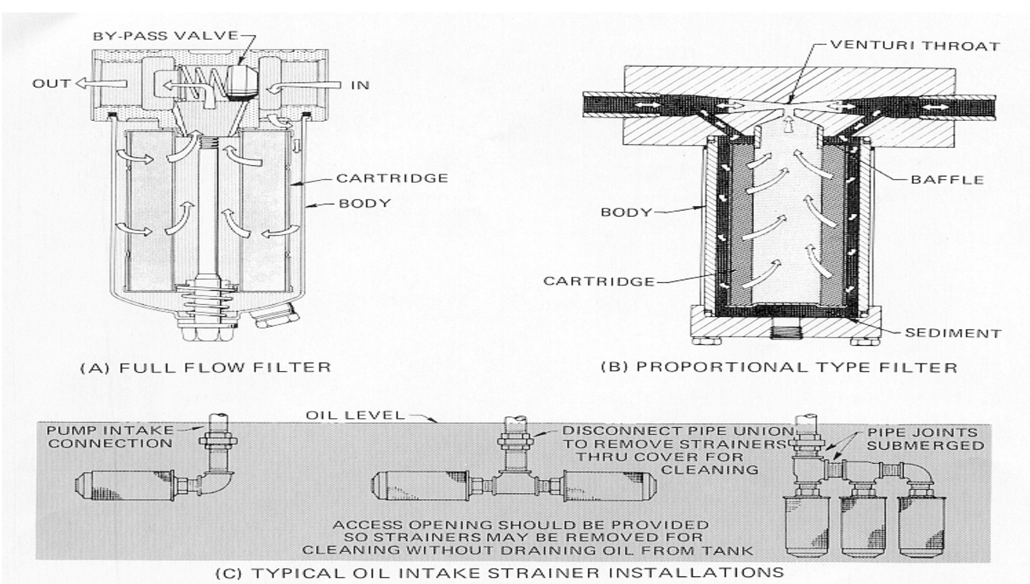


Strainers and Filters

To ensure long life and trouble-free performance of hydraulic components, it is important to keep the hydraulic fluid clean.

Filters, strainers, and magnetic plugs can be used to remove foreign particles from the hydraulic fluid and are most effective as safeguards against contamination. Typical filters and strainers are shown in Fig. 30-1-5.

Fig. 30-1-5 Filters and strainers. (Vickers Incorporated)



Hydraulic Fluids

Hydraulic fluid characteristics have an important effect on equipment performance and maintenance.

In addition to serving as a power transmitting medium, hydraulic fluid must keep wear to a minimum by providing good lubrication.

Hydraulic Pumps

Hydraulic pumps are devices for converting mechanical energy into hydraulic energy. When a hydraulic pump is operated, it performs two functions. First, its mechanical action creates a partial vacuum at the pump inlet that enables atmospheric pressure in the reservoir to force liquid through the inlet line into the pump. Second, its mechanical action delivers this liquid to the pump outlet and forces it into the hydraulic system.

Pumps are broadly classified as either non-positive-displacement or positive- displacement units.

A non-positive-displacement pump produces a continuous flow. However, because of its design, there is no positive internal seal against leakage, and its output varies considerably as pressure varies.

Practically all pumps used in power hydraulic systems — on industrial machinery, mobile vehicles, or aircraft — are of the positive-displacement type.

A positive-displacement pump produces a pulsating flow, but since it provides a positive internal seal against leakage, its output is relatively unaffected by variations in system pressure. See Fig. 30-1-6.

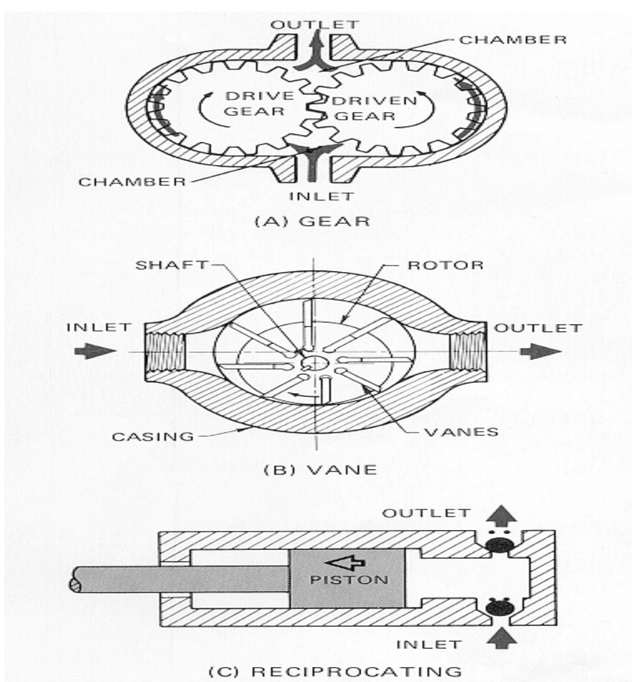


Fig. 30-1-6 Positive-displacement pumps.

Actuators

Hydraulic actuators and hydraulic pumps have opposite functions; the actuators convert hydraulic energy back to mechanical energy to perform useful work. In a typical circuit, the actuator is mechanically linked to the workload, and is actuated by fluid from the pump so that thrust or torque is transferred to the work.

Actuators can be classified broadly as either linear or rotary. A *linear actuator* such as a ram or cylinder is used for such operations as clamping, pressing, or traverse and feed motions. *Rotary actuator* applications include chucking, indexing, and turning.

Linear Actuators The simplest linear actuator is the single-acting cylinder or ram (Fig. 30-1-7A), which applies force in only one direction. Fluid directed into the housing displaces the rod hydraulically; the retracting force can be gravity or some mechanical means, such as a spring.

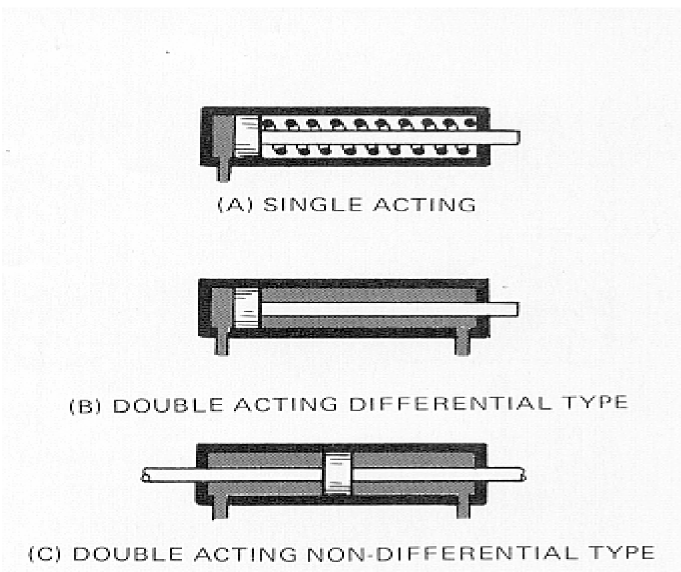


Fig. 30-1-7 Cylinders.

A double-acting cylinder (Fig. 30-1-7B) permits application of hydraulic pressure on either side of the piston to control linear motion in either of two opposite directions. The type shown is called a *differential cylinder* because the piston area at the left is larger, providing a slower, more powerful work stroke when fluid pressure is applied to the LH side. The return stroke will be faster due to the smaller piston area. Reciprocating motions of this type are required on machine tools such as shapers. If equal forces in both directions are required, the piston rod is designed to extend through both ends of the cylinder, as in Fig. 30-1-7C. This is a *non-differential-type cylinder.*

Rotary Actuators Rotary actuators or motors, like rotary pumps, are of either the gear, vane, or piston design. The piston design is further divided into radial or axial types. Actually, many hydraulic pumps can be used as motors with little or no modification.

Valves

Valves are used in hydraulic circuits to control pressure, as well as the direction and rate of fluid flow. They can be classified as pressure controls, directional controls, and flow controls.

Valves, like pipes, are generally rated according to size and pressure. The valve name may be based on its usual function (relief valve) or a feature of its construction (gate valve).

Pressure Control Valves The most common type of pressure control valve is the *relief valve.* A relief valve may be used to provide overload protection for circuit components or to limit the force or torque exerted by a linear actuator or rotary motor. With a relief valve the flow is diverted back to the reservoir.

A relief valve of the simple type is shown in Fig. 30-1-8A. The valve is installed so that one port is connected to the pressure line, the other to the reservoir. The ball is held on its seat by thrust of the spring. Turning the adjusting screw can change spring thrust.

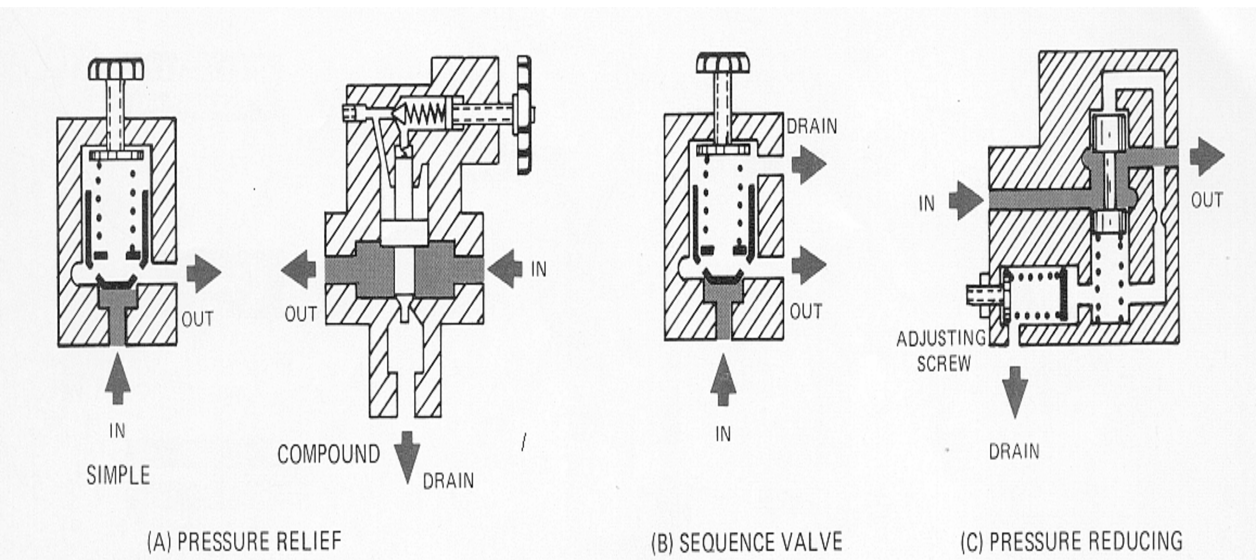


Fig. 30-1-8 Pressure control valves.

When pressure at the valve inlet is insufficient to overcome spring force, the ball remains on its seat and the valve is closed as shown. The position of the ball prevents flow through the valve.

When pressure at the valve inlet exceeds the adjusted spring force, the ball is forced off its seat and the valve is opened. Liquid flows from the pressure line through the valve to the reservoir. This diversion of flow prevents further pressure increase in the pressure line. When pressure decreases below the valve setting, the spring reseats the ball and the valve is again closed.

Sequence valves, as shown in Fig. 30-1-8B, are used on machines requiring operations that must occur in a proper sequence. Sequence valves will not operate until the pressure of one unit has reached a certain level. Sequence valves differ from relief valves in that when a sequence valve is used the flow is diverted to another portion of the system to perform work.

Pressure-reducing valves are used to block or modulate flow at a preset pressure. Unlike the two valves discussed so far, reducing valves are normally open, the most common being a spool valve, which is shown in Fig. 30-1-8C.

Directional Control Valves

Although all *directional control valves have* a common function of controlling direction of fluid flow, they vary considerably in construction and operation.

Directional controls can be classified on the basis of principal characteristics: the type of internal valving element, the method of actuating the valving element, and the number of positions of the valving element as well as the flow paths created in the various positions.

Check valves are the simplest of all directional control valves. They permit fluid to flow in one direction only. See Fig. 30-1-9.

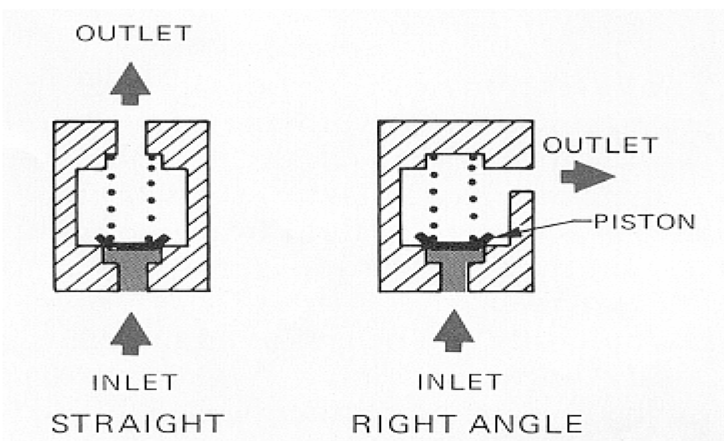


Fig. 30-1-9 Check valves.

Multiple-way valves are known as two-way, three-way, or four-way, depending on the number of primary parts the valve contains. See Figs. 30-1-10 through 30-1-12. The operation of a two-way sliding- spool valve is shown in Fig. 30-1-10.

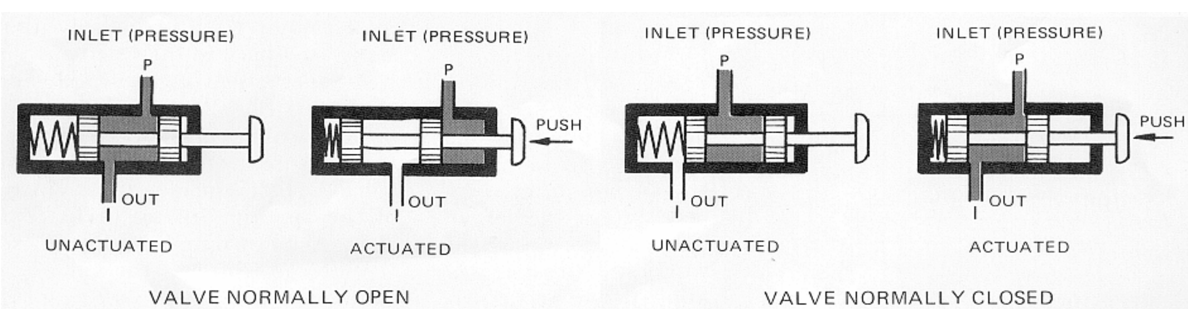


Fig. 30-1-10 Two-way, two-position valves.

Many variations are possible when classifying valves according to the number of positions or flow paths. They may be of the simple on-off variety or have a wide selection of flow paths through them.

Usually containing a sliding spool, two-way valves provide a choice of two flow paths exclusive of the valve's center position. In either shifted position, the pressure port is open to one cylinder port, but the opposite cylinder port is not open to the tank. (In a four-way valve, the opposite cylinder port would be open to the tank, making two flow paths in either shifted position.)

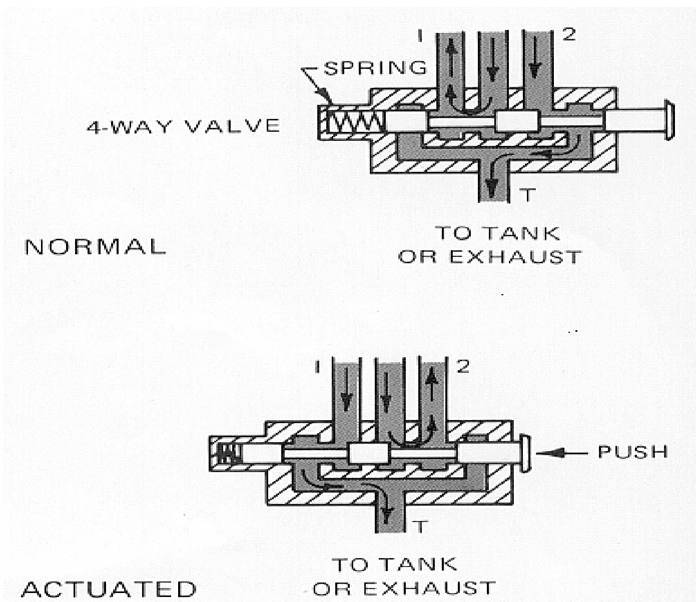


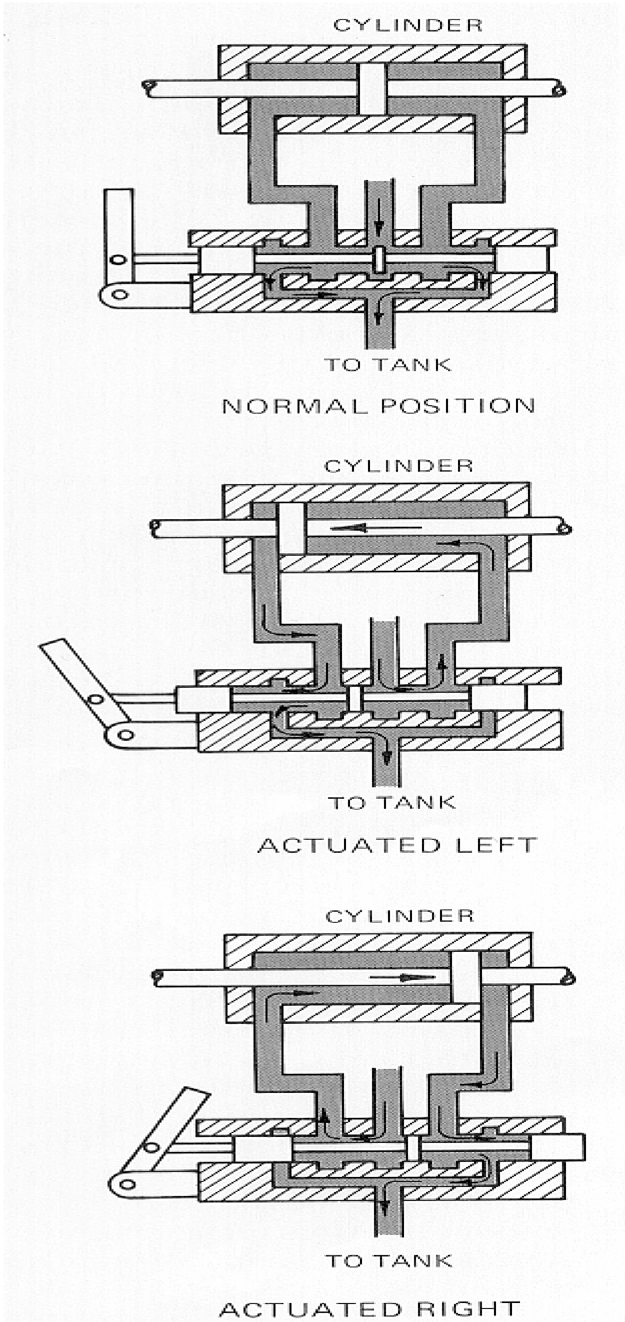
Fig. 30-1-11 Four-way, three-position valve.

Flow Control Valves The widespread use of hydraulic circuitry in machine tool applications stems in part from the ease with which traverse and feed rates can be controlled through the use of various types of flow controls.

The speed of an actuator, whether it be a hydraulic cylinder or a motor, is determined by its displacement and the amount of fluid available to it. Changing the displacement would change the operating speed and would have an inverse effect on the force or torque output. For this and other reasons, such as the impracticability of changing the bore of a cylinder, speed control usually is accomplished by controlling the flow rate.

With full pump delivery directed into a cylinder, the actuator travels at its maximum speed. A larger pump would move it faster; a smaller one would move it more slowly. Logically, then, the use of a variable delivery pump would provide a relatively simple means of controlling actuator speed. Since operating pressure would vary with the workload, the volumetric efficiency of the pump would determine feed-rate accuracy.

A restrictor-type flow control valve (Fig. 30-1-13) has a compensator spool, which is held in position by a light spring, and pressure sensor beyond the throttle. In this type, the compensator spool is normally held in the open position, and tends to shut off, not permitting fluid in excess of the throttle setting to enter the valve. The balance of the pump delivery is then available for other purposes.



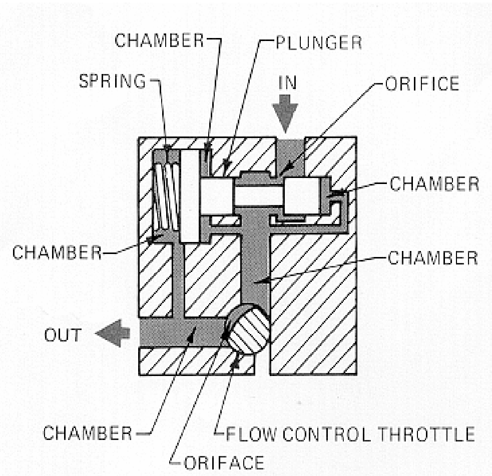


Fig. 30-1-13 Flow control valve.

Fig. 30-1-12 Four-way, three-position valve.

FLUID CIRCUIT DIAGRAMS

An accurate diagram of the fluid circuit is one of the most important pieces of literature accompanying a machine. The information shown in the circuit diagram is essential for an understanding of the operation of the machine and for installation or troubleshooting.

Not all circuit diagrams are complete. For instance, a diagram that is to be used only for piping would not need to show the sequence of operations or sizes and ratings of the components.

Fluid circuit diagrams are of four types, namely, pictorial, cutaway, graphical and combination. The type used depends on the amount and kind of information required. Pictorial and cutaway diagrams are illustrated in Fig. 30-1-14.

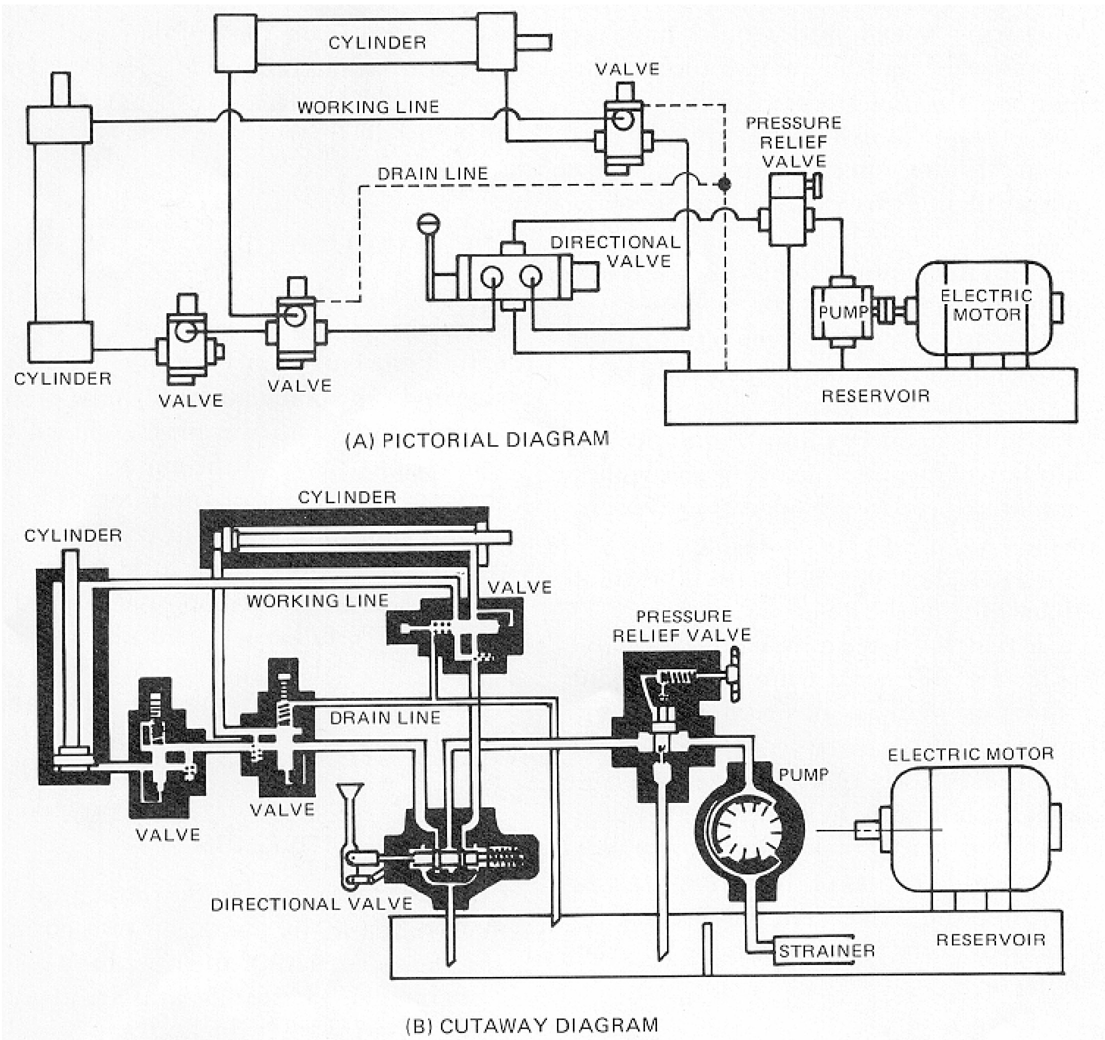


Fig. 30-1-14 Comparison between pictorial and cutaway diagram. (Vickers Incorporated)

Pictorial Diagrams

A pictorial diagram is primarily used to show the piping arrangement of a circuit. The symbols are outline drawings showing the actual external shape of the components, with the piping shown to the various parts of the units. Because they show nothing of the internal construction or function of the components, pictorial diagrams have little value for instruction or troubleshooting. Pictorial symbols are difficult to standardize on a functional basis. Typical pictorial symbols are shown in Figs. 30-1-14A and 30-1-15.

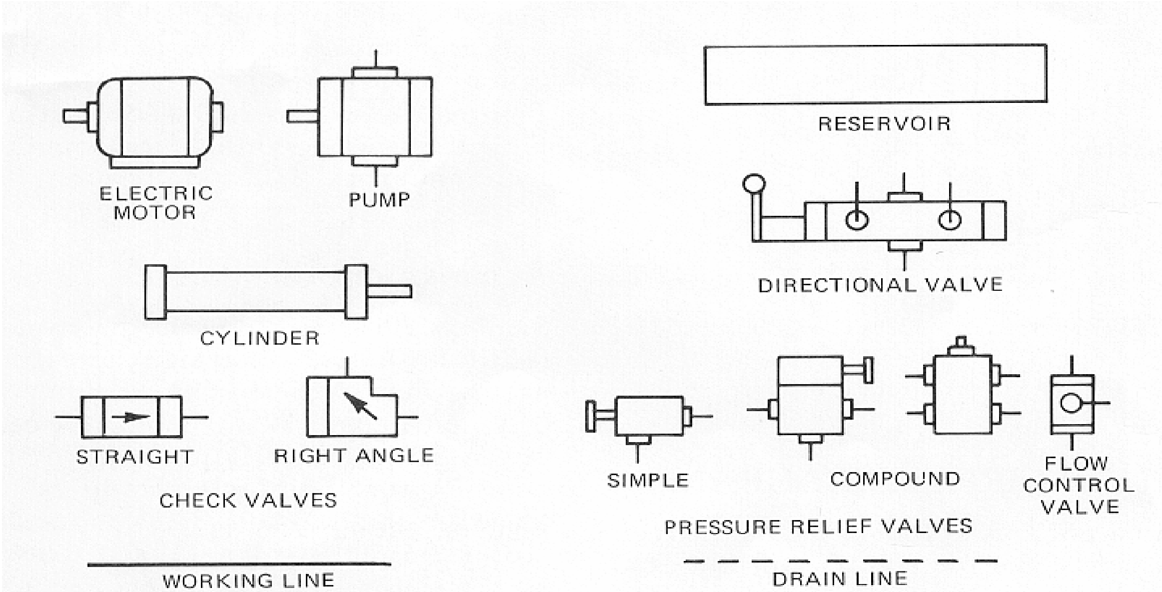


Fig. 30-1-15 Typical pictorial diagram symbols.

Cutaway Diagrams

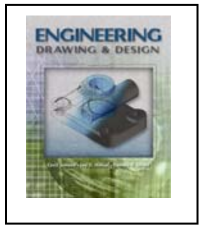
Cutaway diagrams contain much information about the operation of a circuit and the construction and operation of its components. These diagrams are ideally suited for instruction and are widely used for that purpose. Because of the time and cost involved, they are seldom made for other purposes. Cutaway symbols are difficult to draw, and the part functions are not readily apparent. Figures 30-1-5 and 30-1-14B illustrate typical cutaway symbols for common hydraulic parts.

Arrangement of Symbols

Symbols are arranged in the diagram to facilitate the use of straight interconnecting lines. Where components have definite mechanical, functional, or otherwise important relationships to one another, their symbols should be so placed in the diagram. The conductors (interconnecting lines) are drawn straight for clarity. They are not intended to indicate actual installation of pipelines and are drawn as single or double lines depending on the type of diagram. Single lines are used on pictorial diagrams, double lines on cutaway diagrams.

Chapter 30
Fluid Power

UNIT 30-2



Graphical Diagrams

Most application and service engineers for designing and troubleshooting hydraulic circuits prefer *graphical diagrams*. The graphical symbols are combinations of simple geometric figures that are easy to work with and which clearly define the types and functions of the components. No attempt is made to show the shape or internal construction of a component.

Note the differences in the diagrams shown in Fig. 30-2-1.

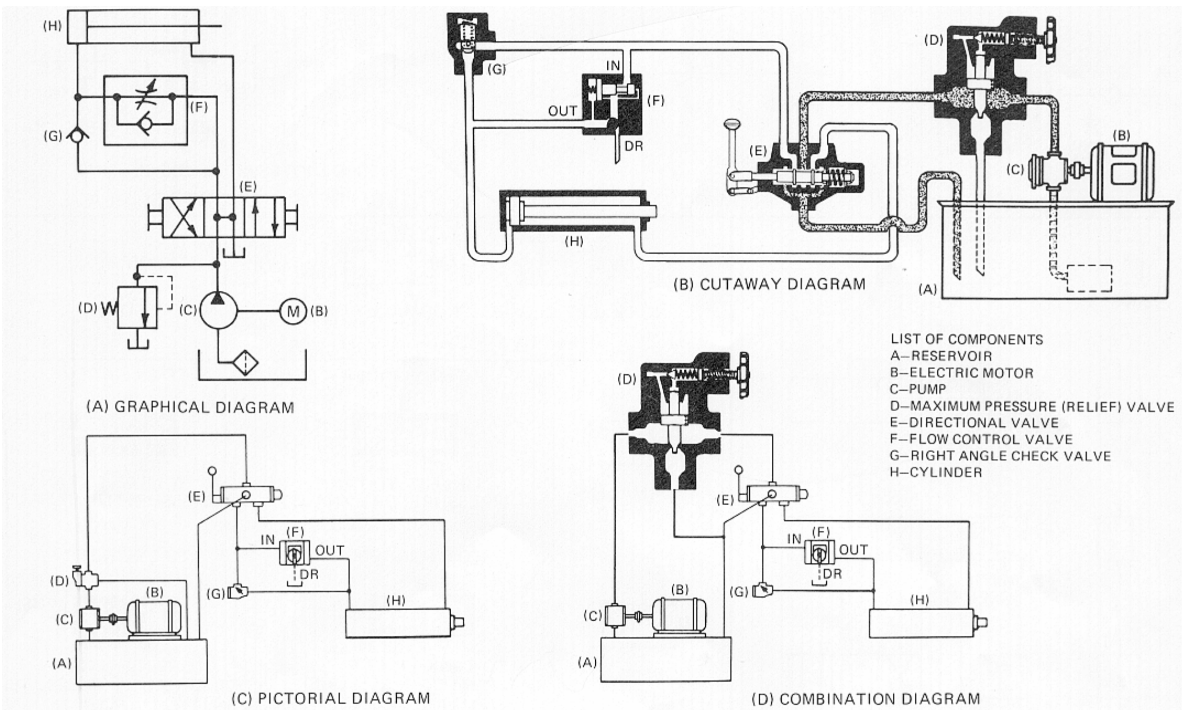


Fig. 30-2-1 Fluid circuit diagrams (Vickers Incorporated).

Some of the standard graphical symbols specified by the Joint Industry Conference (JIC) are shown in Fig. 30-2-2. The symbols can be combined in any form that is necessary to correctly depict a composite unit. Unless multiple diagrams are furnished showing the various phases of operation, the symbols will be shown in a diagram in their normal or neutral position. The reservoir symbol, like that of the electrical ground symbol, may be repeated several times on a graphical diagram.

Directional valves, because of various types of controls and flow paths, require a number of different symbols. A basic directional valve symbol consists of an envelope (square) for each position of the valve. The envelopes are drawn side by side in their correct order with each showing the flow path for its position. The method of actuating a valve is also shown symbolically. See Fig. 30-2-3.

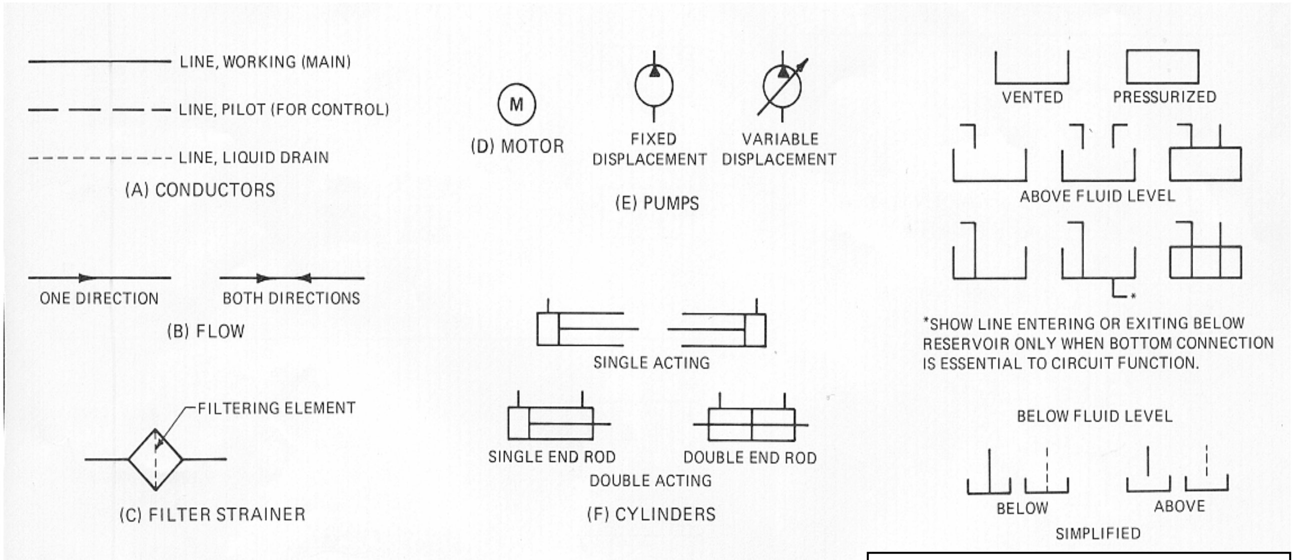


Fig. 30-2-2 Graphical symbols. (Vickers Incorporated)

(G) Reservoir with Connecting Lines

SYMBOL RULES

1. Symbols show connections, flow paths, and function of the component represented. They do not indicate conditions occurring during transition from one flow-path arrangement to another. Further, they do not indicate construction or values such as pressure, flow-rate, and other component settings.

2. Symbols do not indicate the location of ports, direction of shifting of spools, or position of control elements on actual components.

3. Symbols may be rotated or reversed without altering their meaning.

4. Line width does not alter meaning of symbols.

5. Symbols may be drawn any suitable size. Size may be varied for emphasis or clarity.

6. Letter combinations used as parts of graphical symbols are not necessarily abbreviations.

7. Where flow lines cross, a loop is used, except within a symbol envelope. A loop may be used in this case if clarity is improved by its use.

8. In multiple envelope symbols, the flow condition shown nearest a control symbol takes place when that control is caused or permitted to actuate.

9. Each symbol is drawn to show the normal or neutral condition of the component unless several circuit diagrams are furnished showing various phases of circuit operation.

10. Arrows should be used within symbol envelopes to show the direction of flow path in the component as used in the application represented. A double-ended arrow is used to indicate reversing flow.

11. External ports are where flow lines connect to the basic symbol, except where component enclosure is used.

12. External ports are at the intersections of flow lines and the component enclosure symbol when enclosure is used.

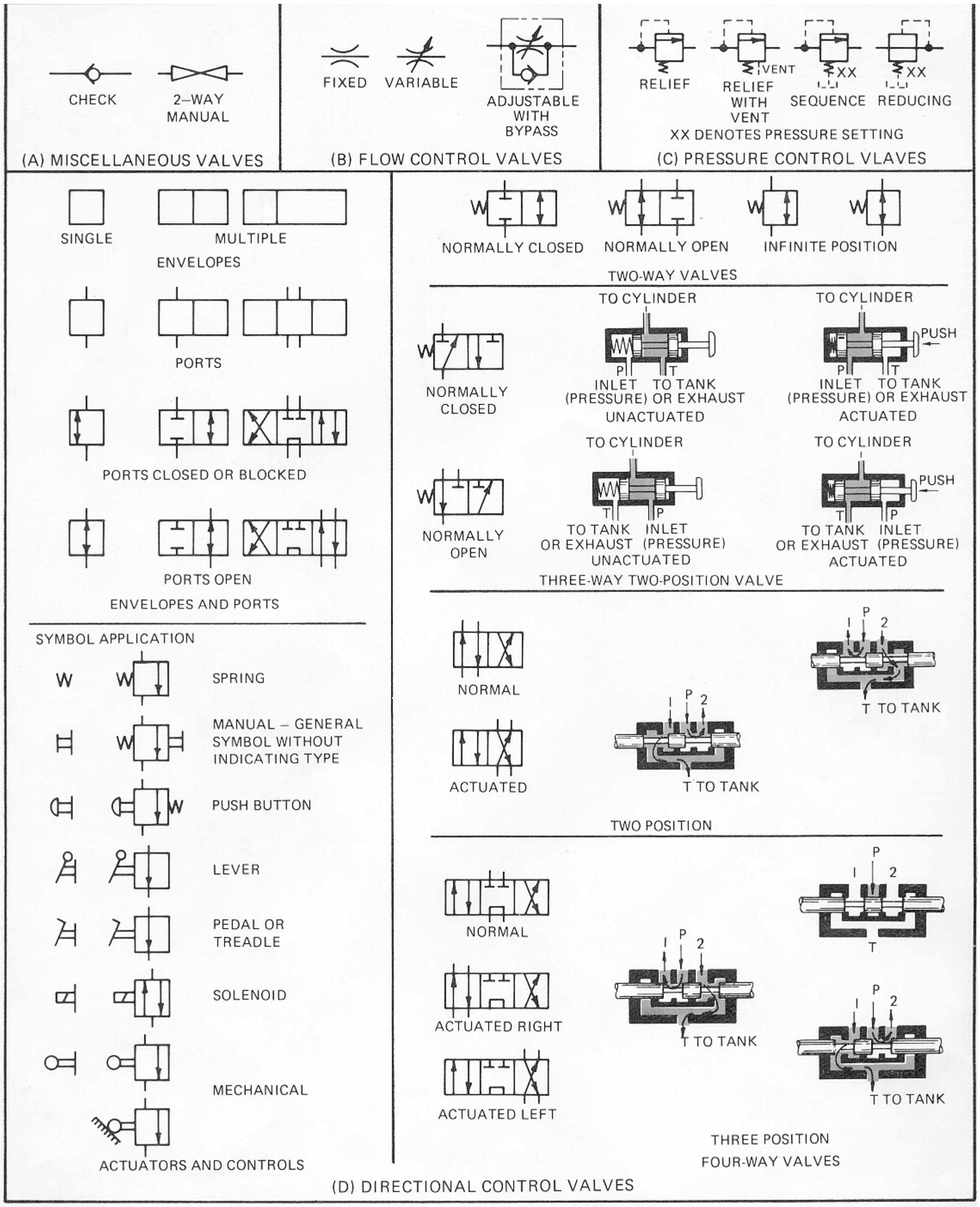


Fig. 30-2-3 Graphical valve symbols.

HYDRAULIC CIRCUITS

EXAMPLE 1 Figure 30-2-4 is a typical example of a simple hydraulic circuit. When the directional control valve (two--position, three-way, spring-operated, push-button control) is in the position shown in Fig. 30-2-4A, the cylinder piston extends. When the piston reaches the end of its stroke, the pump flow is then diverted through the pressure control (relief) valve.

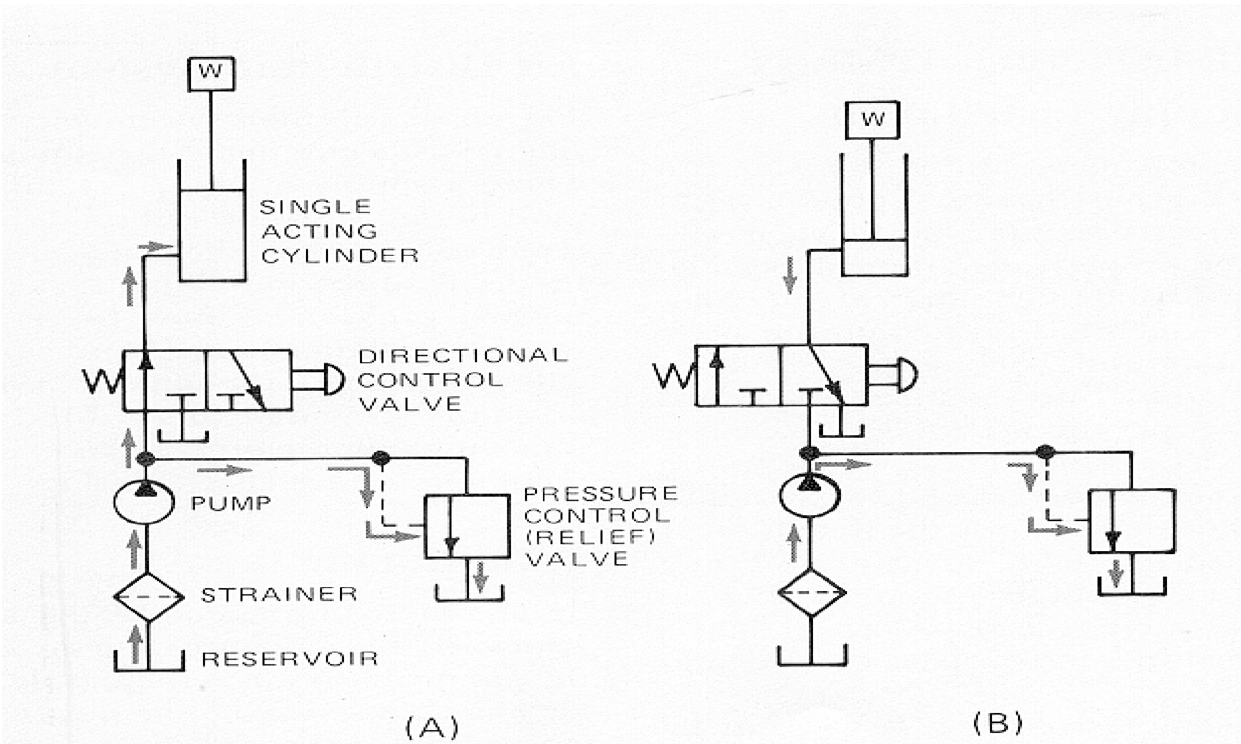
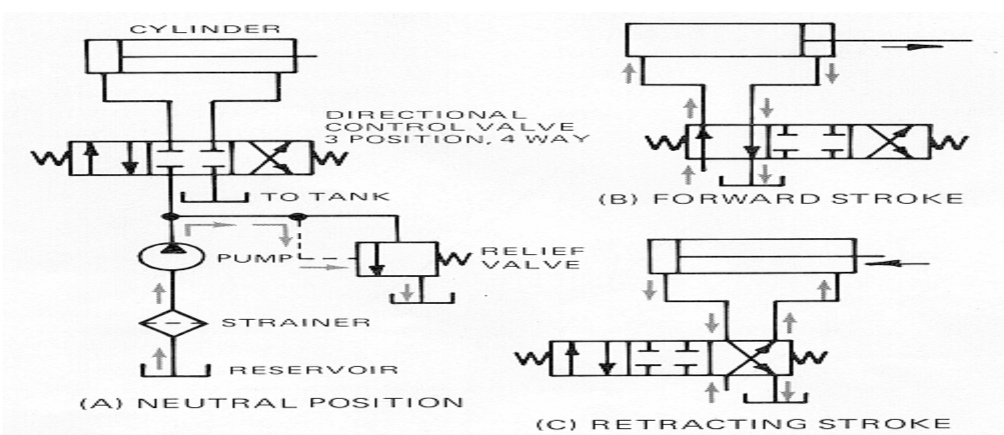


Fig. 30-2-4 Simple hydraulic circuit.

When the push button is operated on the directional control valve, the port to the pump is blocked, as shown in Fig. 30-2-4B. The weight (mass) of the piston forces the hydraulic fluid from the cylinder through the directional control valve to the reservoir, and the piston retracts. Since pump flow through the directional control valve is blocked, the fluid is diverted through the pressure control (relief) valve back to the reservoir.

Fig. 30-2-5 Graphic diagram showing a three-position, four-way valve controlling a cylinder.



EXAMPLE 2 Figure 30-2-5 shows a simple hydraulic circuit using a three-position, four-way valve controlling the movement of a double-acting cylinder. Figure 30-2-5A shows the control valve in its neutral position. Since pump flow through the directional control valve is blocked, the fluid is diverted through the pressure control (relief) valve back to the reservoir.

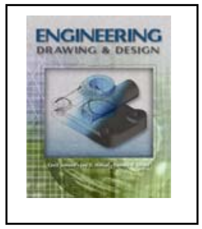
When the operator shifts the control valve to the right, fluid is directed to the head of the cylinder (Fig. 30-2-513). The fluid at the other end of the cylinder is directed back to the reservoir. The pump continues to pump oil after the cylinder rod has completed its stroke. This excess oil is returned via the relief valve to the reservoir.

At the end of the forward stroke, the operator shifts the control valve to the left that causes the cylinder rod to retract (Fig. 30-2-5C). Fluid is directed to the rod end of the cylinder and the fluid from the head end returns to the reservoir. When the operator releases the control valve handle, the valve returns to its neutral position.

References and Source Material

1. Vickers Incorporated.
2. *Machine Design*, fluid power reference issues.

Chapter 30
Fluid Power



UNIT 30- 3

Pneumatics

Compressed air has been used as a means of transmitting power for a long time, but in recent years pneumatics has taken on a new sophistication. With the availability of miniaturized valves and fluidic devices, air can now supply the nerves and brains, as well as the muscles, of complex automated equipment.

What is air? Air may be defined as a colorless, odorless, tasteless gas, principally composed of nitrogen, oxygen, carbon dioxide, and water vapor. Its molecules are widely separated and in constant motion, traveling in straight lines. At sea level, air exists at a pressure of 14.7 lb/in.^{2} (101.3 kPa). Air mixes readily with other fluids.

BASIC LAWS
There are several simple basic laws governing the behavior of air that are important to pneumatic system design.

Boyle's Law This law defines the relationship between volume and pressure and states that if the temperature is constant, the volume of a given mass of gas varies inversely as its absolute pressure. It can be written

$P_1V_1 = P_2V_2$
Where
P_1 = the initial pressure (absolute)
V_1 = the initial volume
P_2 = the final pressure (absolute)
V_2 = the final volume

Charles' Law This law refers to the behavior of a gas when changes in temperature take place and states that when there is no change in volume, the pressure of a gas varies directly with its absolute temperature.

Pascal's Law This law states that the pressure of a gas in a container is transmitted undiminished in all directions and acts at right angles to the surfaces of the container. See Fig. 30-1-1.

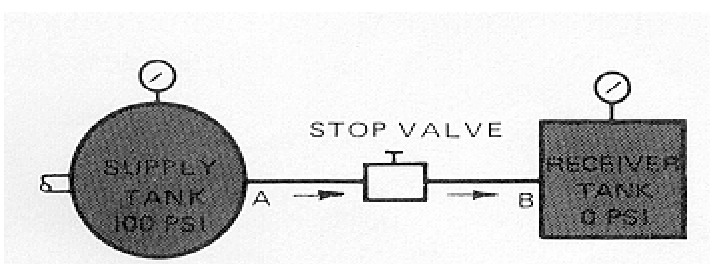


Fig. 30-3-1 Receiver critical back pressure is 53% supply pressure.
Airflow

Air will only flow when a difference of pressure exists and flows *toward* the lower pressure. The rate of flow depends on the initial pressure, the difference in pressure, and the size, shape and smoothness of the orifice. The shape and smoothness of the orifice are important. A straight or smoothly curved pipe assists airflow, and smooth inner walls reduce friction. Rough surfaces slow adjacent layers of air and reduce the effective area of the pipe.

Critical Back-Pressure Ratio

In an enclosed air system, one other factor must be considered. Figure 30-3-1 shows a supply tank at a constant pressure of 100 lb/in.^{2} connected through a stop valve to a receiver tank at atmospheric pressure (0 lb/in.^{2}). If the stop valve is opened, air will flow from' *A* to *B* at a rate dependent on the orifice and pipe characteristics. Continuing flow will reduce the differential pressure between the supply and receiver tanks, but it is an observed phenomenon in gas behavior that the rate of flow does not change until the receiver tank pressure has reached 53 percent of the supply pressure, in this case, 53 lb/in.^{2}. Conversely, if the pressure in the receiver falls below 53 lb/in.^{2}, any further decrease in pressure will not increase airflow. This is called the *critical back pressure ratio,* and can be important when selecting the size of a valve.

PNEUMATIC EQUIPMENT
Air Supply Installation

Before any pneumatic equipment can operate, it must have a supply of air at the correct pressure, in sufficient volume, and properly conditioned. See Fig. 30-3-2. The supply starts at the compressor which has a rated output pressure in pounds per square inch or pascals and a rated volume in standard cubic feet per minute (SCFM) or cubic meters per second. This is often known as *free air delivered* (FAD). A standard cubic foot (ft^3) of air is the weight of air contained in 1 ft^3 of space at 707 and 14.7 lb/in.^{2} absolute. A standard cubic meter of air is the mass of air that is contained in I m^3 of space at 21ºC and 101.3 kPa.

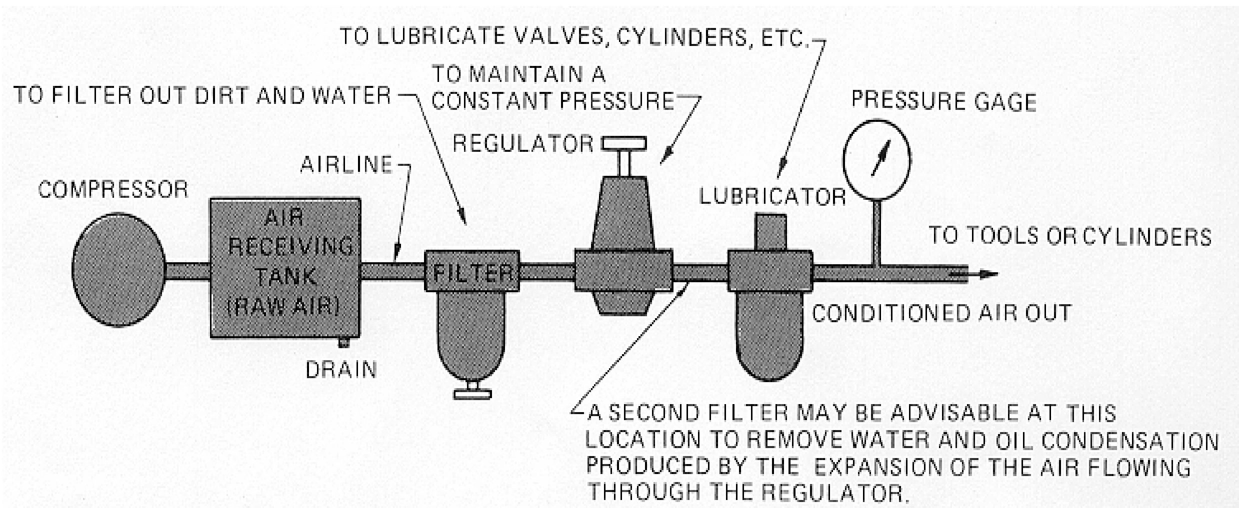


Fig. 30-3-2 Basic pneumatic components.

The compressor obeys Boyle's law by pushing air at atmospheric pressure into a smaller volume to increase the pressure. Unfortunately, Charles' law dictates that as pressure increases, so does temperature; and warm air contains more water vapor than cool air.

To decrease water content, a filter should be fitted immediately downstream of the compressor where moisture can be precipitated and drained off.

Although there is a definite trend toward oil-free compressors, industrial compressors are still predominantly of the oil-flooded type. Most have internal oil separators that are of quite high efficiency, but a certain amount of oil vapor does get through. This oil can contain wear particles from compressor parts; it also tends to be burned due to the heat of compression. To prevent contamination of the air system, it is recommended that an efficient oil separator be fitted between the compressor discharge point and the air receiver.

Air Distribution System

The air distribution system will be considered as beginning at the storage tank where a supply of air is available with most of the oil vapor and solids already removed. Between the tank outlet and the feeds to the individual systems, the biggest problem is how to get rid of water. A certain amount of precipitation will take place in the tank, so a drain is normally provided there. Methods of removing water in other parts of a pneumatic circuit are shown in Fig. 30-3-3.

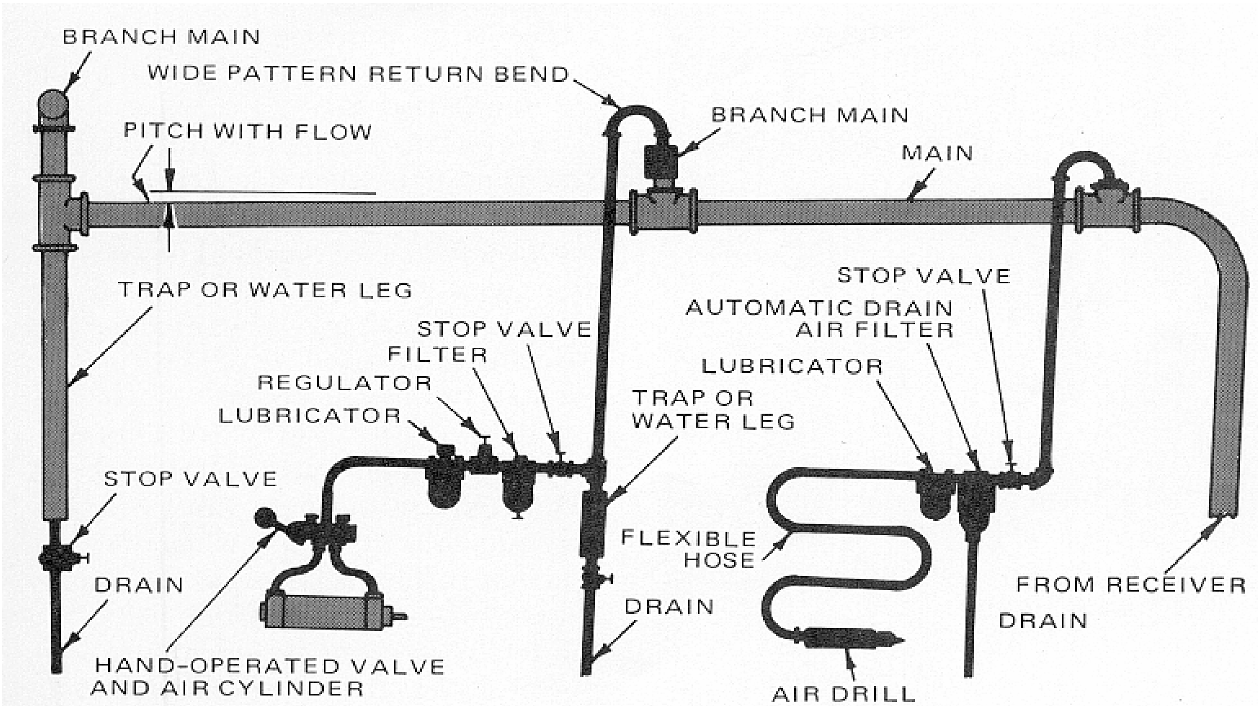


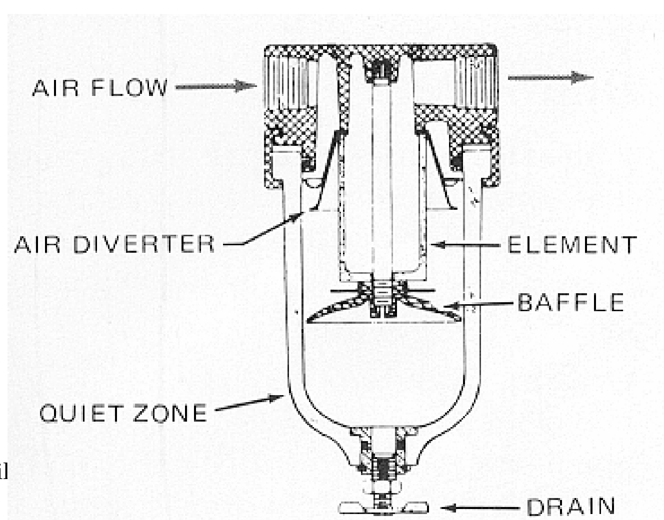
Fig. 30-3-3 Air distribution system (Design Engineering).

Conditioning the Air

So far, the compression of the air, the removal of the moisture from the air, and the piping of the air to the supply points has been discussed. The next concern is to condition the air before it enters the tool, control, or power elements to do some useful work.

Filters The average filter available (Fig. 30-3-4) is designed to do two jobs: remove moisture and remove dirt. When air enters the filter, its path is changed abruptly to a rotary direction, so centrifugal force hurls any particles of water outward. Here they collect on the sides of the filter bowl and gravitate to the bottom where a baffle prevents air turbulence. This area is called the *quiet zone* and is drained by an automatic or manual valve.

Fig. 30-3-4 Typical air filter.



Dirt exists to a greater or lesser extent in various forms in any plant system and is intercepted in most filters by a cartridge element. These elements are rated by the size, in microns, of particles they will intercept. A micron μ is .000 254 in. or 0.001 min (μm).

For work or power air, a filter of 50 to 60 μm rating is normally sufficient, since this air comes in contact with contamination from cylinder or shaft packings. Control air is not normally subject to this, so should be passed through a secondary filter of about 5-micron rating. This finer filtration will add appreciably to the efficiency and life of the control section of the circuit.

Pressure Regulators

The three main reasons for regulating air pressure are:

1. To keep wasted air to a minimum
2. To achieve maximum consistency in circuit performance
3. To maintain an optimum balance between work output of components and their wear rate

A regulator must be chosen to give the correct working range, usually 0 to 125 lb/in^2 (0 to 1000 kPa).

In locating the regulator, always try to get it upstream of a lubricator, since air can be contaminated by the interaction of some oils on the regulator diaphragm.

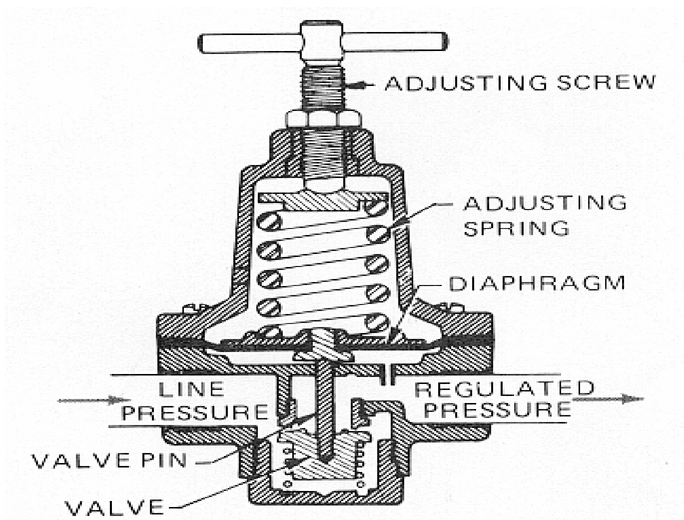
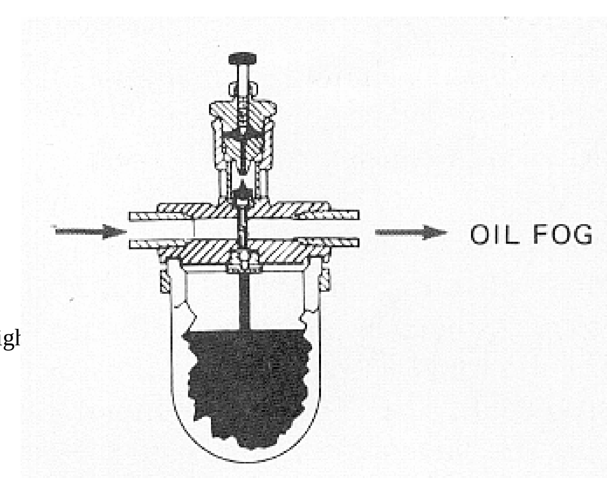


Fig. 30-3-5 Simple spring-type regulator.

Air Lubricators

The standard-type lubricator (Fig. 30-3-6) operates by creating a pressure differential between the lubricant container and a metering chamber. This causes the oil to enter the metering chamber and disperse into the pipeline as fog. Lubricators are



designed to operate with a certain size pipe and airflow.

Fig. 30-3-6 Air lubricator, oil-fog type.

Common types of lubricators in use are the oil-fog type and the micro-fog type. The *oil-fog-type* disperses relatively large drops of oil which have a tendency to fall out early, the normal carrying distance before fallout being about 15 ft (5 in) in a straight length of pipe.

The *micro-fog type* disperses much smaller oil particles that remain in suspension more easily. The suggested carrying distance before fallout for this type is 25 ft (8m) in a straight pipe.

In choosing the lubricant, it is preferable to use the grade recommended by the component manufacturers.

AIR CIRCUIT COMPONENTS

Air circuit elements can be considered under the three separate functions they perform: power, control, and signal.

Power Elements

Cylinders The most common power elements are cylinders, and many factors influence their choice.

If work is to be performed in one direction only, then a *single-acting cylinder* (Fig. 30-1-7A) may be used. This type is retracted by an internal spring, an external load or gravity, or bucking air. If work is to be done in both directions, i.e., if the return load exceeds cylinder friction, a *double-acting cylinder* (Fig. 30-1-713) is needed.

The size of the cylinder will depend on the magnitude of load and the distance it must be moved. The bore can be found from the formula $A = FIP,$ where F is the load and P is the air pressure available. The stroke should equal the distance to be moved.

After it is decided which cylinder will be used, its air consumption must be calculated. This is the volume found by calculating the volume of the free end of the cylinder, adding the volume of the piston rod end if the piston is double-acting, and multiplying by the frequency in strokes per minute.

This calculation is important, but it is often neglected. It must be done not only to decide the size of lubricator required, but also to check if the plant system has the capacity to operate the circuit.

Air Motors *Air motors* are used to convert the energy of compressed air into continuous torque. They are not the most efficient means of producing torque, since the average motor needs about 5 hp (4 kW) at the compressor to produce 1.25 hp (I kW) at the motor, but they still have a lot in their favor.

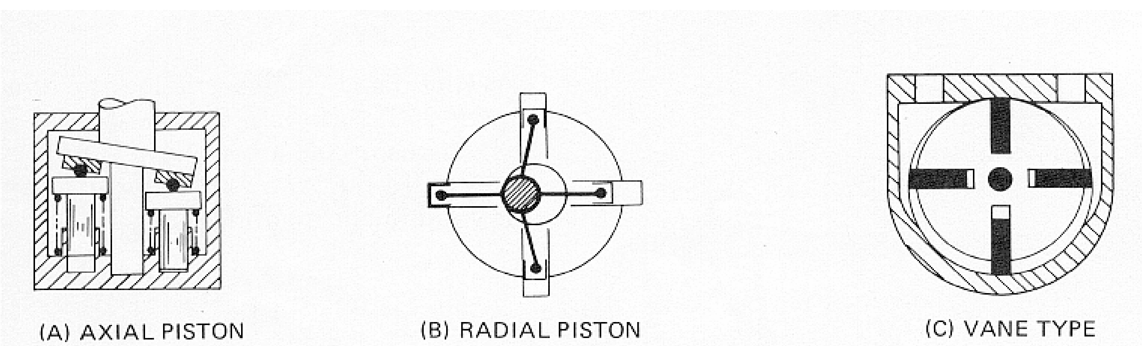


Fig. 30-3-7 Air motors.

With the growing popularity of pneumatic controls, air motors can make some machines or systems independent of electricity, particularly if an internal combustion engine drives the compressor. They cannot be harmed by stalling; they do not overheat, since the air expanding through the motor has a cooling effect; they have a very high power-to-mass ratio; and they are very reliable (seldom break down, only wear out slowly with lots of warning).

There are three main types. These are illustrated in Fig. 30-3-7. The two-piston types are the workhorses, giving high power at lower speeds. *Vane types* are the racehorses, suitable for lighter loads at higher speeds, and they are more compact. The majority of low-kilowatt (horsepower) motors in use are of this type.

In selecting an air motor, it must be remembered that power is proportional to revolutions per minute and pressure. This is the pressure at the motor inlet, so air lines must be big enough to pass the required volume of air. If several motors are operating intermittently from the same air system, surge tanks or air reservoirs should be provided. The motor chosen should give the required power and revolutions per minute at about one-half the maximum pressure, so that there will be no power loss under adverse conditions.

Control Elements

Power Valves *Power valves* direct airflow to and from the work elements.

There are various designs of valve action, and it is helpful if the action requires low thrust to actuate the valve. More important, the required thrust should be constant and unaffected by variations in pressure or airflow through the valve or by changes in friction within the valve.

To eliminate unnecessary air wastage as the valve shifts, the action should block the air supply from the connecting flow paths in the valve as it moves through mid-position.

In most applications, the valve action should be dented to keep it in its selected position in the event of failure in the controlling medium (electricity or air).

A good valve action provides a variety of flow paths by accepting and valving air at any port. This allows the use of the same valve for different circuit functions, such as normally open, normally closed, two-way, three-way, dual-pressure, and others.

There are three methods commonly used to actuate a power valve: mechanical, electrical, and air. In a two-position valve, any combination of these may be used.

The selection of power valves is governed by the airflow required, the flow paths needed, and the method of actuation.

Valves are termed by the number of flow paths they provide, either two- or three-position.

Two-position means that two flow conditions exist that are relative to the position of the valve.

Three-position is similar but has a third flow condition when the valve mechanism is centered.

One other factor must be known when describing a power valve. That is the number of ways it may be used and refers basically to the number of ports or connections in the valve body.

Figure 30-3-8 shows two types of two-way, two-position valves. Air connected to one port on the right valve will only flow out of the other port when the valve is actuated. This is known as a normally closed, two-way two-position valve. On the left is a normally open, two-way, two-position valve, since air flows until the valve is actuated.

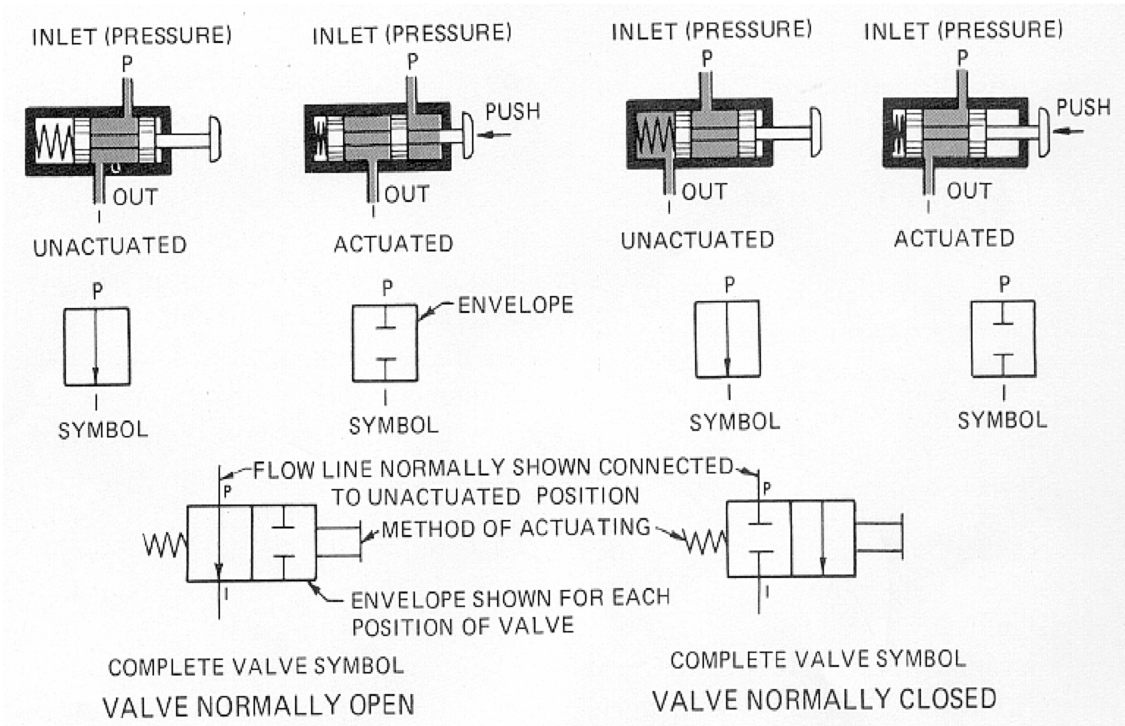


Fig. 30-3-8 Two-way, two-position valves.

PNEUMATIC CIRCUIT DIAGRAMS

Pictorial and Cutaway Diagrams The same types of symbols as those shown in the hydraulic pictorial and cutaway diagrams also apply to pneumatic circuits. See Unit 30-1.

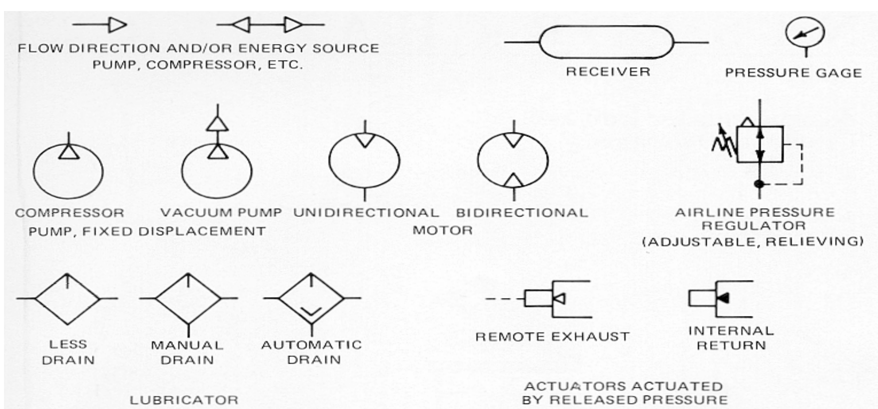


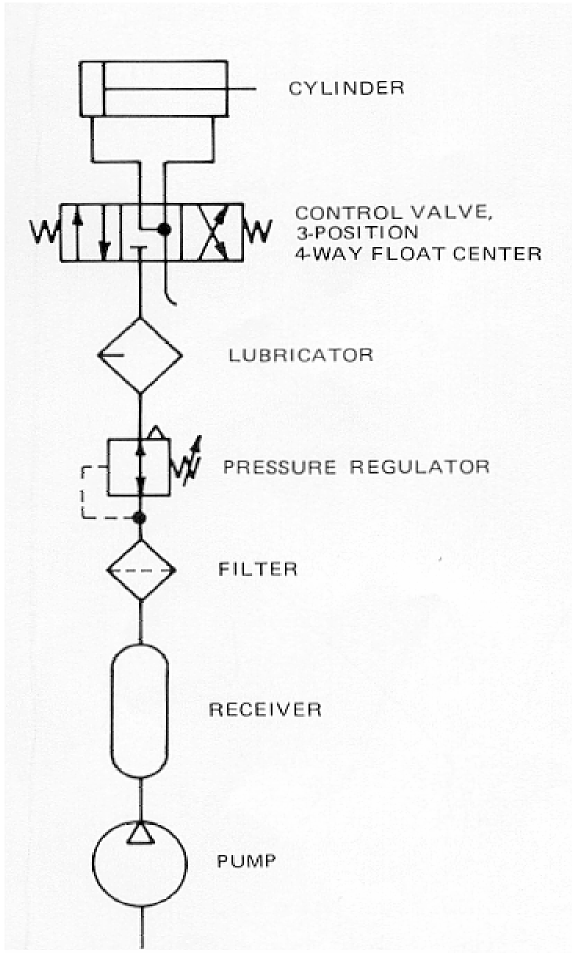
Fig. 30-3-9 Pneumatic graphics symbols.

Graphic Symbols With the exception of the symbols shown in Fig. 30-3-9, pneumatic graphic symbols are identical to those used in hydraulic circuits. See Figs. 30-2-2 and 30-2-3.

Pneumatic Circuits

EXAMPLE 1 (See Fig. 30-3-10) When the operator shifts the control valve to the right, air is directed to the head end of the cylinder. The return air is directed by way of the control valve. The pump continues to pump air after the cylinder rod has completed its stroke. This excess air is disposed of by the pressure regulator valve to the atmosphere.

Fig. 30-3-10 Simple pneumatic circuit.



When the operator releases the control-valve handle, the spring-centered valve returns to neutral. The pressure on the cylinder is relieved while the pressure inlet remains closed, preventing the valve from draining the compressor. With the pressure removed from both ends of the cylinder, the cylinder rod can be moved readily. This action is called *floating* and is used in both air and hydraulic circuitry.

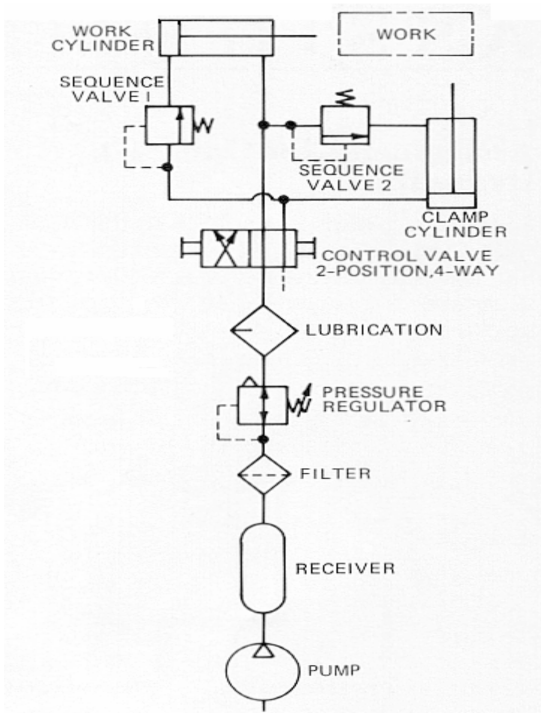


Fig. 30-3-11 Sequence circuit.

EXAMPLE 2 A typical sequence circuit is shown in Fig. 30-3-11. The sequence of operation is (1) extend clamp cylinder, (2) extend work cylinder, (3) retract work cylinder, and (4) retract clamp cylinder. When the control valve is shifted, air is directed into the head of the clamp cylinder extending the piston and clamping the part. Air also flows to sequence valve 1, but no flow occurs through the valve because of the spring-loaded ball. After the clamp cylinder has completed its stroke, pressure builds up in the line and overcomes the spring tension in the valve, permitting air to pass through the valve to the head of the work cylinder. The piston of the work cylinder extends to perform the work. The pressure regulator valve controls the pressure in the line.

When the control valve is released, air pressure flows into the rod end of the work cylinder, retracting the piston. The air also flows to sequence valve 2 but is blocked by the spring-loaded valve. The air from the work cylinder head is forced through the sequence and control valve to the atmosphere.

After the work cylinder is full) retracted, the pressure again builds up and overcomes the spring tension in sequence valve 2, forcing air into the roc end of the clamp cylinder and thus retracting the piston and releasing the work. The air in the head of the work cylinder is forced out of the cylinder through the sequence and control valves to the atmosphere.

References and Source Material

1. J. Mooney, "Course on Basic Pneumatics," *Design Engineering.*

2. Holman Bros. Limited, Maxam Nopak Division.

3. *Machine Design,* fluid power reference issues.

