Section 10
BASIC HYDRAULICS

INTRODUCTION
Fluid power has become indispensable to the industrial world. The Lubrication Engineer must often provide both expert knowledge of the fluids used in hydraulic systems and assistance in the purchase, troubleshooting and redesign of those systems. Specifying requirements for new hydraulic systems may be another aspect of the Lubrication Engineer’s job.

Because hydraulic systems are becoming increasingly complex, often employing electronic control, the engineer must constantly update his knowledge. This Section will outline the basics of modern hydraulic systems and offer a bibliography for those who need more detailed knowledge. Equipping oneself with this knowledge and becoming involved in keeping hydraulic systems operating well can only enhance the job security of the Lubrication Engineer and make him or her a more valuable employee.

FUNDAMENTALS
Benefits
Hydraulics offers many benefits, including compactness, ease of control, built-in overload protection and lower cost, and replaces complex mechanical systems of levers and gears or motor/gear reducer combinations. To be sure, there are disadvantages, chiefly leakage and a shortage of qualified mechanics; but these can be overcome.

Supporting Principles
The usefulness of hydraulics begins with two basic principles. First is Pascal’s Law, discovered by Blaise Pascal in 1620, which states that “pressure exerted on a confined liquid is transmitted undiminished in all directions and acts with equal force on all equal areas” (Fig. 1).

The second important principle regarding hydraulics is that liquids are relatively incompressible. The word “relatively” is used because when liquids are subjected to extremely high pressures (several thousand lb per sq. in.), volume diminishes somewhat.
Though this slight compressibility does not cause any problems under normal hydraulic conditions, the designer must consider it in systems employing servo or proportional valves. This point will be discussed later.

**Force and Pressure**

The principles discussed above give liquids a distinct advantage over mechanical systems in the transmission of power. For instance, when a blow is struck on the end of a metal bar, the direction of thrust cannot be altered; the main force of the blow is carried straight through the bar to the other end, as shown in Fig. 2. This happens because the bar is rigid, which means that with mechanical systems the direction of the force can be changed only by the use of gears and other complex mechanisms.

When a force is applied to a confined liquid, however, the liquid exhibits the same effects of rigidity as a solid; but the force is transmitted not only straight through to the other end but also in every other direction throughout the confined liquid (Fig. 2). When the force is spread out over a large area, as it is in the example, it is customary to speak of it as pressure. We must now distinguish the concept of force from the concept of pressure.

A force is a concentrated effort with direction, generally measured in lb (English system) or Newtons (metric system); it can also be represented by a vector. Pressure, the result of a force spread over an area, is usually measured in lb/sq in. (psi) or kilograms/square centimeter (kg/sq cm). Force itself can be visualized as concentrated at a point.

In the example described above and illustrated in Fig. 2, the hammer blow could be measured in lb of force. However, the fluid inside the container would experience a "pressure" equal to the lb of force divided by the inside area of the piston in contact with the fluid, expressed as psi. The piston area is used because it can move and do work. If the column of fluid changed, exposing more or less fluid to the fixed cylinder walls, the pressure would not change, so long as the piston area remained constant. It is important to remember that although the liquid is pressurized, the actuator piston "exerts" a linear force. (The concept of torque or force in a rotary direction will be introduced later.)

Figure 3 further exemplifies the distinction between pressure and force. The small force (weight of mouse) pushing downward on its small piston area will generate a certain pressure

\[
\text{mouse weight} \\
\text{(small piston area)}
\]

if the large piston is held in place. When a heavy load is placed on the large piston (the elephant) and the large piston is free to move, the large piston will move upward if the
pressure generated by the mouse multiplied by the area of the large piston generates a force greater than the weight of the elephant. The large piston will move downward if the pressure generated by the mouse multiplied by the large piston area is lower than the weight of the elephant. Another way of stating this is:

If small force divided by small area > large force divided by large area, elephant moves up. If small force divided by small area < large force divided by large area, elephant moves down.

Figure 4 shows how this “multiplication of force” occurs by utilizing different piston areas.

Multiplication of Force

The multiplication of force illustrated in the foregoing examples is not obtained without sacrifice. The small force must travel greater distance than the large force, because of the small amount of fluid that moves with each stroke of the small piston and the greater space it must fill under the large piston. The “work” (in a technical sense) put into the system, however, must equal the work produced by the system (neglecting friction). If work is defined as “a force multiplied by the distance through which it moves,” then the small force x large distance = large force x small distance. Therefore, hydraulics does not multiply work or power; it can multiply force, but it can only transmit work or power.

Work and Power

“Work” and “power” are completely different concepts and must not be confused. The definition of work provided above did not take into account the time required to accomplish a given amount of work. The units of measurement for the work definition given above are lb-ft (English system) or Newton-meters (metric system). The speed at which a given amount of work is accomplished greatly affects the power requirement. In the 18th century, James Watt gave us a handy way to measure power that is still in use today. As he tried to sell his steam engines for driving machinery, he had to explain to businessmen how many horses they would replace. Experimenting with some large horses and loads, Watt determined that a single large draft horse could perform about 33,000 ft-lb of work in one minute (or 550 ft-lb/s). This figure, arbitrary as it is, has become the standard used in the English system to calculate power requirements: once you determine the work you want done hydraulically and the time in which it must be done, determining the horse power of the prime mover is an easy task.

Bernoulli’s Theorem

Daniel Bernoulli discovered in the 18th century that when the flow through a pipe is constant, it possesses two forms of energy: potential and kinetic. The potential energy takes the form of “static” pressure, normally termed gauge pressure. The kinetic energy is derived from the velocity of the fluid and its weight. What this means is that when liquid flows through a restriction, as illustrated in Fig. 5, it gains speed but loses pressure (static); as it emerges from the restriction, it loses speed but gains static pressure. If the speed were converted into velocity pressure (by calculation or special apparatus), it would be apparent that the sum of the static and velocity pressures at any point along the pipe in Fig. 5 is approximately the same. This is not always true because of friction losses; but in a short section of pipe employing a restriction, as in the illustration, such losses are not readily detectable. It must also be remembered that the quantity of fluid that passes any point along the pipe per unit of time is consistent throughout. So when a restriction is present, the velocity must increase to maintain the gpm or lpm.
Velocity

Velocity is an important consideration in hydraulic design because of friction losses. As friction losses increase in a circuit, more power is needed to ensure adequate pressure at the actuator. Velocity can affect friction in two ways. Flow in any system may be either laminar or turbulent (Fig. 6). Laminar flow is a smooth movement of fluid through the system as a result of proper control of velocity and restrictions. Turbulent or rough flow is caused by excess velocity, roughness on the internal surface of piping, obstructions and the presence of too many elbows or bends. Smooth (laminar) flow of hydraulic fluids minimizes friction and pressure drop, which is proportional to velocity. Since turbulent flow causes much greater friction and pressure drop, it should be avoided. "Reynolds Number" (beyond the scope of this Section) is used to calculate the separation between laminar and turbulent flow, but rules of thumb for maximum velocities have been developed to help designers size fluid conductors without resorting to complicated calculations. These rules are:

- suction lines: 4 ft/s
- return lines: 8 ft/s
- pressure lines: 15 ft/s

The important point to note here is that hydraulic flow is always accompanied by pressure drop along the line of flow. The designer’s job is to minimize this loss within the requirements of the system controlling velocity, oil viscosity, change of fluid direction and other causes of resistance to flow.

Vacuum and Atmospheric Pressures

Hydraulic pumps are commonly said to “suck” fluid into their suction ports. Anyone serious about mastering hydraulics should forget that notion. What actually happens when a hydraulic pump is started up, is that a vacuum is created at the suction port (if the pump is in good shape) and fluid is pushed into that void by atmospheric pressure (and the weight of fluid when the pump is mounted below the tank). If the pump is mounted on top of the reservoir, atmospheric pressure must do all the pushing. If the pump is mounted under the tank, or at least below the liquid level, the weight of the fluid above the suction port helps as well. Of course, friction in the suction line works against the flow (Fig. 7). Atmospheric pressure at sea level is generally stated as 14.7 psi, or 1 lb/sq in. absolute, to distinguish it from gauge pressure; 14.7 psia is equivalent to 0 psi gauge. The weight of the air above the surface of the earth generates the 14.7 psia, and that is all that is available (at sea level) to push the fluid into a pump mounted on top of a reservoir (less is available, naturally, at higher elevations).

If a pump that could generate a perfect vacuum were pumping water, atmospheric pressure could push the water up only to a theoretical maximum height. This theoretical height is the same as the height of a column of water that can exert 14.7 psi at its base; in other words, the weight of the column of water in the suction line would be balanced by the absolute pressure generated by the atmosphere in the following manner: Water weighs 62.4 lb/cu ft. If a box one foot cubed were filled with water (box weightless), each of the 144 sq in. at the bottom would feel a pressure of 62.4 lb divided by 144 sq in., or 0.433 lb/sq in. Therefore, we can say that water generates .433 psi/ft of depth. By this reasoning, if a pump could generate a perfect vacuum at its entrance and the suction pipe had no friction, 14.7 psia of atmospheric pressure could push water up the suction line a distance of 14.7 psi divided by .433 psi/ft, or 33.95 ft. Petroleum oil, lighter than water, could theoretically be pushed much higher (Fig. 8)

Pump Cavitation and Pseudo-Cavitation

Hydraulic fluids contain a certain amount of dissolved air, simply because the weight of the atmosphere forces it
into the fluid. The amount varies with the fluid; petroleum oil, for example, may contain 8-9% air by volume. However, this dissolved air does not affect the volume of the liquid. Air can also be entrained in the fluid because of agitation in the reservoir without sufficient residence time to dissipate it; entrainment can also result from leaks on the inlet side of the pump due to loose fittings, low oil level in the reservoir or a worn pump shaft seal. A vacuum in the inlet line will cause these air bubbles to increase in size as they approach the pump. When they enter the pump, the bubbles actually sound like rocks or marbles going through, and the noise level increases tremendously. When they reach the pressure side of the pump, the bubbles collapse, or "implode," damaging the metal of the pump. Since this is essentially compressed air, high localized temperatures that can carbonize the oil are also present.

In addition to dissolved and entrained air, another potential source of trouble on the inlet side of pumps is vaporization of the fluid. Although we normally think that only extremely volatile fluids vaporize, any fluid can vaporize, though water-based hydraulic fluids are much more susceptible to this problem than petroleum fluids. Technically, the vapor pressure of a liquid is the absolute pressure at which a liquid will vaporize at a given temperature. For example, the vapor pressure of water at 212°F is 14.7 psia. We tend to say, "Water boils at 212°F," ignoring atmospheric pressure. But, in truth, water "boils" or vaporizes at a lower temperature in an elevated location like Denver because atmospheric pressure there is lower, i.e., the pressure available is not high enough to keep the fluid in liquid form. (Therefore, what we call a "3-minute egg" at sea level takes longer than three minutes at a higher location.) Conversely, your automobile radiator has a pressure cap (usually about 15 psi) because the designers want the water to remain liquid at a higher than atmospheric pressure. At a pressure of 30 psi (cap setting plus atmospheric), your radiator water probably will not boil (vaporize) until the temperature exceeds 250°F.

What does all this have to do with your hydraulic pump? If the vacuum created on the inlet side is excessive (higher than manufacturer's recommendations) and/or the fluid is running hotter than it should, the fluid may vaporize or boil right in the suction line. These bubbles of fluid vapor act just like the dissolved and entrained air discussed above: they sound like marbles going through the pump, collapse on the pressure side and gouge bits of metal out of the pump parts, greatly shortening pump life. Though the damage may be visible only with magnification on precision pumps, it is still devastating.

The three conditions described above, dissolved air, entrained air and fluid vaporization, can severely damage pumps. Technically, the term cavitation refers only to damage caused by dissolved air and vaporization. The damage caused by entrained air, whether it comes from air leaking into the inlet side of the pump or excessive agitation in the reservoir, is called pseudo-cavitation; but it is just as damaging as the real thing. Because of space limitations, this Section cannot offer a more detailed discussion of cavitation.

All of the references listed at the end of the Section include more satisfactory discussions of this important phenomenon.

One of the best ways to avoid these problems is to use a positive head on hydraulic pumps, mounting the pumps beside or under the reservoir with short suction lines. This practice uses the weight of the fluid, as well as atmospheric pressure, to force the fluid into the pump. "Saving floor space," the most common rationale for mounting hydraulic pumps on top of reservoirs, is no bargain when all the potential problems are considered.

**Hydraulic System Components: General**

Hydraulic systems generally consist of many components, and some systems have more categories of components than others; nevertheless, all systems include the following eight components:

- A way to move fluid (pump)
- A power source (electric motor)
- A container for fluid (reservoir)
- Transmission lines (pipe, hose, tubing)
- A way to limit pressure (relief valve)
- A way to direct flow (directional valve)
- Something to do the work (actuator)
- Fluid (petroleum oil, water, etc.)

One might object to this list because it does not include temperature gauges, level gauges, pressure switches or any of a dozen other components, but not all systems have them.

The list above is universal, and the eight items may be found in all systems.

**Hydraulic Graphical Symbols**

Many years ago when hydraulics first became popular, drawings were needed to show how the components were to be connected at installation and to help people troubleshoot the systems when something went wrong. These drawings, very similar to piping drawings, were known as pictorial drawings; as it happened, they were useful for installation but nearly useless for trouble-shooting. To compensate, trade
associations devised a group of graphic symbols that were accepted and used for many years throughout the United States. These symbols have gradually evolved as international standards promoted by the International Standards Organization (ISO) and relied upon by most industrialized nations. Nearly universal use of these symbols has boosted international trade.

Unlike the pictorial drawing, the graphical symbol for a particular hydraulic component does not look like the component at all; instead, it depicts only the function of the component. The symbols are developed from circles, squares and lines; a basic group appears at the end of the chapter. Because ISO symbols are so widely used, a drawing made in Japan, for instance, can easily be understood by someone versed in hydraulics in an English-speaking country and vice-versa. Any complete textbook of hydraulics will include a glossary of current symbols.

In the following pages, next to each picture of a hydraulic component, the ISO symbol for that component will appear, perhaps with some additional symbols to illustrate variations one might encounter.

**Pumps (General)**

The primary function of a hydraulic pump is not to generate pressure, as is widely believed, but to move fluid. Pressure may be characterized as the product of the load to be moved, friction in the lines or any other restrictions on the fluid, as indicated in Fig. 9. If the pump shown in the figure simply pushed fluid through an open pipe, very little pressure would register on the gauge. If the line were significantly extended, internal pipe friction would cause more pressure to register on the gauge; the extra length of pipe would serve to restrain the fluid. If then the long pipe became a tortuous path with the addition of elbows and other restrictions, still more pressure would be registered on the gauge. Finally, if the pipe were connected to a cylinder and a heavy load were imposed, significant additional pressure would show on the gauge. Again, we state that the primary function of hydraulic pumps is to move fluid. Remember this to avoid monumental confusion in understanding hydraulic circuits or troubleshooting problems. However, the statements above greatly oversimplify the engineering principles involved. For more extensive discussion of these principles, consult any good engineering text on the subject.

Hydraulic pumps are termed positive-displacement pumps to distinguish them from the non-positive, or centrifugal, pumps used for fluid transfer at lower pressures. Positive-displacement pumps are further subdivided into fixed-displacement and variable-displacement types. “Fixed displacement” means that with each rotation of the pump, a measured amount of fluid is moved. Since this fluid must always have someplace to go, it follows that some kind of unloading system must be provided to forestall any build-up of dangerous pressures and high temperatures. “Variable displacement” means that the pump moves fluid to maintain an established pressure (generated by the load) but can change its displacement internally to deliver zero flow if necessary. This kind of pump greatly reduces heat generation.

In the fixed-displacement category, the designs usually found in hydraulic systems are vane, gear and piston. In the variable-displacement category, axial piston type pumps are the most common, but vane designs are also popular.

Fig. 9-Pumps generate flow—not pressure.
Gear Pumps

Figures 10 and 11 illustrate the two general categories of gear pumps, external gear and internal gear. The external gear type consists of two gears enclosed in a closely fitted housing: the gears rotate in opposite directions, one driven by a motor (or other prime mover), the other an idler. Fig. 10 shows that the gears must operate so that the fluid comes in at the inlet, then splits to be carried between the teeth and housing around the outside of the gears. The fluid cannot go through the center (another common misconception) because there is no clearance. The two streams of fluid are recombined on the outlet side and pushed out into the pressure line. The sideplates beside the gears are very close-fitting to minimize the flow that leaks back to the inlet side.

Notice that the bearings in this gear pump receive force only from the pressure side back to the inlet or low-pressure side. For this reason, gear pumps are called unbalanced pumps; the bearings, the weakest link in the design, must be large to carry the load. (The balanced vane pump design, to be covered later, overcomes this problem.) Because of this unbalanced design, the gears are continually being shoved from the pressure side toward the inlet, creating the potential for the gear teeth to dig into the housing on the inlet side after the bearings have begun to wear. Some pumps are designed so the housing can be reversed if wear becomes a problem.

The internal gear pump illustrated in Fig. 11 has the same characteristics as the external pump just described: it has two gears, one external, the other internal; the external gear is driven by the motor, and the internal gear is an idler. However, the internal gear has one pocket more than the number of teeth on the external gear, so that after they mesh at one point, the teeth and mating pockets move at different speeds. Their different diameters also cause them to move away from each other, thereby increasing chamber size. This formation of a larger chamber generates a vacuum which permits atmospheric pressure and gravity to fill the inlet side of the pump. Then, as the size of the chamber diminishes on the outlet side, fluid is forced out into the system. Obviously, the internal gear pump has the same unbalanced features as the external type. Though gear pumps are usually the least expensive of the three types being discussed, they are the most dirt-tolerant; generally, they are used in hydraulic systems up to about 1500 psi, occasionally to 3000 psi. Efficiency drops off sharply as pressures rise in gear pumps, because of side-plate slippage and clearances between teeth and housing periphery.

Vane Pumps

The principal parts of a vane pump are a slotted rotor, vanes, a ring with an elliptical inner contour and an assembly of housing, shaft and bearing. The highly polished vanes fit smoothly in the rotor slots; as the rotor rotates, the vanes are thrown out against the elliptical ring by centrifugal force, as shown in Fig. 12. As indicated, vane pumps can be balanced in design: when the pump is designed with two inlets on opposite sides and two outlets also opposite each other,
the forces created by pressure from outlet toward inlet are effectively cancelled. This design offers the additional benefit of minimizing the bearing loads. In addition to the centrifugal force that holds the vanes against the ring, ports direct fluid pressure to the space under each vane to hold the vanes tightly against the ring. To minimize vane wear from this source, the vanes are relieved slightly, using pressure at the outer tip to oppose the pressure under the vane tip in the slotted rotor.

Figure 13 shows that a vane pump can be designed as a variable-displacement pump. The major difference between such a pump and the fixed-displacement design is that the ring is circular, capable of sliding back and forth in the housing. If the ring centerline is pushed as far away as possible from the rotor centerline, the cavities formed by the vanes increase on the inlet side and decrease on the outlet side, and the pump operates at maximum volume. However, if the ring is centered around the rotor, the cavities are of equal size all around and no fluid enters or leaves. With the compensator spring, pressure can be set so that pump volume approaches zero. For example, if the system pressure is to be limited to 1000 psi, the compensator spring is set for that level. When the pump and motor are idle, the ring is shoved over against the rotor. When the motor is turned on and the pump begins to rotate, its volume output is at a maximum. As the system becomes pressurized and pressure approaches the compensator setting, the ring is shoved toward center, consequently reducing volume, because the chambers formed are nearly equal in size around the rotor. Unless the chamber size increases, no vacuum is generated, hence no flow.

Vane pumps operate at relatively high efficiency throughout their life because the vanes advance in the rotor slots as the tips wear. Eventually, the vanes fall out of the slots and the pump fails catastrophically.

Fig. 13-Unbalanced variable-displacement vane pump
(Courtesy of Vickers, Inc.).

First installment in a series based on Section 10 of the Lubrication Engineers Manual. The next installment will appear in the April 1998 issue of Lubrication Engineering.