CHAPTER 2

Hydraulic Transmission of Force and Energy

Before dealing with energy transmission through a liquid, it will help our understanding of hydraulics to first concentrate on some characteristics of a liquid, and then how a force is transmitted through a liquid.

fluid

A fluid is a substance that can flow and possess no definite shape. A fluid can be a liquid or gas.

liquid

A liquid, like a gas, is a substance made up of molecules. Unlike a gas, however, these molecules are closely attracted to one another. Also, unlike a solid, these molecules are not so attracted to each other that they are in a rigid position.

molecular energy

Liquid molecules are continuously moving. They slip and slide past one another even when the liquid is apparently at rest. This movement of molecules is molecular energy.

liquids take any shape

Since this slipping and sliding action is continuously taking place, a liquid is able to take the shape of any container. It may or may not fill the container depending upon the quantity of liquid. The ability of a liquid to accomplish this is directly related to its viscosity. Viscosity is discussed in more detail in later chapters.

liquids are relatively incompressible

With molecules in close contact with one another, liquids exhibit a characteristic of solids. Liquids are relatively unable to be compressed.

This is the reason a diver tries to "knife" his way into the water and avoid a belly smacker.

Since liquids are relatively incompressible and can take the shape of any container, they possess certain advantages for transmitting a force.
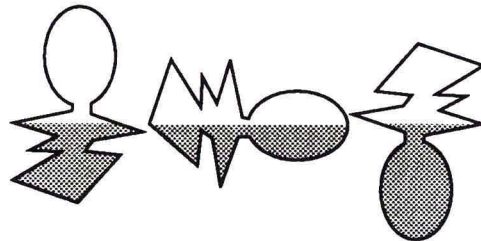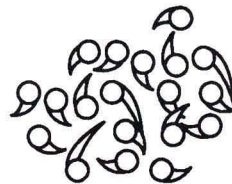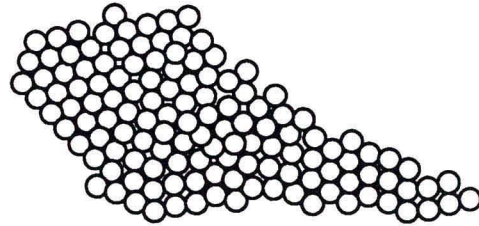
force transmission

The four methods of energy transmission (mechanical, electrical, hydraulic, pneumatic) are capable of transmitting a static force (potential energy) as well as kinetic energy. When a static force is transmitted in a liquid, it happens in a special way. To illustrate, we will compare how it is transmitted through a solid and through a confined liquid.

force transmitted through a liquid

Unlike a solid, a force applied to a confined liquid is transmitted equally throughout the liquid in the form of hydraulic pressure.

If we pushed on a container filled with liquid, the pressure of the applied force would be transmitted equally throughout the liquid.
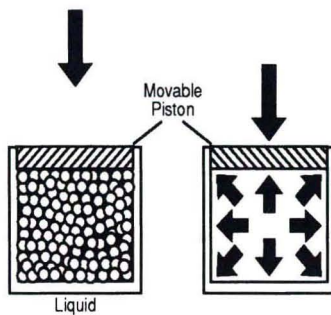
A confined liquid will transmit pressure in the same manner regardless of how it is generated. As far as the liquid is concerned, an applied force results in pressure whether the application of force comes from a hammer, by hand, weight, fixed or adjustable spring, compressed air, or any combination of forces.

Since fluid can take the shape of any container, pressure will also be transmitted regardless of the shape of the container.

Pascal's law

The property of a liquid to transmit pressure equally throughout itself is known as "Pascal's Law," in honor of Blaise Pascal who defined it.

The mathematical expression which describes Pascal's Law is the same as that used to describe any pressure:

$$\text{pressure (psi)} = \frac{\text{force (lbs.)}}{\text{area (in}^2\text{)}}$$
$$\text{Bar} = \frac{\text{force (Newton)}}{\text{area (meter}^2\text{)}}$$

pressure gage

A pressure gage is a device which measures the intensity of a force applied to a liquid. Two types of pressure gages that are commonly used in hydraulic systems are the Bourdon tube gage and the plunger gage.

Movable Piston

Liquid
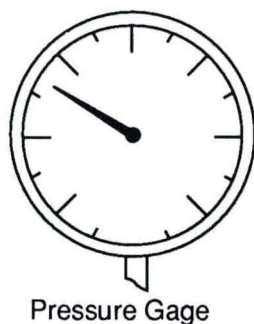
Pressure Gage

Bourdon tube pressure gage

A Bourdon tube gage basically consists of a dial face calibrated in units of psi, bar, PA and needle pointer attached through a linkage to a flexible metal coiled tube, called a Bourdon tube. The Bourdon tube is connected to system pressure.

how a Bourdon tube gage works

As pressure in a system rises the Bourdon tube tends to straighten out because of the difference in areas between its inside and outside diameters. This action causes the pointer to move and indicate the appropriate pressure on the dial face.

Bourdon tube gages are generally precision instruments with accuracies ranging from 0.1% to 3.0% of full scale. They are frequently used for laboratory purposes and on systems where pressure determination is important.
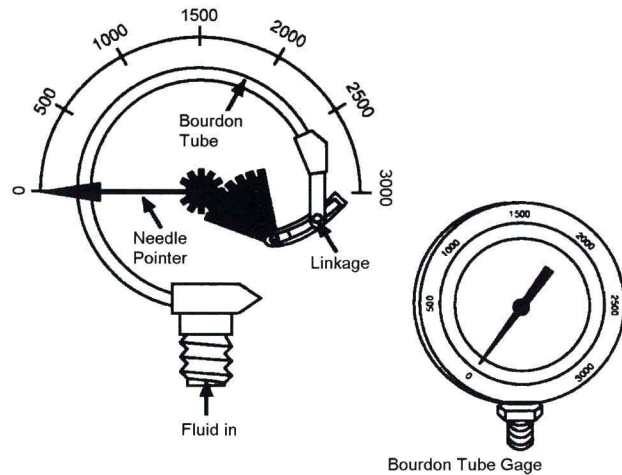
plunger pressure gage

A plunger gage consists of a plunger connected to system pressure, a bias spring, pointer, and a calibrated scale calibrated in appropriate units of psi (bar).

how a plunger gage works

As pressure in a system rises, the plunger is moved by the pressure acting against the force of the bias spring. This movement causes the pointer attached to the plunger to indicate the appropriate pressure on the scale.

Plunger gages are a durable, economical means of measuring system pressure.
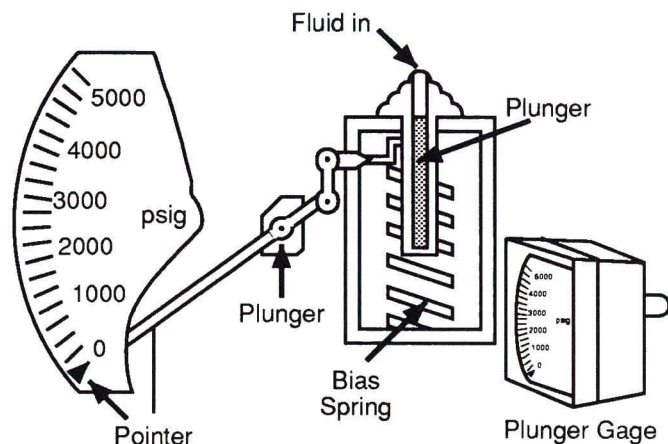
hydraulic pressure to mechanical force

Applying a force to a liquid and transmitting the resulting pressure throughout a liquid in various shaped containers does very little good for its own sake. Hydraulic pressure must be converted into mechanical force before any work can be done. This is the function of a hydraulic actuator - to accept hydraulic pressure and convert it into a mechanical force.
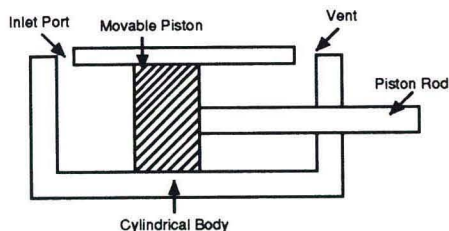
One type of actuator is the hydraulic cylinder.

Bourdon Tube Gage

Plunger Gage

Actuators
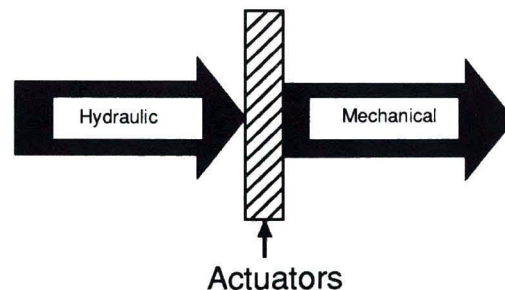
hydraulic cylinder

A hydraulic cylinder accepts hydraulic pressure and converts it into a straight-line or linear mechanical force and with the appropriate mechanical connections can convert to rotary motion.

what cylinders consist of

Hydraulic cylinders basically consist of a cylinder body, a closure at each end, a movable piston, and attached to the piston a piston rod. At one end, the cylinder body has an inlet port by which the fluid enters the body. The other end is vented.

how cylinders work

With the inlet port of the cylinder connected to the system, the cylinder becomes part of the system. In our illustration, when a force is applied at point A, the resulting pressure is transmitted throughout the system and to the piston in the cylinder. The pressure acts on the piston resulting in a mechanical force at point B.
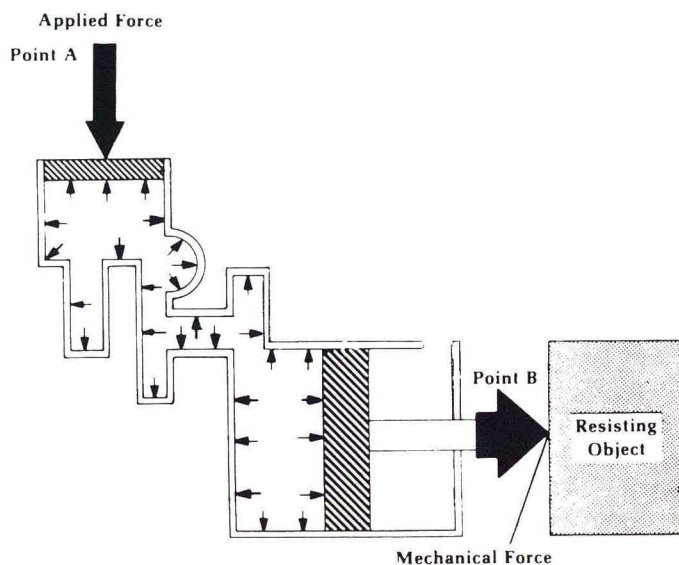
applying pressure

In transmitting pressure through a confined liquid, some sort of movable member has been used to apply the pressure. In the examples used so far, the movable member has been a piston.

To determine the intensity of the force or pressure being applied to the system, the force is divided by the area of the movable member. (P = F/A).

mechanical force multiplication

Mechanical forces can be multiplied using hydraulics. The determining factor for force multiplication is the square inch area (cm²) on which hydraulic pressure is applied. Since pressure is transmitted equally throughout a confined liquid, if the piston in a cylinder has more area than the movable member on which the force is added, the output force will be greater than the input force. With a smaller cylinder area the force would be less for the same system pressure (500 psi/34.5 bar).
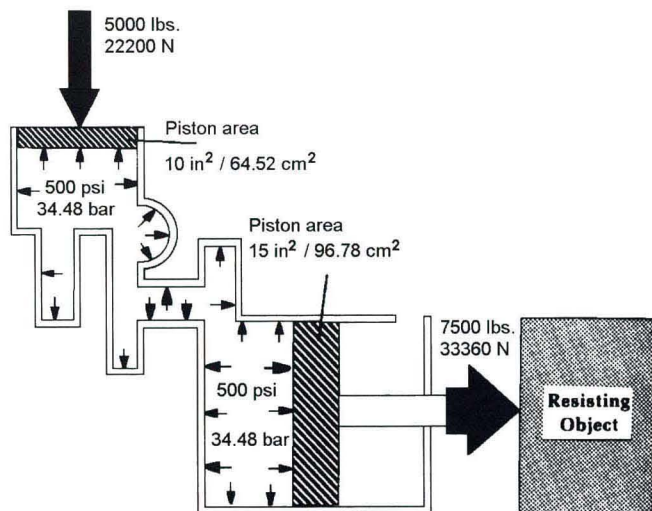
In our example, assume that the resisting object is stationary and will not move. A 5000 lb. (22200 N) force acting on the 10 in² (65.52 cm²) area piston results in a pressure of 500 psi (34.5 bar) being transmitted throughout the system. The 500 psi (34.5 bar) acts on the cylinder piston with an area of 15 in² (96.78 cm²) and results in a mechanical force of 7500 lbs. (33360 N).

$$\begin{array}{l} \text{force} = \text{pressure} \times \text{area (lbs.)} \\ \qquad\quad \text{(PSI)} \qquad \text{(in}^2) \\ \text{(Newton)} = \text{*(bar)} \quad \text{(cm}^2) \times 10{,}000 \\ \qquad\quad \text{*In Newton / m}^2 \end{array}$$

F = P x A

intensifier

An intensifier multiplies hydraulic pressure.

what intensifiers consist of

The common intensifier basically consists of a housing with inlet and outlet ports and a large area piston connected by a rod to a small area piston. The area between the two pistons is vented.

how intensifiers work

An intensifier multiplies, or intensifies an existing hydraulic pressure by accepting hydraulic pressure at the large area piston and applying the resultant force to the small area piston. Fluid pressure is therefore intensified or multiplied at the actuator.

In our example, assume that the resisting object is stationary and will not move. A 5000 lb. (22200 N) force at point A ultimately results in a 30,000 lb. (133200 N) mechanical force at point B. This is accomplished by applying hydraulic pressures to various piston areas.

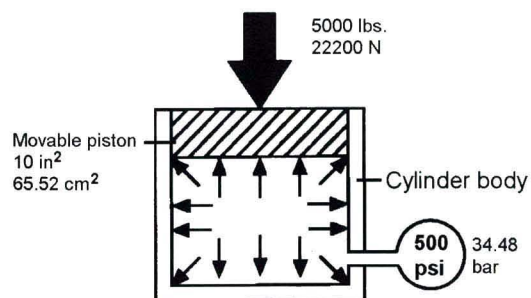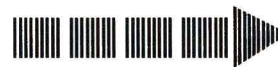A common application for an intensifier is a clamping device.
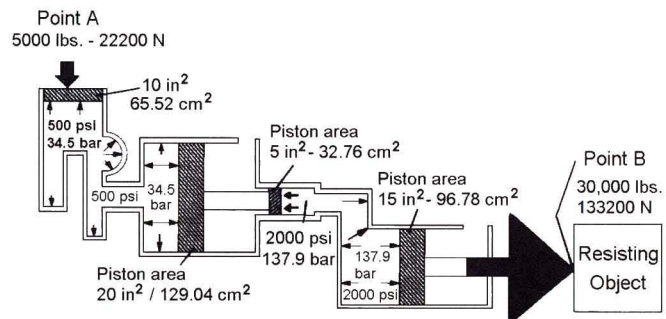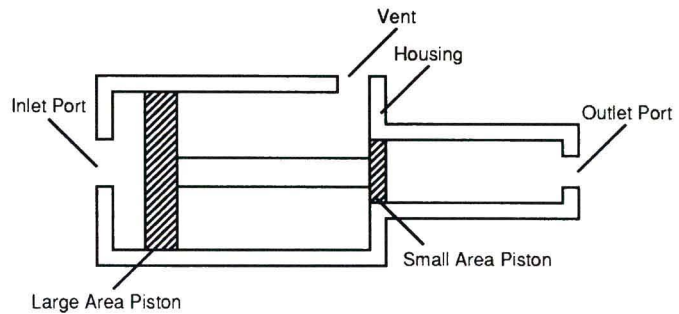
hydraulic transmission of energy

The reason for using hydraulics or any other type of energy transmission on a machine, is to perform useful productive work.

As illustrated previously, accomplishment of work requires the application of energy to a resisting object resulting in the object moving through a distance. To do any work then, a hydraulic system requires something which can apply energy.

hydraulic accumulator

Up to this point, the device used to apply a pressure to a confined liquid has consisted of a movable piston on which the force is applied and a cylinder body to confine the liquid. This device is called an accumulator.

5000 lbs.
22,200 N

10 in²

15 in²

Offers a resistance of 6000 lbs. 26,700 N

500 psi
34.5 bar

400 psi
27.5 bar

Resisting Object

5000 lbs.
22,200 N

10 in²
65 cm²

Piston area
15 in²
96 cm²

Offers a resistance of over 7500 lbs. 33,360 N

500 psi
34.5 bar

500 psi
34.5 bar
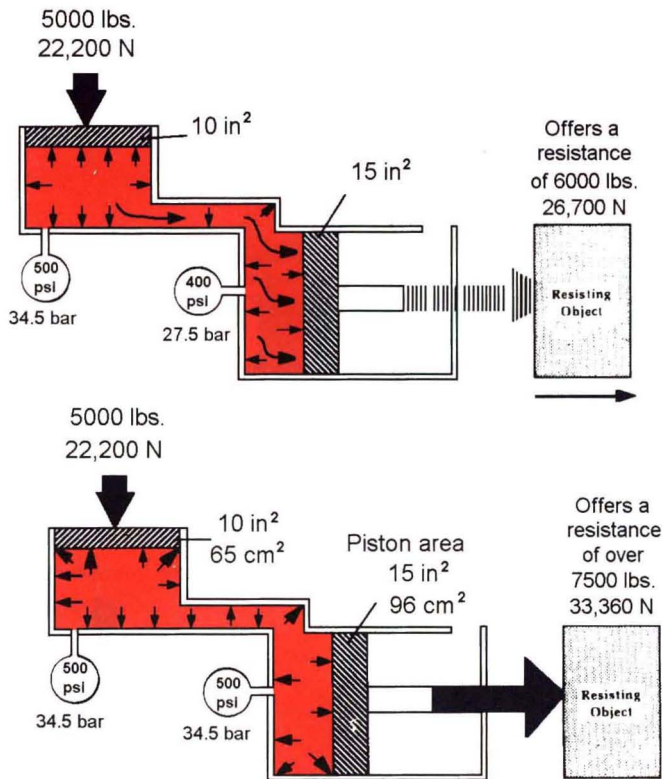
Resisting Object

An accumulator may store hydraulic pressure which is potential energy. This pressure can turn to working energy (flow and pressure).

In our illustration, the pressure stored in the accumulator is used to move the resisting object. 400 psi (27.6 bar) of the 500 psi (34.5 bar) accumulator pressure is used to overcome the resistance offered by the load. The remaining pressure is transformed into a liquid flow.

An accumulator has its disadvantages when applying energy to a resisting object. If the resistance is large enough, there will be no movement and therefore no work. In addition, an accumulator has a definite volume. Once it is discharged, flow ceases.

A device is needed which can apply the necessary pressure to overcome a resistance and whose flow is continuous. This device is a positive displacement pump.

positive displacement pump

With constant cycling of its movable member, a positive displacement pump will deliver a constant flow of liquid, and will apply (within limits) whatever pressure is required.

In other words, a positive displacement pump develops working energy - kinetic energy (flow) and pressure.

what a positive displacement pump consists of
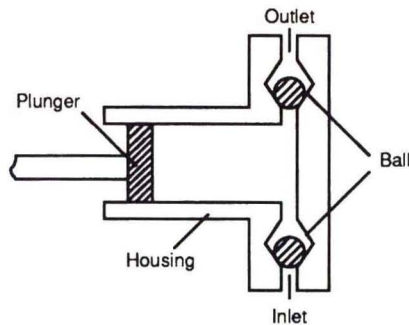
A positive displacement pump basically consists of a movable member inside a housing. The pump in the illustration has a plunger for a movable member. The shaft of the piston is connected to a prime mover (an engine or electric motor) which is modified to produce a constant reciprocating motion of the plunger. The inlet port is connected to fluid reservoir. At inlet and outlet ports, a ball allows liquid to flow only one way through the housing.

how a positive displacement pump works
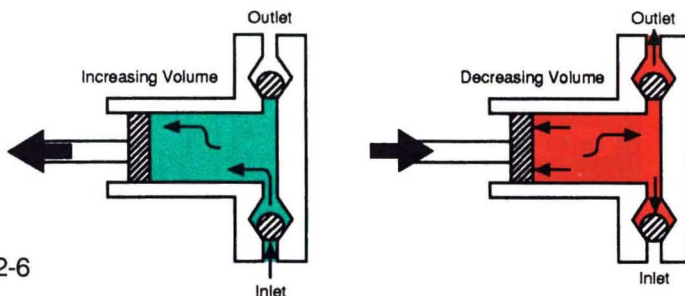
As the piston is pulled out, an increasing volume is formed within the housing. The ball at the inlet port allows fluid to enter filling the void.

Outlet

Plunger

Ball

Housing

Inlet

Outlet

Increasing Volume

Inlet

Outlet

Decreasing Volume

Inlet

After the housing is filled, the plunger is pushed in. The ball at the inlet closes and the ball at the outlet port unseats. A decreasing volume is formed within the housing. The plunger applies the pressure necessary to get the liquid out into the system.

The constant cycling of the piston results in a pulsating rate of flow at whatever pressure is required.

rotary positive displacement pump

The most commonly used positive displacement pump in a machine's hydraulic system is not a reciprocating plunger, but a rotary type. A rotary positive displacement pump develops a relatively smooth, pressurized flow of liquid, and it can be easily driven by an electric motor or internal combustion engine. For each revolution the pump is rotated, a definite volume of liquid is displaced.

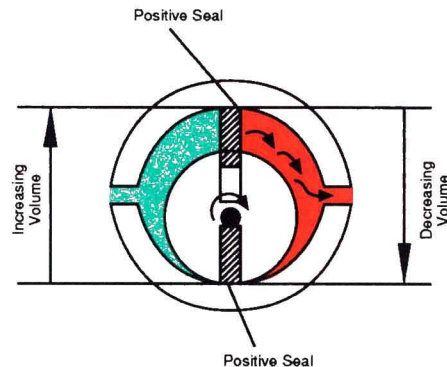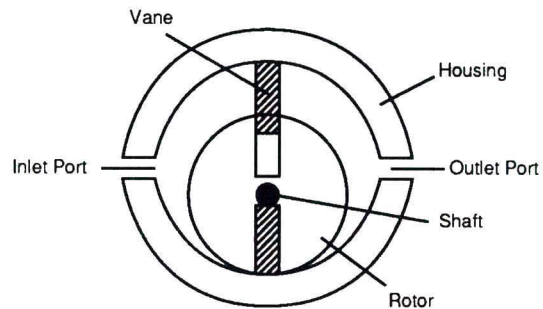### what rotary positive displacement pumps consist of

A rotary positive displacement pump basically consists of a housing with inlet and outlet ports, and a rotating group which develops fluid flow and pressure. One type of rotating group in the illustration consists of a rotor and vanes which are free to move in and out.
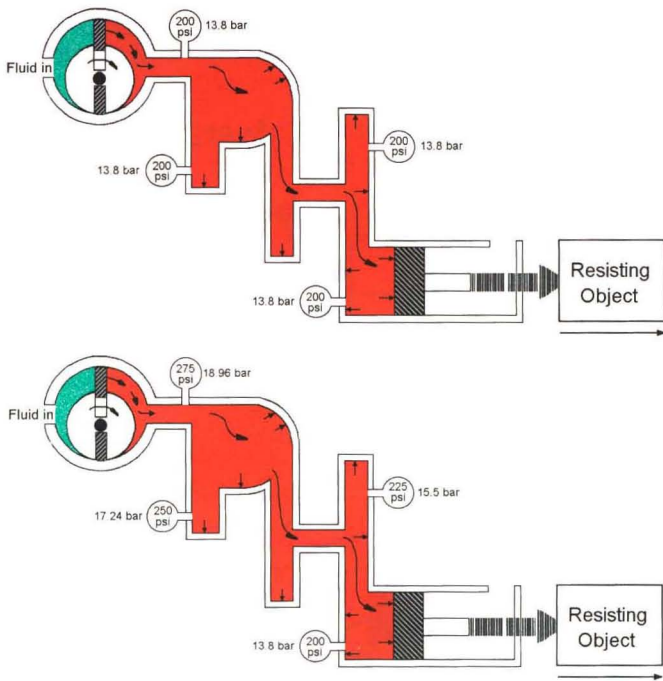
how the pump operates

The rotating group of the pump is positioned off-center to the housing. The rotor is connected to a prime mover by means of a shaft. As the rotor is turned, the vanes are initially thrown out by centrifugal force and contact the housing forming a positive seal. The increasing volume at the inlet side allows liquid to fill the pump. The decreasing volume at the outlet forcefully pushes the liquid out into the system. The amount of pressure applied to the liquid by the pump will only be as great as the least resistance to flow in the system.

resistance vs. pressure

In a hydraulic system, there is a direct relationship between pressure and resistance. Pressure is applied by the pump in forcing fluid out into the system. The amount of pressure is determined by the degree of resistance. If the resistance is high, the pump must apply an equally high pressure. If the resistance is low, the pump applies a low pressure.

200 psi / 13.8 bar

Fluid in

200 psi / 13.8 bar

13.8 bar / 200 psi

13.8 bar / 200 psi

Resisting Object

275 psi / 18.96 bar

Fluid in

225 psi / 15.5 bar

17.24 bar / 250 psi

13.8 bar / 200 psi

Resisting Object

10 f/s
3.04 m/s

5 gal. - 18.95 L

20 f/s
8.097 m/s

5 gal. - 18.95 L

Resistance to flow determines how much pressure is exerted.

resistance to the flow of a positive displacement pump

Resistance to the flow of a positive displacement pump comes basically from two sources - the object resisting being moved, and the flow forces needed to move the liquid itself.

If the resistance of the liquid could be eliminated from the system illustrated, the only resistance to pump flow would be the resisting object, which can be overcome with a pressure of 200 psi (13.8 bar) at the actuator. The pump would apply the required 200 psi (13.8 bar) to get the liquid out into the system. This hydraulic working energy would be applied to the actuator and the object would move.

Resistance of a liquid to the pump's flow is always present. To discharge its flow against the liquid's resistance, the pump absorbs more energy from its prime mover, and applies an additional pressure to the liquid.

extra energy changes form

The additional energy applied by the pump does not result in additional hydraulic working energy at the actuator, because it is used up by a liquid's resistance. The working energy is "used up"—not in the sense of being destroyed, but it changes to heat energy resulting in a rise in the temperature of the fluid. As was pointed out previously, this is the inefficiency in a system.

velocity vs. flow rate
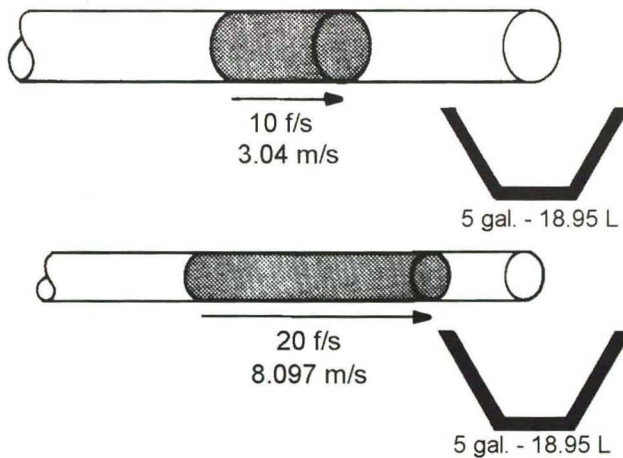
In a dynamic system, fluid flowing through a pipe is traveling at a certain speed. This is the fluid's velocity which is usually measured in feet per second (f/s) or meters per second (m/s).

The volume of fluid flowing through tubing in a period of time is a rate of flow. Flow rate in a typical hydraulic system is usually measured in gallons per minute (gpm) or litres per minute (lpm).

The relationship between velocity and flow rate can be seen from the illustration. In order to fill the 5 gallon (18.95 L) container in one minute, a 5 gallon (18.95 L) volume of fluid in the large tube must travel at a speed of 10 feet per second (3.048

m/s). In the small tube a 5 gallon volume (18.95 L) must travel at a speed of 20 feet per second (6.096 m/s) in order to fill the container in one minute.

In both cases the rate of flow is 5 gpm (18.95 lpm). The fluid velocities are different.

friction generates heat

In a hydraulic system, friction, and therefore heat, is generated because of the liquid flowing through the pipe. The faster a liquid travels, the more heat is generated.

In industrial applications, the recommended maximum fluid velocity between pump and actuator is usually 15 fps (4.572 m/s).

changing fluid direction generates heat

A mainstream of liquid flowing along in a straight line generates heat when it crashes into other liquid molecules while forced to change direction because of a pipe bend or elbow. Depending upon the conduit size, one 90° elbow could generate as much heat as several feet of the flow conduit.
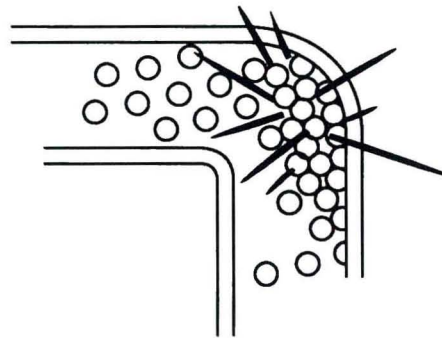
pressure differential

Pressure differential is simply the difference in pressure between any two points in a system.

It is a symptom of what is happening in a system :

1. By indicating that working energy in the form of a moving, pressurized liquid is present in the system.

2. By measuring the amount of working energy that changes to heat energy between the two points.

In our illustration, the pressure differential between the two gage points is 20 psi (1.38 bar). This indicates that:

1. Working energy is moving from gage 1 toward gage 2.

2. While moving between the two gage points, 20 psi (1.38 bar) of the working energy is transformed into heat energy because of liquid resistance.

gage 1

200 psi 13.79 bar

gage 2

180 psi 12.41 bar
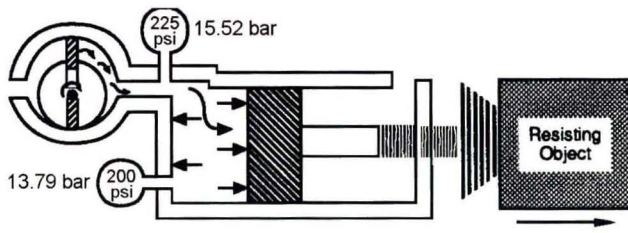
**hydraulic system designed
to avoid generation of heat**

The generation of heat by working energy travel-
ing through a system to a point of work is system
inefficiency. To make a hydraulic system more
efficient, a designer chooses oil with the appropri-
ate viscosity, uses piping of a proper size, and
keeps the number of bends to a minimum.

exercise
## hydraulic transmission of energy
35 points

INSTRUCTIONS: For each incomplete sentence, one choice will correctly complete the statement. After reading the sentence and the possible choices, circle the letter next to the most correct answer. After all six statements have been completed, place the letter for each answer in the appropriately labeled box. The letter combination should form a word. Total points possible 35; 5 points per answer, 5 points for correct word.

1. With a constant cycling of its movable member, a positive displacement pump develops a constant flow of liquid, and at the same time will apply whatever _____ is needed to overcome any _____ .
   B. force, actuator
   R. flow, resistance
   M. speed, load
   E. pressure, resistance

2. Liquid enters and is forced out of a pump by _____ .
   L. generating an increasing and decreasing volume within its housing.
   R. centrifugal force forming a positive seal between vane and housing.
   A. absorbing additional energy from its prime mover.
   E. overcoming any resistance to flow.

3. The resistance to pump flow comes from the _____ and _____ .
   I. viscosity, friction
   S. load, liquid
   N. viscosity, changing direction
   F. velocity, liquid

4. A flowing liquid's viscosity, friction, and change of direction all result in _____ .
   U. an increase in efficiency.
   O. a low pressure differential.
   P. the generation of heat.
   N. working energy increasing in velocity.

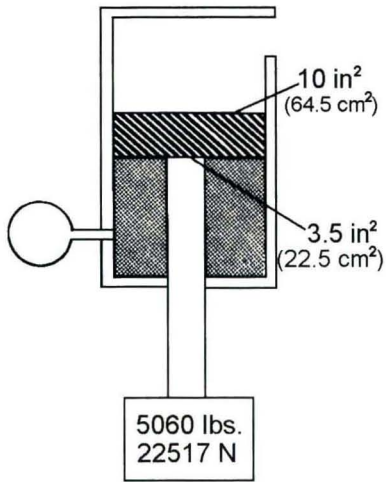gage 1   gage 2
200 psi 13.79 bar   180 psi 12.41 bar
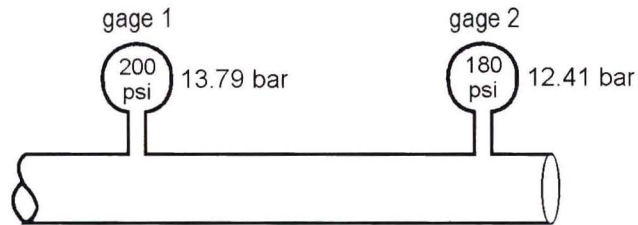
5. Pressure differential in a hydraulic system (as illustrated)
   A. is a symptom that something is wrong.
   R. illustrates that Pascal's Law is not applicable to a dynamic system.
   I. indicates that working energy is present in the form of a moving, pressurized liquid.
   G. shows that a pressurized liquid is flowing upstream to a point of work.

6. A positive displacement pump applies a higher pressure to the fluid than required at the actuator because of _____ .
   N. viscosity
   L. fluid changing direction
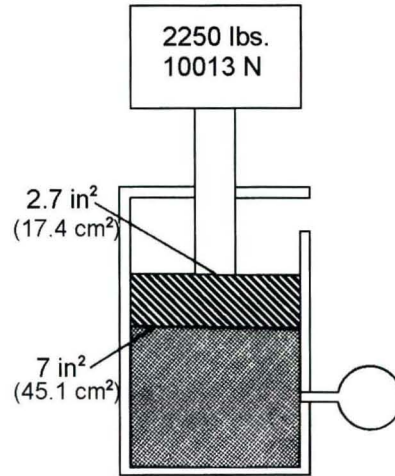   S. fluid friction
   M. all of above

Answer 3	Answer 5	Answer 6	Answer 4	Answer 2	Answer 1

2-11

exercise
hydraulic transmission of force

1. What does the gage read?

10 in²
(64.5 cm²)

3.5 in²
(22.5 cm²)

5060 lbs.
22517 N

2. What does the gage read?

2250 lbs.
10013 N

2.7 in²
(17.4 cm²)

7 in²
(45.1 cm²)

3. What pressure is needed to suspend the 1980 lb. load?

9 in²
58.07 cm²

1.3 in²
8.4 cm²

1980 lbs.
8811 N
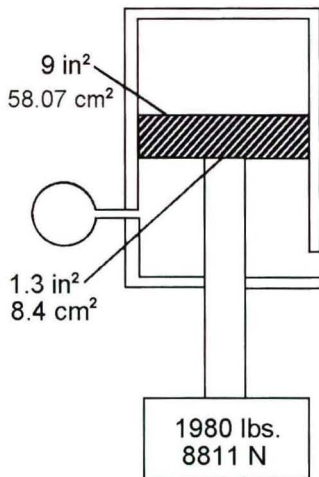
4. What pressure is needed to raise the 3130 lb. load?

3130 lbs.
13929 N

2 in²
12.9 cm²

6 in²
38.71 cm²
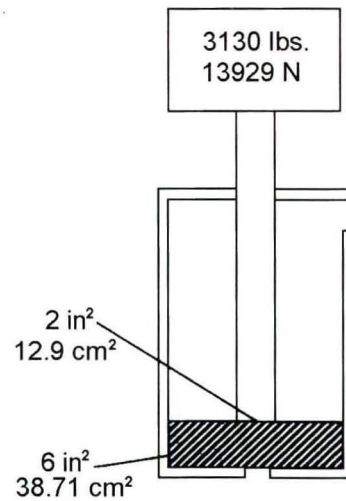
5. What pressure is needed to move out the load?

4.2 in²
27.1 cm²

1.8 in²
11.6 cm²

1800 lbs
8010 N

Force will
move load
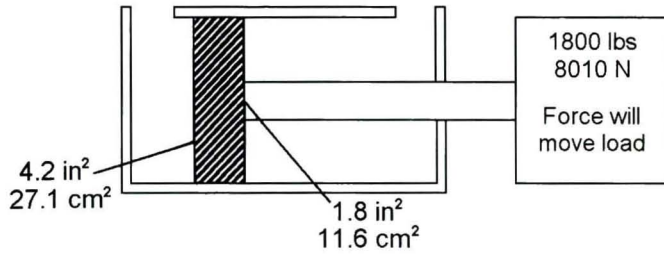
6. What pressure at the intensifier inlet
will result in 13,000 PSI at the outlet?

2.5 in²
16.13 cm²

Inlet ——

— Outlet

20 in²
129 cm²