Hydraulic Fundamentals

Hydraulic Advantages

Hydraulics has many advantages not always found in electrical and mechanical type drives.

- Hydraulic cylinders and motors can be operated at **variable speeds**. By varying the volume flowing into the actuator (cylinder or motor) the speed is changed.

- The hydraulic cylinder or motor can be **stalled** under a load. Hydraulic systems use relief valves or pump compensators to limit the maximum system pressure.

- The actuator can be instantly **reversed** under load. This is done by changing the position of a directional valve or the direction of flow out of a pump. System relief valves will protect the system from damage caused by the inertia of the moving load.

- Shock caused by the moving load can be **absorbed** in the hydraulic system. Crossport relief valves and hydraulic accumulators are used for this purpose.

Compressibility of Fluids

The air in pneumatic systems compresses significantly so shock absorption is much less of a concern than in a hydraulic system. Hydraulic oil is considered to be non-compressible. Oil will compress ½% when pressurized to 1000 PSI. This equals approximately .06 inches reduction in volume per foot of length.

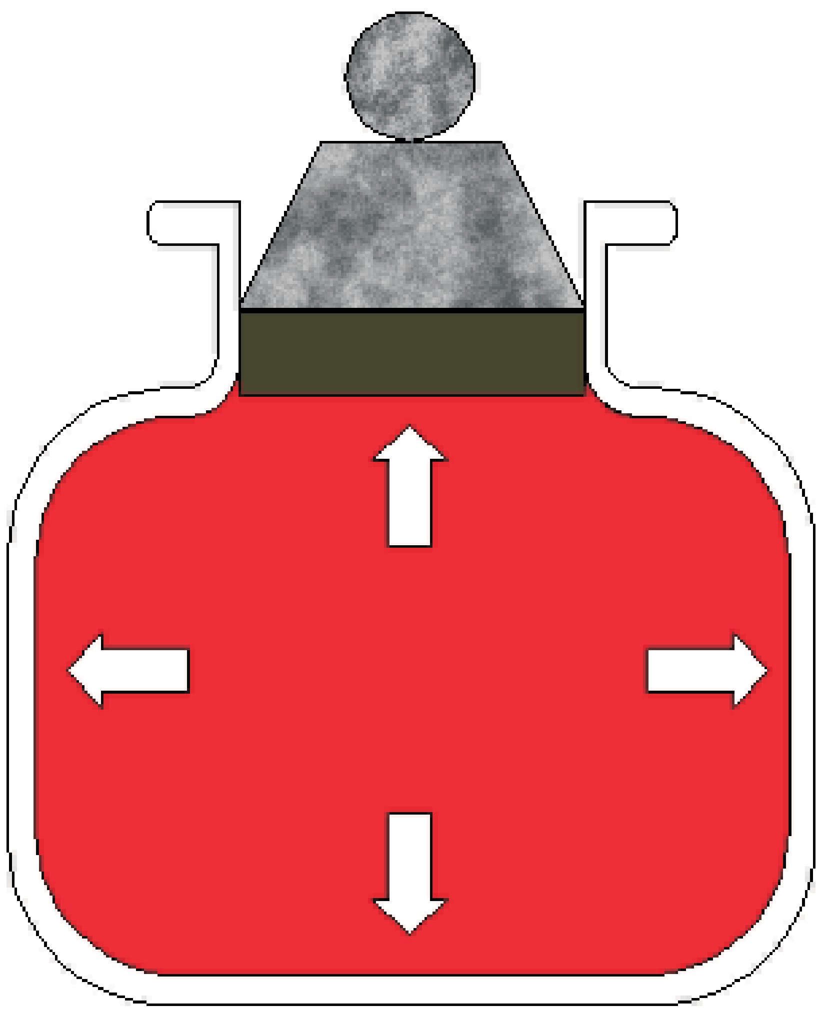
Pascal's Law

In the 17th century a French scientist, Blaise Pascal, discovered a principle which explains how force is transmitted through a confined fluid.

Pascal's Law says that::

Pressure in a confined body of fluid will act equally in all directions.

In the example shown below, a container filled with oil has an anvil placed on top of it. As the pressure increases inside the container from the weight of the anvil, the same amount of *pressure will act equally in all directions* on the inner walls of the container.



In the example shown in Figure 1, a load of 1000 lbs. needs to be moved. When the handle is moved to the left, a force of 100 lbs. is exerted on the 1 square inch piston. The fluid is pressurized to 100 pounds per square inch or 100 PSI. According to Pascal's Law, the 100 PSI is transmitted equally throughout the container. 100 pounds of force is exerted by the pressurized fluid on each of the 10 square inches on the ram. This generates a force of 1000 lbs. which raises the platen.

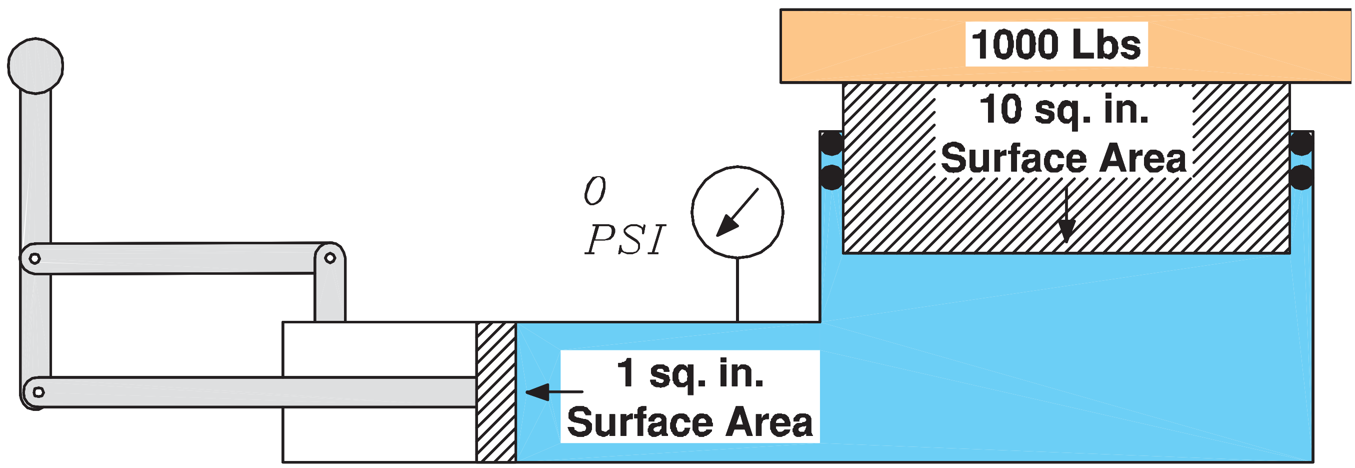


Figure 1

Conservation of Energy

A basic law of physics says that energy cannot be created or destroyed. It would seem that the example in Figure 1 creates energy. Energy is the ability to do work. Work is done when a force is exerted and moved a certain distance.

Work = Force x Distance

Looking at the example in Figure 2, let's say that the small piston is moved 10 inches. A volume of 10 cubic inches is displaced. The large piston will only move 1 inch. The amount of energy exerted on the small piston is the same as that exerted on the large piston to move the 1000 lb. load.

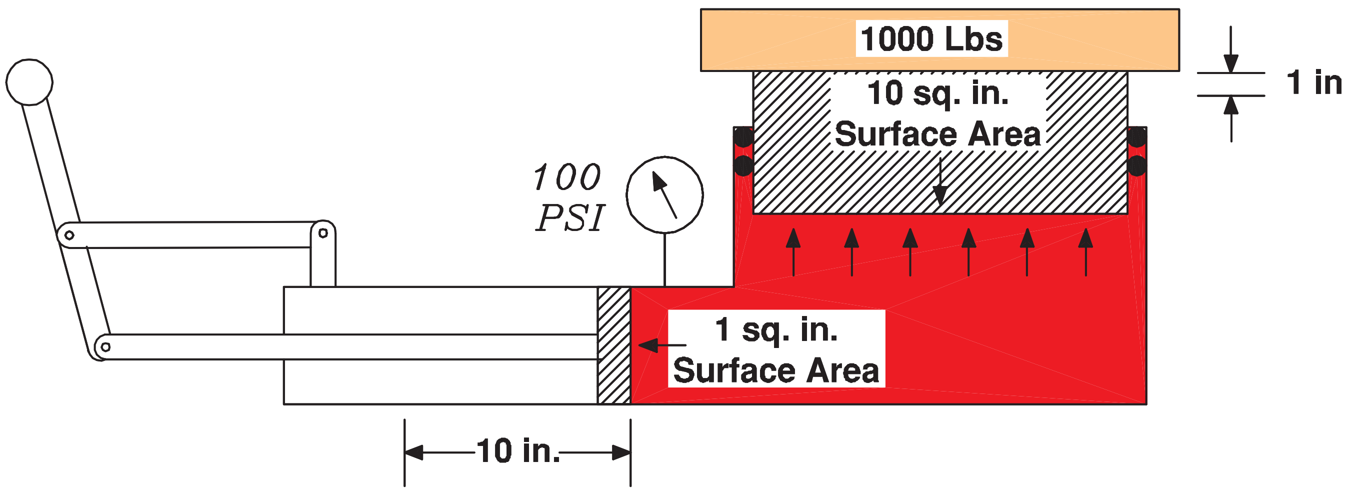


Figure 2

Work = Force x Distance

Work (small piston) = 100 lbs. x 10 inches

Work (small piston) = 1000 in.-lbs.

Work (large piston) = 1000 lbs. X 1 inch

Work (large piston) = 1000 in.-lbs.

Work (small piston) = Work (large piston)

Work (small piston) 1000 in.-lbs. = Work (large piston) 1000 in.-lbs.

Hydraulic Power

Power is the rate that work is done. Power can be expressed in the following manner.

$$\text{Power} = \frac{\text{Force} \times \text{Distance}}{\text{Time}}$$

In Figure 3, a cylinder is moving a 10,000 lb. load a distance of 12 inches. It takes 10 seconds to fully extend the cylinder. If the cylinder were required to extend in 5 seconds then twice as much power would be required.

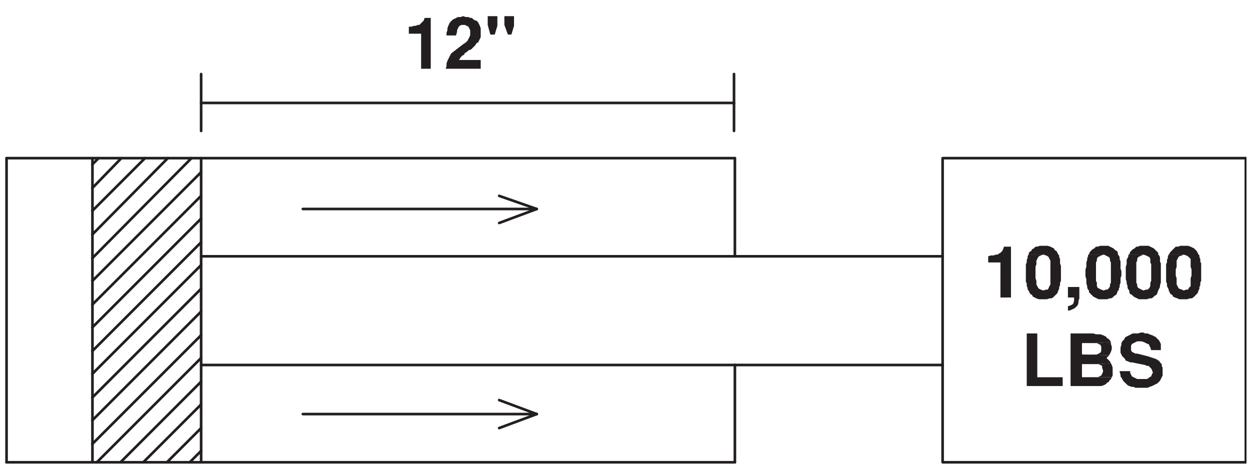


Figure 3

To achieve this increased speed, the rate that the oil is pumped into the cylinder would have to be doubled. We will see later in this section that the rate of oil flow (GPM) is a factor of hydraulic power.

Pressure

Pressure in a hydraulic system is generated by a resistance to flow. In Figure 4A the hand valve is fully open allowing the pumped fluid to flow into the oil drum at 0 PSI.

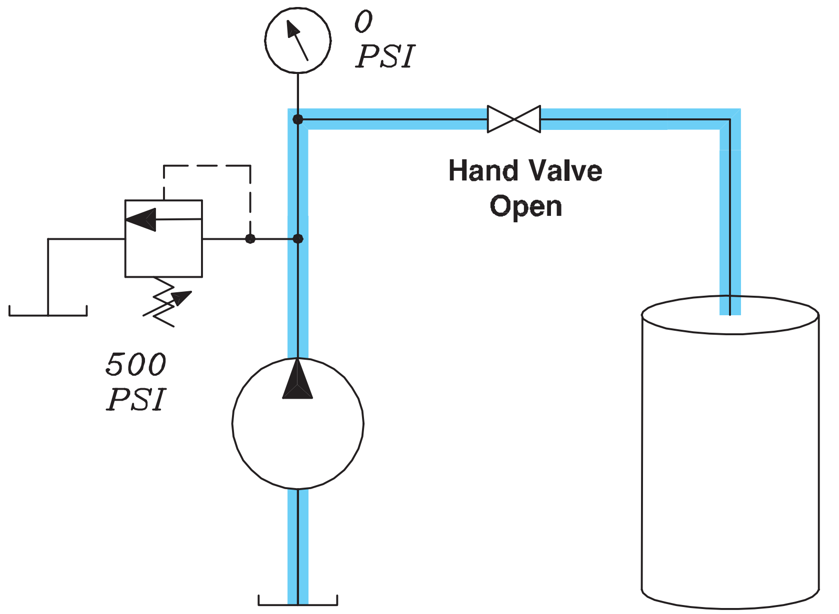


Figure 4A

The Difference Between
Pressure & Flow

In Figure 4B the hand valve is closed. The pressure will then begin to build until it overcomes the resistance of the relief valve spring, 500 PSI. At that time the pressure gauge will indicate 500 PSI and the pump flow will return to tank through the relief valve.

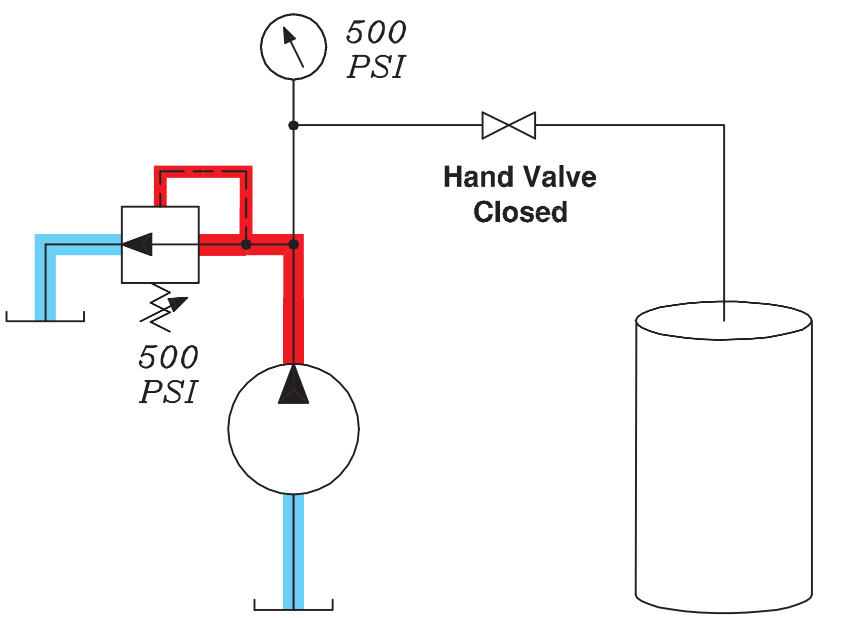


Figure 4B

Cylinder Force

The amount of force that can be developed by a cylinder depends on the pressure and the square inch surface area of the piston.

Force = Pressure x Square Inch Area

We will use a 4” diameter piston with a 2” rod as an example in Figure 5.

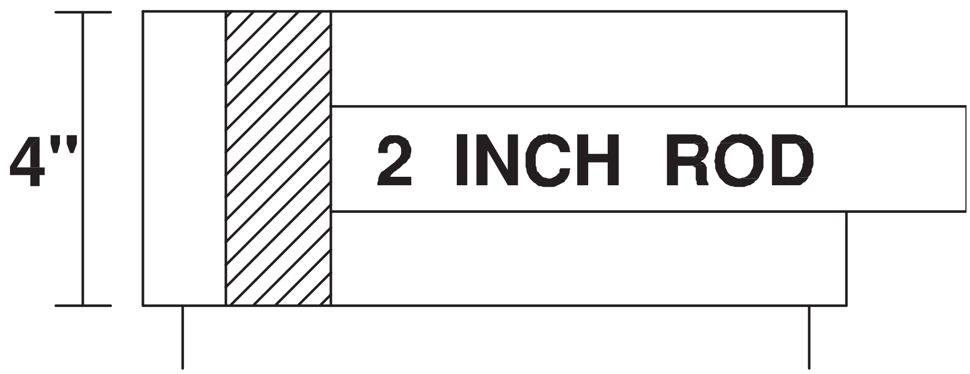


Figure 5

To find the force exerted by the cylinder we must find the square inch area of the piston. To find the area, the following formula is used. (D = Cylinder Diameter)

Square Inch Area = D^2 x .7854

Square Inch Area = 4^2 x .7854

Square Inch Area = 16 x .7854

Square Inch Area = 12.56

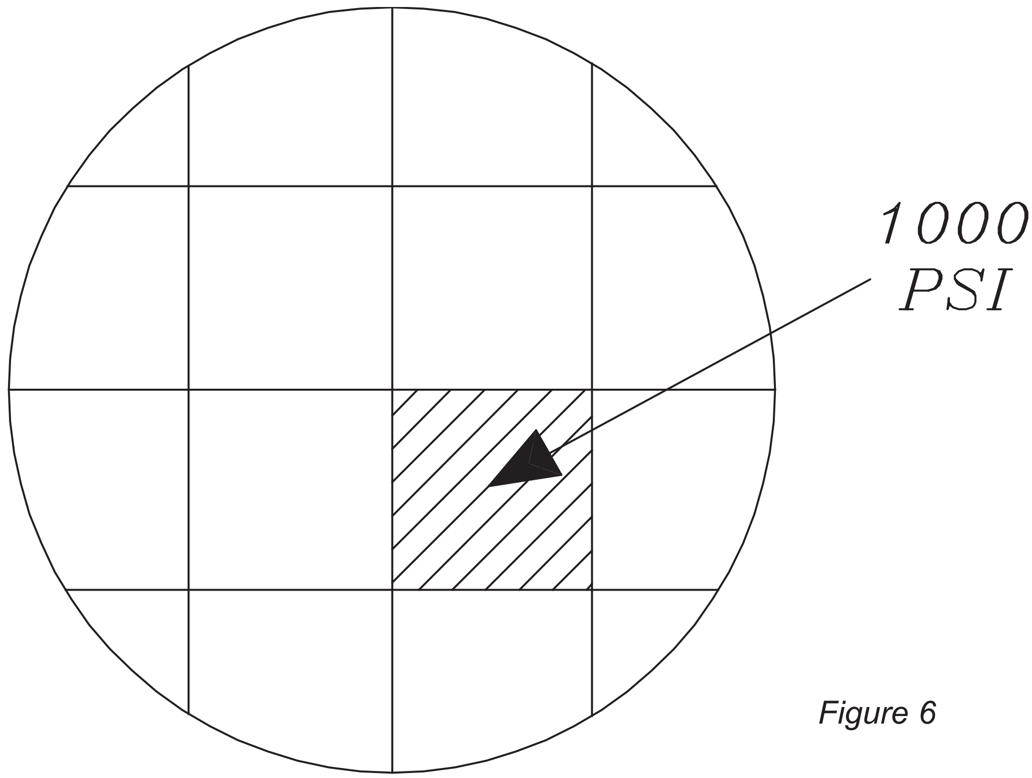


Figure 6

If the pressure were to build to 1000 PSI, then 1000 lbs of force would be exerted on each of the 12.56 square inches (Figure 6). By inserting our numbers in the formula below, we can find the force exerted by the cylinder.

Extend Force = PSI x Area

Extend Force = 1000 PSI x 12.56

Extend Force = 12,560 lbs.

When the cylinder is retracted, less force will be developed with the same pressure. This is because the rod occupies a specific number of square inches of area on the piston. To find the force that can be exerted when the cylinder retracts, we must first find the available surface area. This is done by subtracting the rod area from the full piston area.

Rod Side Square Inch Area = Full Piston Area - Rod Area

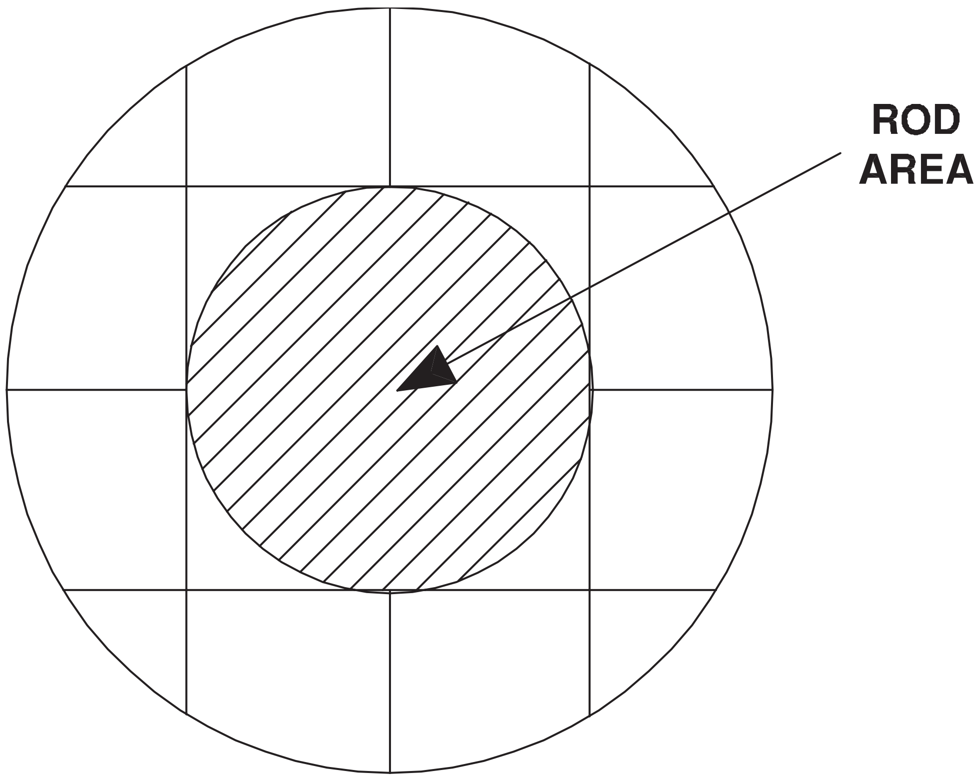
The area of the 2” rod must first be found.

Rod Area = D^2 x .7854

Rod Area = 2^2 x .7854

Rod Area = 4 x .7854

Rod Area = 3.14



The available area on the cylinder rod side can now be determined.

Rod Side Square Inch Area = Full Piston Area - Rod Area

Rod Side Square Inch Area = 12.56 - 3.14

Rod Side Square Inch Area = 9.42

With a rod side square inch area of 9.42 and the pressure at 1000 PSI the cylinder retract force can be found.

Retract Force = PSI x Area

Retract Force = 1000 PSI x 9.42

Retract Force = 9,420 lbs.

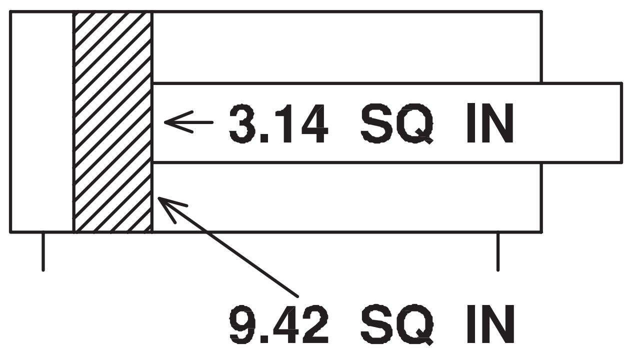


Figure 8

Because of the greater square inch area on the full piston side, more force is exerted when extending the cylinder.

Extend Force = 12,560 lbs.

Retract Force = 9,420 lbs.

Although more force is developed when extending, later in this section we'll see that the cylinder will retract faster than it extends.

Pressure Required to Move a Load

When oil is directed to a cylinder or hydraulic motor to move a load, the pressure will only build high enough to move the load. In Figure 9 a cylinder with 20 square inches of area is attempting to raise a 10,000 lb. load.

We again use our force formula but it is rearranged to find PSI.

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

$$\text{PSI} = \frac{10{,}000}{20}$$

$$\text{PSI} = 500 \text{ PSI}$$

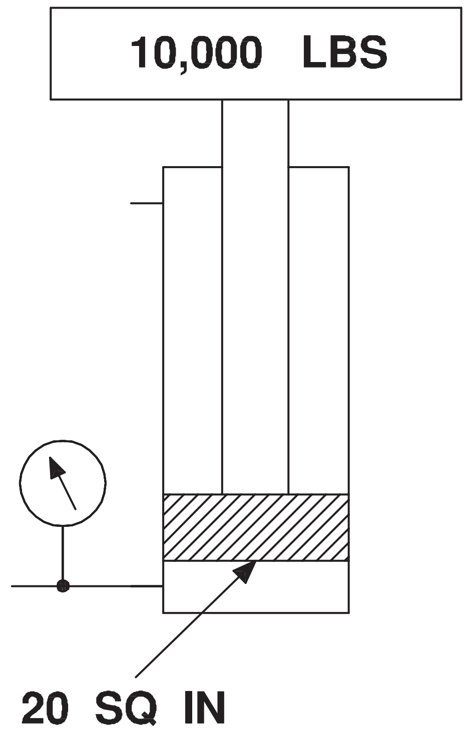


Figure 9

Volume

The speed that a cylinder moves and a hydraulic motor rotates depends on two factors:

- Rate of Oil Flow
- Actuator Size

The component that delivers the flow to the actuator is the hydraulic pump. The purpose of the pump is to supply a volume of oil to the system. **The pump does not pump pressure.** As we have discussed earlier, pressure is developed when a resistance is present in the circuit.

All hydraulic pumps are positive displacement. This means that the pump will supply a specific volume of fluid to the system every time the pump shaft is rotated. This volume of fluid is expressed in cubic inches.

Pumps are normally rated, however, in gallons per minute (GPM), and not cubic inches. To find the total number of cubic inches a pump supplies, multiply the GPM x 231. (There are 231 cubic inches in 1 gallon).

Cylinder Speed

To find the cylinder rod speed the following formula can be used:

$$\text{Rod Speed (Inches per minute)} = \frac{\text{GPM} \times 231}{\text{Cylinder Area}}$$

Let's use a 4" diameter cylinder with a 2" diameter rod and a 24" stroke (Figure 10). The pump is supplying 10 GPM into the cylinder.

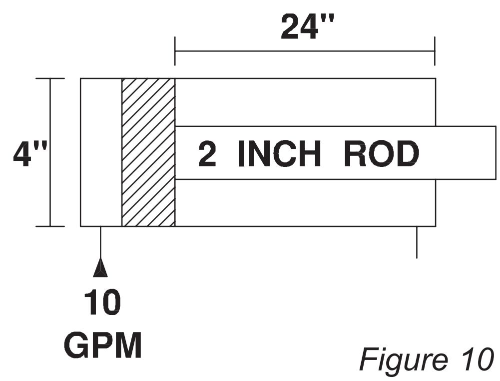


Figure 10

Earlier in this section the area of a 4" cylinder was calculated to be 12.56 square inches.

$$\text{Extend Rod Speed} = \frac{10\ \text{GPM} \times 231}{12.56}$$

$$\text{Extend Rod Speed} = \frac{2310}{12.56}$$

Extend Rod Speed = 183.92 inches per minute

= 3.06 or 3 inches per second

Divide the cylinder stroke by the speed to determine the total extend time. Since the cylinder stroke is 24” the cylinder will extend in 8 seconds.

$$\left(\frac{24}{3} = 8\right)$$

To retract the cylinder the only number that changes is the cylinder area. Again, earlier in this section we found the area on the rod side of the cylinder to be 9.42 square inches. The pump volume (10 GPM) is now directed to the cylinder rod side (Figure 11).

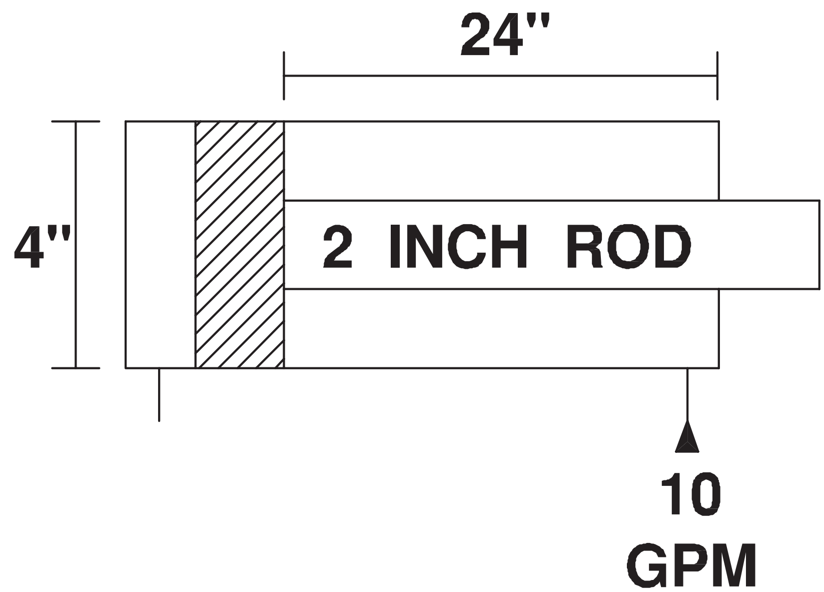


Figure 11

$$\text{Retract Rod Speed} = \frac{10 \times 231}{9.42}$$

$$\text{Retract Rod Speed} = \frac{2310}{9.42}$$

Retract Rod Speed = 245.22 inches per minute

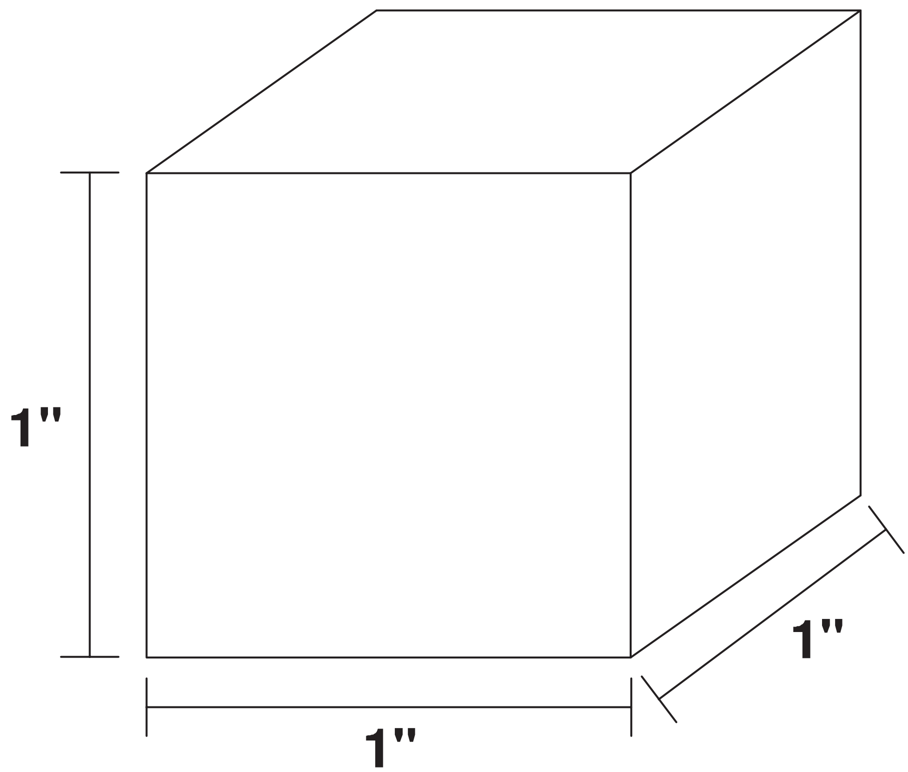
$$\frac{245}{60 \text{ seconds}} = 4.09 \text{ or } 4 \text{ inches per second}$$

Since our cylinder stroke is 24” the cylinder will retract in approximately 6 seconds.

$$\left(\frac{24}{4} = 6\right)$$

Hydraulic Motor Speed

Hydraulic motors are rated according to the number of cubic inches of oil required to rotate the shaft one revolution. This is known as the displacement of the motor.



One Cubic Inch

To find the drive speed for a given motor the following formula can be used:

$$\text{Motor RPM} = \frac{\text{GPM} \times 231}{\text{Cu. In. Displacement}}$$

As an example, let's use a 10 cu. in/rev. displacement motor that is supplied by a 10 GPM Pump.

$$RPM = \frac{10 \text{ GPM} \times 231}{10 \text{ Cu. In. /Rev.}}$$

$$RPM = \frac{2310}{10}$$

$$RPM = 231$$

Anytime a motor is changed and replaced with a different displacement, the speed will change. For example, if the existing motor is replaced with a 20 cu. in/rev displacement motor, then the speed will be half that of the 10 cu. in/rev motor:

$$RPM = \frac{10 \times 231}{20 \text{ Cu. In. /Rev.}}$$

$$RPM = \frac{2310}{20}$$

$$RPM = 115.5$$

Hydraulic Pipe Size

To reduce friction (heat) and turbulence in the line, the proper pipe size should be used. Schedule 40 pipe can be used for suction and return lines. Schedule 80 or 160 should be used for the pressure lines. The lines in the system should be sized as follows:

Pump Suction - 2-5 ft/sec.

Return Lines - 10-15 ft/sec.

Pressure Lines (500 – 3000 PSI) - 15 – 20 ft/sec.

Pressure Lines (Above 3000 PSI) - 30 ft/sec.

Pipe Size (Inches)	Schedule 40 Pipe					
	GPM @ 2 FPS	GPM @ 5 FPS	GPM @ 10 FPS	GPM @ 15 FPS	GPM @ 20 FPS	GPM @ 25 FPS
1/8	.35	.89	1.8	2.7	3.5	4.4
1/4	.65	1.6	3.2	4.9	6.5	8.1
3/8	1.2	3.0	6.0	9.0	12.0	15.0
1/2	1.9	4.8	9.5	12.0	19.0	23.8
3/4	3.3	8.4	16.7	25.1	33.4	41.8
1	5.4	13.5	27.0	40.6	54.1	67.7
1 1/4	9.4	23.4	46.8	70.3	93.7	117
1 1/2	12.7	31.9	63.7	95.6	127	159
2	21.0	52.5	105	157	210	263
2 1/2	30.0	75.0	150	225	300	375
3	46.3	116	232	347	463	579

Pipe Size (Inches)	Schedule 80 pipe					
	GPM @ 2 FPS	GPM @ 5 FPS	GPM @ 10 FPS	GPM @ 15 FPS	GPM @ 20 FPS	GPM @ 25 FPS
1/8	.23	.57	1.1	1.7	2.3	2.8
1/4	.45	1.1	2.2	3.4	4.5	5.6
3/8	.88	2.2	4.4	6.6	8.8	11.0
1/2	1.5	3.7	7.3	11.0	14.7	18.3
3/4	2.7	6.8	13.6	20.3	27.1	33.9
1	4.5	11.3	22.5	33.8	45.0	56.3
1 1/4	8.0	20.0	40.1	60.2	80.3	100
1 1/2	11.1	27.7	55.3	83.0	110	138
2	18.5	46.2	92.5	139	185	231
2 1/2	26.5	66.4	133	199	265	332
3	41.4	103	207	310	414	517

Hydraulic Horsepower

We discussed earlier that power is the speed of doing work. Work is moving a force a certain distance. In the hydraulic system speed and force are represented by Gallons Per Minute (GPM) and Pressure (PSI). The following formula can be used to find the horsepower delivered by a hydraulic system:

$$HP = GPM \times PSI \times .000583$$

The number .000583 is a pre-engineered constant in the formula. If the hydraulic pump was 100% efficient then the previous formula could be used to find the electric motor horsepower size. Because of internal pump bypassing, friction of the bearings and pump elements, the pump is less than 100% efficient. Therefore, slightly more electrical horsepower must be used to drive the pump.

Electric Motor Horsepower

Most pumps are 85-90% efficient. Piston pumps are more efficient than vane or gear pumps. The efficiency of the pump is established by the pump manufacturer when the pump is tested.

In Figure 12, a 30 GPM pump is supplying a system with a maximum pressure of 1500 PSI. If the pump is 87% efficient we can find the electric motor horsepower required with the following formula:

$$HP = GPM \times PSI \times .00067$$

$$HP = 30\,GPM \times 1500\,PSI \times .00067$$

$$HP = 45{,}000 \times .00067$$

$$HP = 30\ HP$$

Rule of Thumb

It takes 1 horsepower to pump 1 GPM at 1500 PSI. In the example, since our pump volume is 30 and the maximum pressure is 1500 PSI, a 30 horsepower electric motor can be used.

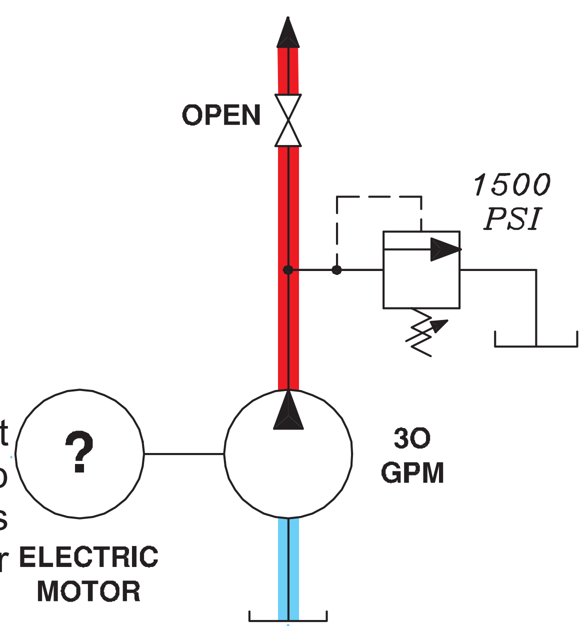


Figure 12

Heat and the Hydraulic System

We discussed earlier in this section the Conservation of Energy. The law stated that energy cannot be created or destroyed. In Figure 12 our pump flow was being delivered to the system to drive our actuator. The energy from the electric motor (30 HP) was converted into hydraulic energy and then back to mechanical energy by our actuator.

In Figure 13 the hand valve is closed. Our pump is still delivering 30 GPM but now the oil is dumping over the relief valve at 1500 PSI.

The electric motor is still pulling 30 HP of electrical energy. However, now instead of being converted into mechanical energy at the actuator it turns into HEAT!

Anytime oil is dumped back to tank and no useful work is done, heat is generated. This is, of course, undesirable. Besides wasting energy the oil will get extremely hot and begin breaking down.

In all hydraulic systems whenever the pump volume is not being used to move the load one of two things should happen:

- The oil is dumped back to tank at low pressure.
- The pump volume is reduced to 0 GPM.

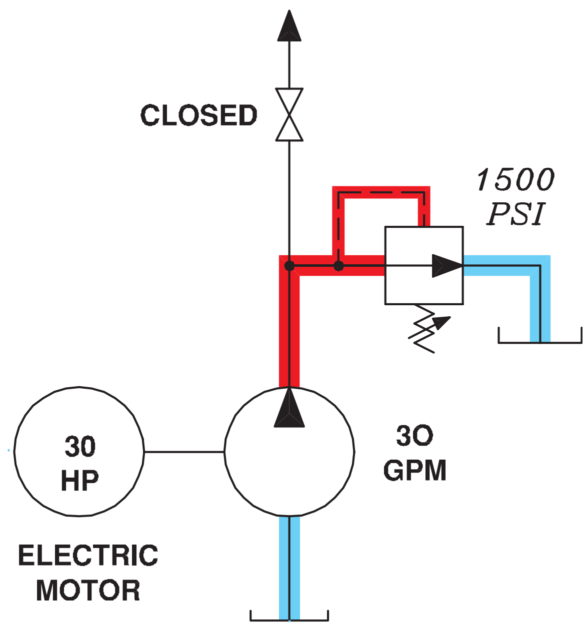


Figure 13

In Figure 14 another hand valve has been installed to dump the oil back to tank at low pressure. The electric motor will only pull enough electrical current to drive the hydraulic system. Therefore, the electric motor horsepower will be very low.

About 5% of the system horsepower is required to pump the fluid back to tank at 0 PSI. The electric motor again only supplies the horsepower needed to drive the hydraulic system. 5% of 30 HP is 1.5 HP. Only 1.5 HP is converted into heat.

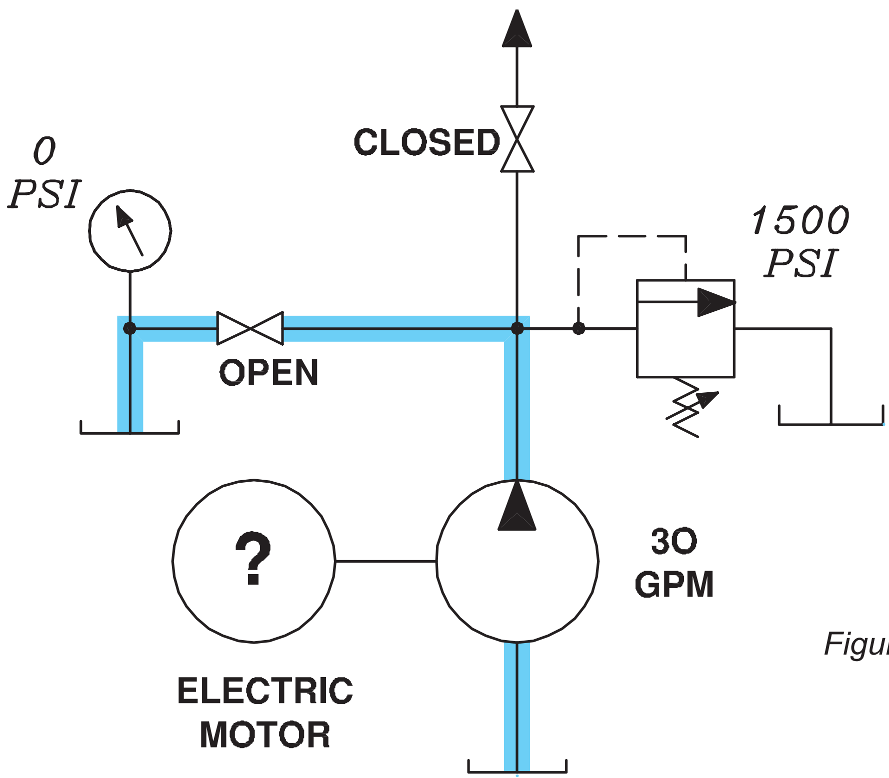


Figure 14