# Hydraulic Fundamentals

## Student Guide

CATERPILLAR®

Asia Pacific Learning

"Provide leading edge learning solutions today for tomorrow's success"

**Caterpillar Service Technician Module**

**APLTCL025**

**HYDRAULIC FUNDAMENTALS**

Published by Asia Pacific Learning
1 Caterpillar Drive
Tullamarine Victoria Australia 3043

Version 3.2, 2003

Copyright © 2003 Caterpillar of Australia Pty Ltd Melbourne, Australia.

All rights reserved. Reproduction of any part of this work without the permission of the copyright owner is unlawful. Requests for permission or further information must be addressed to the Manager, Asia Pacific Learning, Australia.

This subject materials is issued by Caterpillar of Australia Pty Ltd on the understanding that:

1. Caterpillar of Australia Pty Ltd, its officials, author(s), or any other persons involved in the preparation of this publication expressly disclaim all or any contractual, tortious, or other form of liability to any person (purchaser of this publication or not) in respect of the publication and any consequence arising from its use, including any omission made by any person in reliance upon the whole or any part of the contents of this publication.

2. Caterpillar of Australia Pty Ltd expressly disclaims all and any liability to any person in respect of anything and of the consequences of anything done or omitted to be done by any such person in reliance, whether whole or partial, upon the whole or any part of the contents of this subject material.

**Acknowledgements**

A special thanks to the Caterpillar Family for their contribution in reviewing the curricula for this program, in particular:

- Caterpillar engineers and instructors
- Dealer engineers and instructors
- Caterpillar Institutes.

# MODULE INTRODUCTION

## Module Title

Hydraulic Fundamentals.

## Module Description

This module covers the knowledge and skills of Hydraulic Fundamentals. Upon satisfactory completion of this module students will be able to competently service and repair basic hydraulic components.

## Pre-Requisites

The following modules must be completed prior to delivery of this module:

- Occupational Health and Safety
- Mechanical Principles.

## Learning & Development

Delivery of this facilitated module requires access to the Hydraulic Fundamentals Activity Workbook.

The successful completion of the curriculum provides the knowledge for competency assessment, on further learning outcomes, by an Accredited Workplace Assessor.

## Suggested References

- No references recommended.

## Assessment Methods

### Classroom and Workshop

To satisfactorily complete this module, students must demonstrate competence in all learning outcomes. Consequently, activities and assessments will measure all the necessary module requirements.

For this module, students are required to participate in classroom and practical workshop activities and satisfactorily complete the following:

- Activity Workbook
- Knowledge Assessments
- Practical Activities.

### Workplace

To demonstrate competence in this module students are required to satisfactorily complete the Workplace Assessment(s).


© Caterpillar of Australia Pty Ltd

© Caterpillar of Australia Pty Ltd

# KNOWLEDGE AND SKILLS ASSESSMENT

**Learning Outcome 1:** Explain hydraulic principles.

**Assessment Criteria**

1.1. Describe hydrodynamics and hydrostatics in relation to hydraulic systems
- 1.1.1 Energy principles applicable

1.2. State the physical aspects of a gas
- 1.2.1 Gas compresses

1.3. State the properties of a fluid
- 1.3.1 Liquids virtually incompressible
- 1.3.2 Liquids conform to the shape of the container
- 1.3.3 Liquids apply pressure in all directions
- 1.3.4 Purposes of fluids in a hydraulic system

1.4. State Pascal's Law and how hydraulic force can be used to create a mechanical advantage
- 1.4.1 Pascal's Law
- 1.4.2 Fluid power
  - 1.4.2.1 Force transmission
  - 1.4.2.2 Force transmitted through a liquid

1.5. Explain the basic principles of work, flow and pressure, energy transfer and power
- 1.5.1 Fluid weight
- 1.5.2 Atmospheric pressure
- 1.5.3 Barometric pressure
- 1.5.4 Work
- 1.5.5 Flow
  - 1.5.5.1 What is flow
  - 1.5.5.2 Laminar flow
  - 1.5.5.3 Turbulent flow
  - 1.5.5.4 Flow across an orifice
- 1.5.6 Energy transfer
  - 1.5.6.1 Bernoulli's Law
- 1.5.7 Pressure
- 1.5.8 Power
- 1.5.9 Fluid power advantages
- 1.5.10 Key hydraulic principles

1.6. Describe series and parallel hydraulic circuits
- 1.6.1 Series circuit
  - 1.6.1.1 Pressure drop across a series circuit
- 1.6.2 Parallel circuit
  - 1.6.2.1 Pressure drop across a parallel circuit


© Caterpillar of Australia Pty Ltd

1.7. Calculate force, pressure and area in a hydraulic system
- 1.7.1 Formula
- 1.7.2 Force
- 1.7.3 Pressure
- 1.7.4 Area
- 1.7.5 Imperial/Metric conversion factors
  - 1.7.5.1 Length
  - 1.7.5.2 Area
  - 1.7.5.3 Volume
  - 1.7.5.4 Mass
  - 1.7.5.5 Velocity
  - 1.7.5.6 Force
  - 1.7.5.7 Pressure
  - 1.7.5.8 Torque
  - 1.7.5.9 Temperature
  - 1.7.5.10Power
- 1.7.6 Prefixes commonly linked to base units.

**Learning Outcome 2:** Identify and explain the purpose and operation of basic hydraulic circuits and components.

### Assessment Criteria

2.1. Demonstrate knowledge of the basic layout of a hydraulic circuit
- 2.1.1 Tank
- 2.1.2 Pump
- 2.1.3 Main Pressure Relief Valve (PRV)
- 2.1.4 Lines
- 2.1.5 Flow control valves
- 2.1.6 Actuators
- 2.1.7 Filters
- 2.1.8 Motor
- 2.1.9 Graphic symbols

2.2. Identify and describe the function of hydraulic tanks
- 2.2.1 Vented
- 2.2.2 Closed

2.3. Identify, describe the function and explain the operation of hydraulic pumps
- 2.3.1 Positive and non positive displacement
- 2.3.2 Gear
  - 2.3.2.1 Construction
  - 2.3.2.2 Operation
- 2.3.3 Vane
  - 2.3.3.1 Construction
  - 2.3.3.2 Operation
- 2.3.4 Piston
  - 2.3.4.1 Construction
  - 2.3.4.2 Operation
- 2.3.5 Graphic symbols


© Caterpillar of Australia Pty Ltd

2.4. Identify, describe the function and explain the operation of hydraulic control valves
- 2.4.1 Directional
- 2.4.2 Pressure
- 2.4.3 Flow-volume
- 2.4.4 Pilot
- 2.4.5 Open centred
- 2.4.6 Closed centred
- 2.4.7 Graphic symbols

2.5. Identify, describe the function and explain the operation of hydraulic actuators
- 2.5.1 Linear
  - 2.5.1.1 Single acting
    - Construction
    - Cap end head
    - Body
    - Rod end head
    - Piston
    - Piston rods
    - Seals
    - ‘O’ ring with backup ring
    - Lip seal
    - Lip seal with garter spring
    - Lip seal with rod wiper
    - ‘U’ packing
    - ‘V’ packing
  - 2.5.1.2 Operation
    - Integrated counterbalance cartridge
    - Cushion plunger
    - Stroke limiting stop tube
    - Adjustable stop valve
    - Thermal relief valve
    - Operating pressures
  - 2.5.1.3 Double acting
    - Construction
    - Operation
    - Operating pressures
  - 2.5.1.4 Rams
    - Construction
    - Operation
    - Operating pressures
  - 2.5.1.5 Telescopic
    - Construction
    - Operation
    - Operating pressures
- 2.5.2 Rotary (hydraulic motors)
  - 2.5.2.1 Gear
    - Construction
    - Operation


© Caterpillar of Australia Pty Ltd

2.5.2.2 Vane
- Construction
- Operation

2.5.2.3 Piston
- Construction
- Operation

2.5.2.4 Graphic symbols

2.6. Explain the purpose and function of hydraulic oil, filters and coolers

2.6.1 Oil

2.6.1.1 Lubrication

2.6.1.2 Friction

2.6.1.3 Viscosity effects
- To a system
- By temperature
- By pressure
- On lubrication
- Hydrodynamic lubrication
- Clearance flow

2.6.1.4 Water in hydraulic oil

2.6.1.5 Foaming

2.6.1.6 Dirt

2.6.1.7 Cavitation

2.6.2 Filters

2.6.2.1 Reservoir strainer

2.6.2.2 Suction filters
- Location
- Type

2.6.2.3 Pressure filters
- Location
- Type

2.6.2.4 Return line filter
- Location
- Type

2.6.2.5 Full flow filters (including by-pass)

2.6.2.6 Wire mesh filters
- Cleaning

2.6.3 Coolers

2.6.3.1 Air coolers

2.6.3.2 Water coolers

2.6.4 Graphic symbols.


© Caterpillar of Australia Pty Ltd

# TABLE OF CONTENTS

## TOPIC 1: Principles of Hydraulics

Introduction . . . . . 9
Why Are Hydraulic Systems Used? . . . . . 9
Hydraulic Principles . . . . . 10
Fluid Power . . . . . 13
Fluid Power Advantages . . . . . 17
Pressure . . . . . 18
Flow (Q) . . . . . 22
Pressure Drop . . . . . 24
Hydraulics Doing Work . . . . . 29

## TOPIC 2: Hydraulic Circuit & Components

Graphic Symbols . . . . . 32
Hydraulic lines . . . . . 37
Hydraulic Tank . . . . . 38
Graphic Symbol - Hydraulic Tank . . . . . 42
Hydraulic Pumps . . . . . 43
Gear Pumps . . . . . 47
Vane Pump . . . . . 49
Piston Pump . . . . . 52
Graphic Symbol - Pump . . . . . 54
Linear Actuators . . . . . 54
Telescopic Cylinders . . . . . 59
Modified Cylinders . . . . . 60
Cylinder Ratings . . . . . 62
Graphic Symbol - Hydraulic Cylinder . . . . . 62
Rotary Actuators . . . . . 63
Graphics Symbol - Rotary Actuator . . . . . 67
Directional Control Valves . . . . . 67
Pressure Control Valves . . . . . 73
Flow Control Valves . . . . . 76
Graphic Symbols - Valves . . . . . 85
Pressure Control Valve . . . . . 88
Hydraulic Fluid . . . . . 89
Filters & Strainers . . . . . 94
Coolers . . . . . 97
Graphic Symbols - Fluid Conditioner . . . . . 98
Contamination Control . . . . . 99


© Caterpillar of Australia Pty Ltd

© Caterpillar of Australia Pty Ltd

# TOPIC 1

## Principles of Hydraulics

## INTRODUCTION

Hydraulic systems are extremely important to the operation of heavy equipment. Hydraulic principles are used when designing hydraulic implement systems, steering systems, brake systems, power assisted steering, power train systems and automatic transmissions. An understanding of the basic hydraulic principles must be accomplished before continuing into machine systems.

Hydraulics play a major role in mining, construction, agricultural and materials handling equipment.

Hydraulics are used to operate implements to lift, push and move materials. It wasn't until the 1950s that hydraulics were widely used on earthmoving equipment. Since then, this form of power has become standard to the operation of machinery.

In hydraulic systems, forces that are applied by the liquid are transmitted to a mechanical mechanism. To understand how hydraulic systems operate, it is necessary to understand the principles of hydraulics. Hydraulics is the study of liquids in motion and pressure in pipes and cylinders.

## WHY ARE HYDRAULIC SYSTEMS USED?

There are many reasons. Some of these are that hydraulic systems are versatile, efficient and simple for the transmission of power. This is the hydraulic system's job, as it changes power from one form to another.

The science of hydraulics can be divided into two sciences:

- Hydrodynamics
- Hydrostatics.


© Caterpillar of Australia Pty Ltd

## Hydrodynamics

This describes the science of moving liquids.

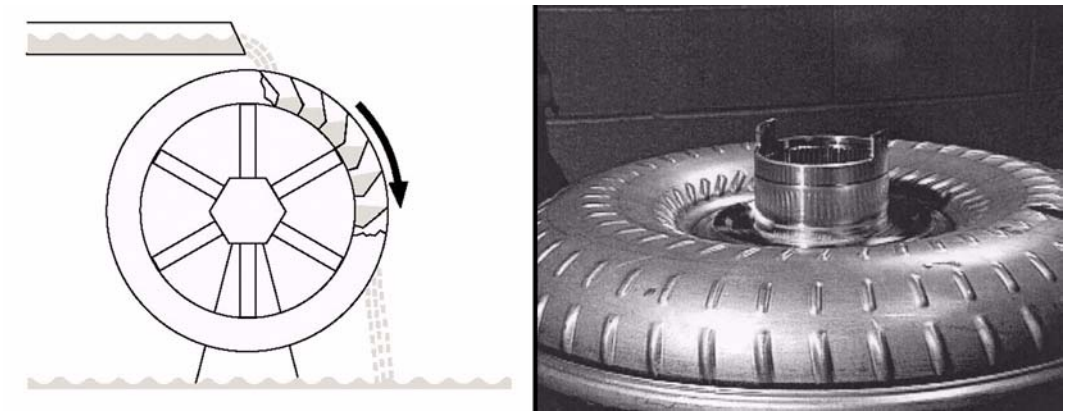

**Figure 1 - a & b**

Applications of hydrodynamics:

- water wheel or turbine; the energy that is used is that created by the water's motion (Figure 1a)
- torque converter (Figure 1b).

## Hydrostatics

This describes the science of liquids under pressure.

Applications of hydrostatics:

- hydraulic jack or hydraulic press
- hydraulic cylinder actuation.

In hydrostatic devices, pushing on a liquid that is trapped (confined) transfers power. If the liquid moves or flows in a system then movement in that system will happen. For example, when jacking up a car with a hydraulic jack, the liquid is moved so that the jack will rise, lifting the car. Most hydraulic machines or equipment in use today operate hydrostatically.

# HYDRAULIC PRINCIPLES

There are several advantages for using a liquid:

1. Liquids conform to the shape of the container.

2. Liquids are practically incompressible.

3. Liquids apply pressure in all directions.


© Caterpillar of Australia Pty Ltd

## Liquids Conform to Shape

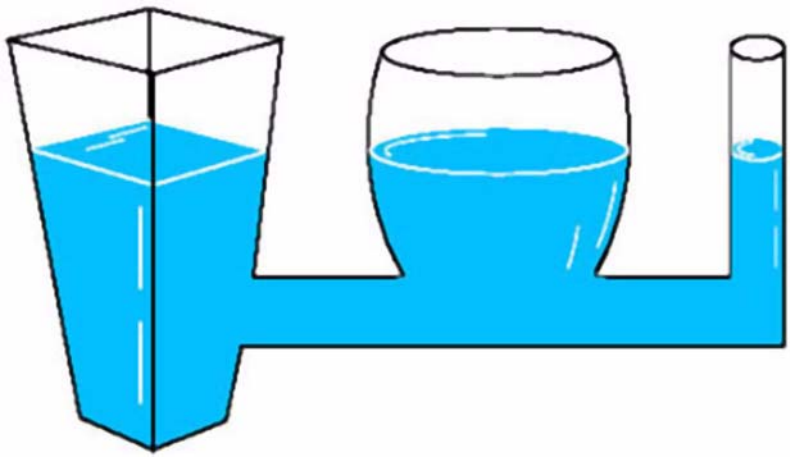

**Figure 2**

Liquids will conform to the shape of any container. Liquids will also flow in any direction through lines and hoses of various sizes and shapes.

We have three oddly shaped containers shown in Figure 2, all connected together and filled to the same level with liquid. The liquid has conformed to the shape of the containers.

## A Liquid is Practically Incompressible

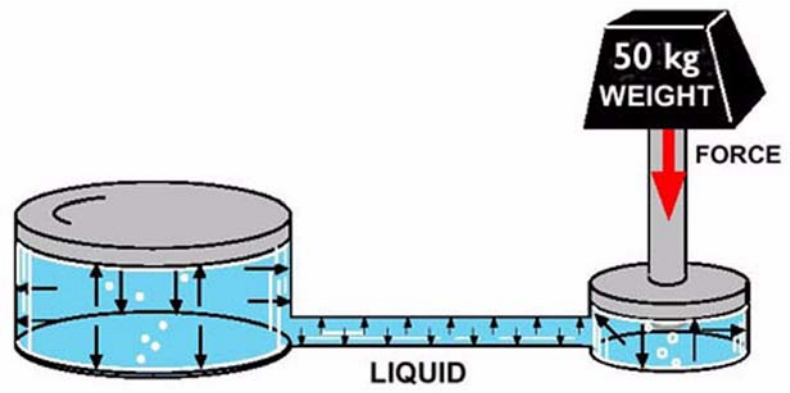


**Figure 3**

Hydraulic oil compresses approximately 1 - 1.5% at a pressure of 3000 psi (20,685 kPa). For machine hydraulic applications, hydraulic oil is considered as ideal and doesn't compress at all.

When a substance is compressed, it takes up less space. A liquid occupies the same amount of space or volume even when under pressure.

Gas would be unsuitable for use in hydraulic systems because gas compresses and takes up less space.


© Caterpillar of Australia Pty Ltd

## Liquids Apply Pressure in All Directions

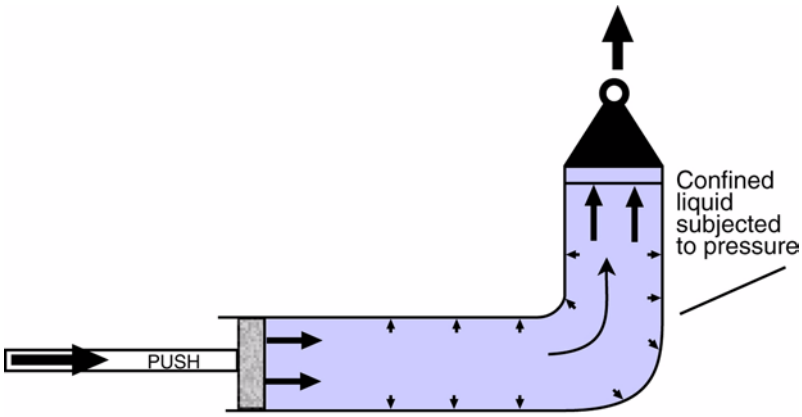


**Figure 4**

There is equal distribution of pressure in a liquid. The pressure measured at any point in a hydraulic cylinder or line will be the same wherever it is measured (Figure 4).

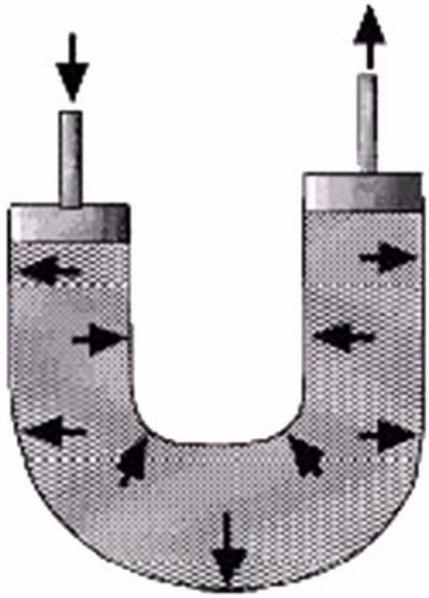

**Figure 5**

When a pipe connects two cylinders of the same size (Figure 5), a change in volume in one cylinder will transmit the same volume to the other. The space or volume that any substance occupies is called ‘displacement’. Liquids are useful for transmitting power through pipes, for small or large distances, and around corners and up and down. The force applied at one end of a pipe will immediately be transferred with the same force to the other end of the pipe.

Most hydraulic systems use oil, because it cannot be compressed and it lubricates the system.


© Caterpillar of Australia Pty Ltd

Water would be unsuitable because:

1. it freezes at cold temperatures and boils at 100$^{o}$C

2. it causes corrosion and rusting and furnishes little lubrication.

## Purpose of the Fluid

Many types of fluids are used in hydraulic systems for many reasons, depending on the task and the working environment, but all perform basic functions:

**First**, the fluid is used to transmit forces and power through conduits (or lines) to an actuator where work can be done.

**Second**, the fluid is a lubricating medium for the hydraulic components used in the circuit.

**Third**, the fluid is a cooling medium, carrying heat away from the “hot spots” in the hydraulic circuit or components and discharging it elsewhere.

And **fourth**, the fluid seals clearances between the moving parts of components to increase efficiencies and reduce the heat created by excess leakage.

# FLUID POWER

In the seventeenth century, a French Philosopher and Mathematician named Blaise Pascal, formulated the fundamental law which forms the basis for hydraulics.

Pascal’s Law states:

“Pressure applied to a confined liquid is transmitted undiminished in all directions, and acts with equal force on all equal areas, and at right angles to those areas.”

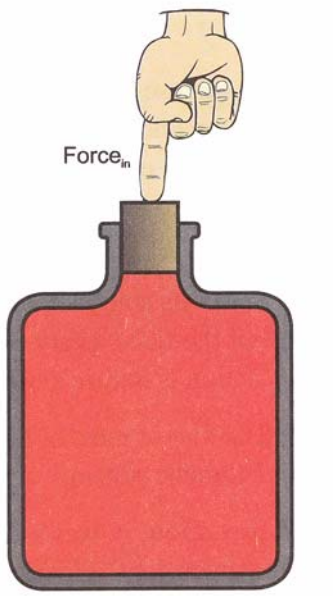


**Figure 6 - Applying pressure to a liquid**

This principle, also referred to as the laws of confined fluids, is best demonstrated by considering the result of driving a stopper into a full glass bottle (Figure 6).


© Caterpillar of Australia Pty Ltd

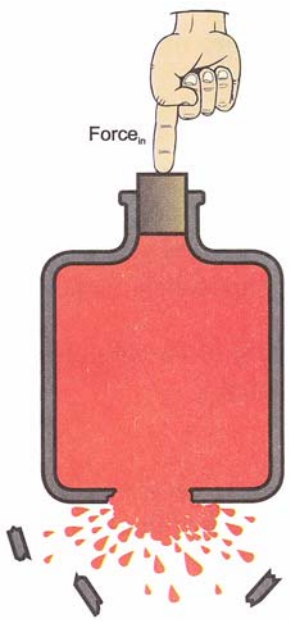


**Figure 7 - Container bursting due to pressure**

Because liquid is essentially incompressible, and forces are transmitted undiminished throughout the liquid and act equally on equal areas of the bottle, and the area of the body of the bottle is much greater than the neck, the body will break with a relatively light force on the stopper. Figure 7 illustrates this phenomenon.

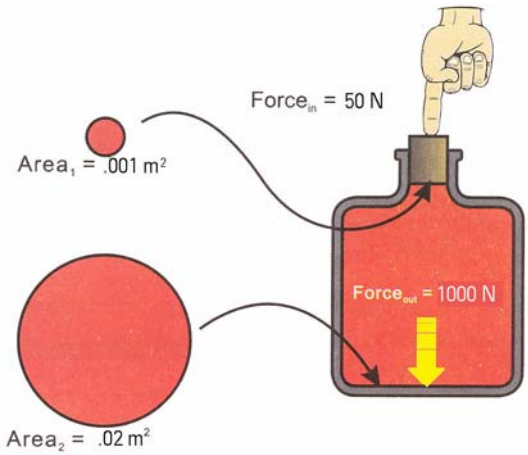


**Figure 8 - Pressure, area, force relationship**

Figure 8 illustrates the relationship of areas that causes a greater force on the body of the bottle than is applied to the neck. In this illustration, the neck of the bottle has a cross sectional area of .001m$^2$. When the pressure created by this force is transmitted throughout the fluid, it influences all adjacent areas with equal magnitude. It stands to reason that a larger area (a greater number of square inches) will be subjected to a higher combined force.

The bottom of the bottle in Figure 8 has a total area of .02m$^2$ as shown, and the force applied by the liquid is 50N. Therefore, the combined force over the entire bottom area is the sum of 50N acting on each of the .001m$^2$ areas. Because there are 20 areas of .001m$^2$ to make up 0.02m$^2$ and 50N on each, the combined force at the bottom of the bottle is 1000N.


© Caterpillar of Australia Pty Ltd

This relationship is represented by the following formula:

Force = Pressure x Area.

This formula allows the Force to be determined and the Pressure and the Area when two of the three are known.

F = Pressure X Area
Pressure = Force ÷ Area
Area = Force ÷ Pressure

**Figure 9**

P = Pressure = Force per unit of area.

The unit of measurement of pressure is the Pascal (Pa).

F = Force - which is the push or pull acting upon a body. Force is equal to the pressure times the area (F = P x A).

Force is measured in Newtons (N).

A = Area - which is the extent of a surface. Sometimes the surface area is referred to as effective area. The effective area is the total surface that is used to create a force in the desired direction.

Area is measured in square metres ($m^2$).

The surface area of a circle (as in a piston) is calculated with the formula:

Area = Pi (3.14) times radius-squared.


© Caterpillar of Australia Pty Ltd

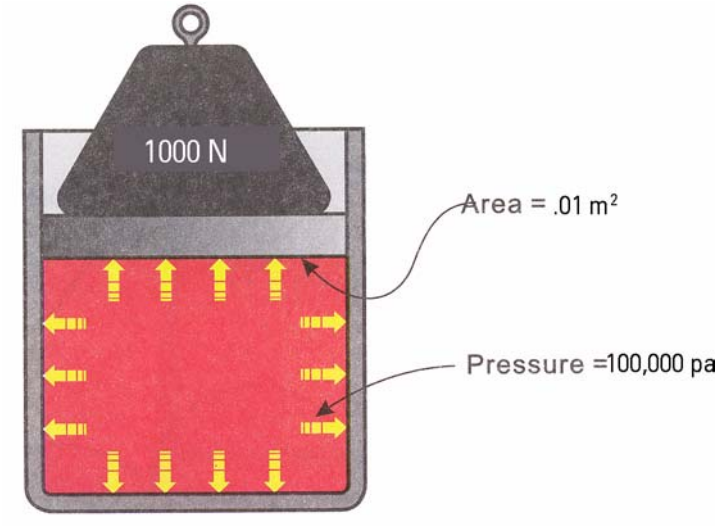


**Figure 10 - Pressure created by weight**

The same relationship is used to determine the pressure in a fluid resulting from a force applied to it. Figure 10 shows a weight being supported by fluid over a .01m$^2$ area. By rearranging the above formula, the fluid pressure of 100,000Pa can be determined by:

Pressure = Force ÷ Area

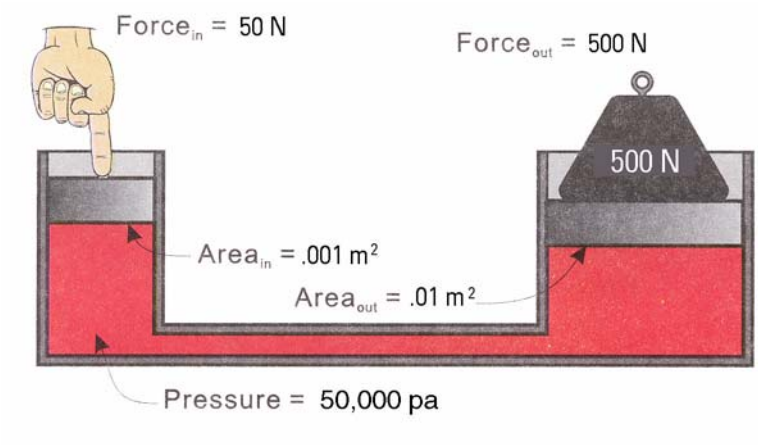


**Figure 11 - Transmitting force by fluid**

Pascal demonstrated the practical use of his laws with illustrations such as that shown in Figure 11. This diagram shows how, by applying the same principle described above, a small input force applied against a small area can result in a large force by enlarging the output area.

This pressure, applied to the larger output area, will produce a larger force as determined by the formula on the previous page. Thus, a method of multiplying force, much the same as with a pry-bar or lever, is accomplished using fluid as the medium.


© Caterpillar of Australia Pty Ltd

## FLUID POWER ADVANTAGES

Multiplying forces is only one advantage of using fluid to transmit power. As the diagram in Figure 11 shows, the forces do not have to be transmitted in a straight line (linearly). Force can be transmitted around corners or in any other non-linear fashion while being amplified. Fluid power is truly a flexible power transmission concept.

Actually, fluid power is the transmission of power from an essentially stationary, rotary source (an electric motor or an internal combustion engine) to a remotely positioned rotary (circular) or linear (straight line) force amplifying device called an actuator. Fluid power can also be looked upon as part of the transformation process of converting a benign form of potential energy (electricity or fuel) to an active mechanical form (linear or rotary force and power).

Once the basic energy is converted to fluid power, other advantages exist:

1. Forces can be easily altered by changing their direction or reversing them.

2. Protective devices can be added that will allow the load operating equipment to stall, but prevent the prime mover (motor or engine) from being overloaded and the equipment components from being excessively stressed.

3. The speed of different components on a machine, such as the boom and winch of a crane, can be controlled independently of each other, as well as independently of the prime mover speed.

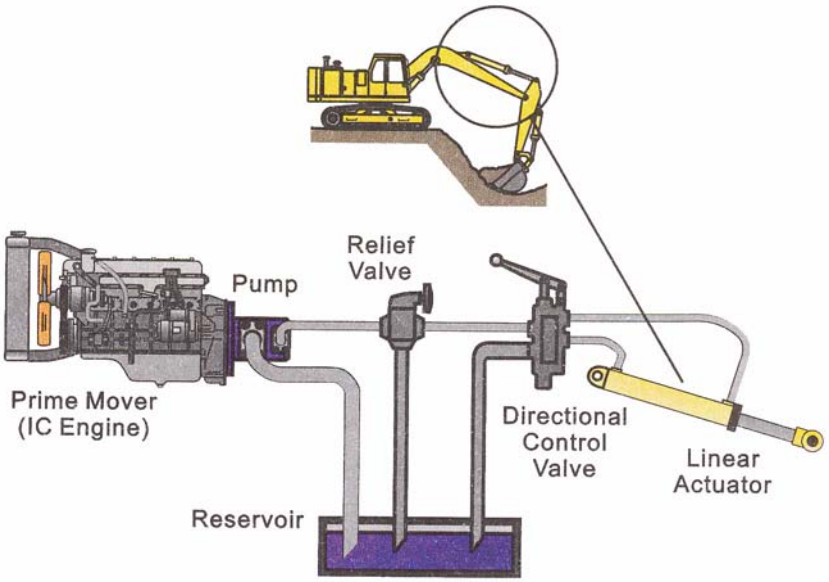


**Figure 12 - Simplified Hydraulic Circuit**

A complete hydraulic system consists of a reservoir of fluid, a hydraulic pump driven by an internal combustion (IC) engine or an electric motor, a system of valves to control and direct the output flow of the pump, and actuators that apply the forces to conduct the work being performed. Figure 12 is a simplified illustration of these major components.


© Caterpillar of Australia Pty Ltd

# PRESSURE

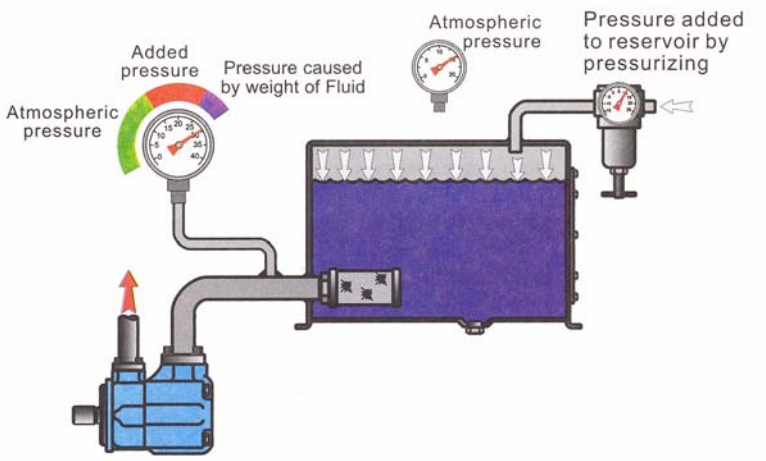


**Figure 13 - Pressure at reservoir outlet**

The system fluid is forced out of the reservoir into the inlet side of a pump by the sum of several pressures that act on the fluid (Figure 13). The first pressure is the one caused by the weight of the fluid; the second is caused by the weight of the atmosphere; a third may be present if a pressurised reservoir is employed.

## Fluid Weight

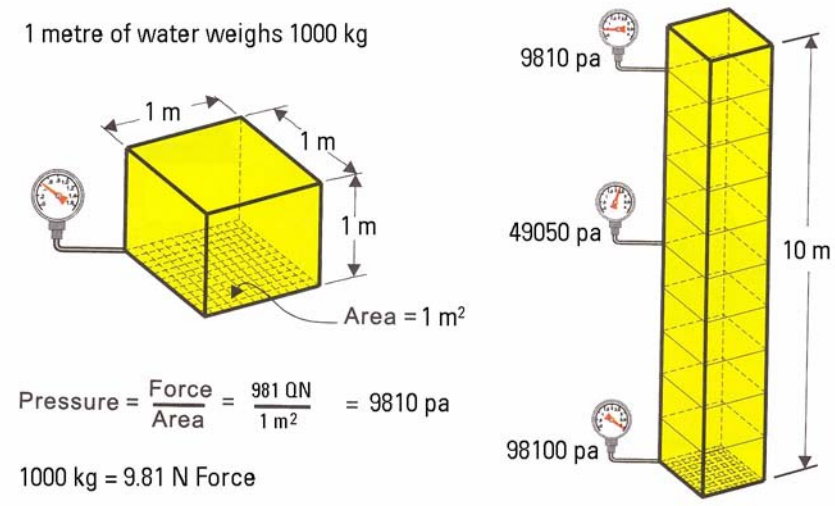


**Figure 14 - Pressure caused by weight of water**

A cubic meter of water weighs approximately 1000kg. This weight acts downward due to the force of gravity, and causes pressure at the bottom of the fluid. Figure 14 shows how this weight is distributed across the entire bottom of the water volume. In this example, the entire weight is supported by an area measuring one metre by one metre or $1m^2$.

The pressure of acting at the bottom of 1 cubic metre of water is 9810kPa.

A two metre tall column of water would develop twice as much pressure if spread over the same area (i.e. 19620 Pa).


© Caterpillar of Australia Pty Ltd

This is the same pressure felt on eardrums when swimming under water, and experience says that the pressure increases with depth. The pressure can be expressed as follows:

Pressure (Pa) = water depth (m) x 9810 Pa per metre of depth.

Other fluids behave the same as water, the difference being relative to the difference in weight of the fluids. The difference is usually defined by the Specific Gravity of the fluid (SG), which is the ratio of the fluid's weight to the weight of water.

SG = Weight of fluid ÷ Weight of water

A typical specific gravity for oil used in hydraulic systems is approximately 0.92, meaning the weight of the oil is 92% of the weight of water. The relationship of the first formula then becomes:

Pressure (Pa) = Fluid Depth (m) x 9810 Pa/m water x SG.

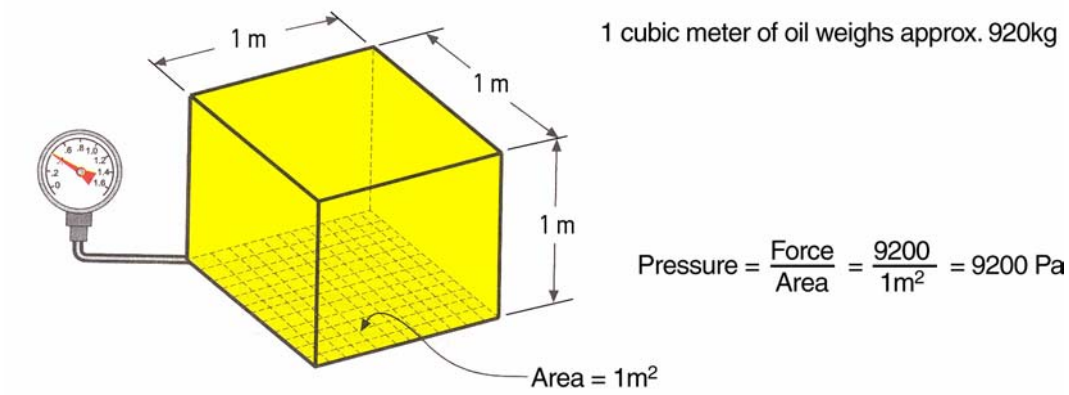


**Figure 15 - Pressure caused by the weight of oil**

Pure water weighs 1000kg per cubic metre at 4$^{o}$C, the temperature at which it is most dense. The weight will be slightly less at higher temperatures, but the difference is generally ignored in hydraulic calculations.

Typical hydraulic oil in a reservoir creates a pressure of 9200 Pa per metre of height, as illustrated in Figure 15. This pressure at the bottom of a reservoir helps to push the fluid out of the reservoir and into the inlet of a hydraulic pump, if the pump inlet is below the fluid level.


© Caterpillar of Australia Pty Ltd

## Atmospheric Pressure

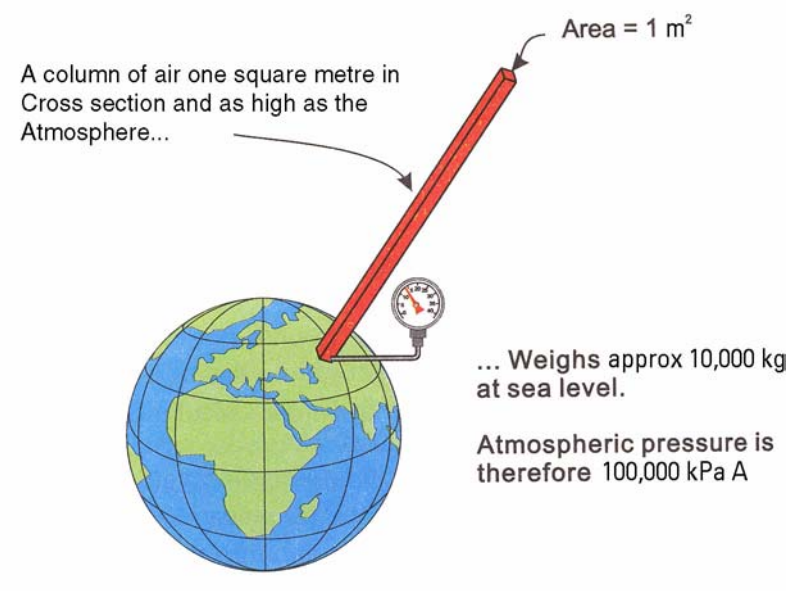


**Figure 16 - Weight of air causes atmospheric pressure**

Generally air is considered as not having weight. Any reasonable quantity of it is so light that the weight is usually ignored. A column of air measuring one metre by one metre across (1 square metre of area), and extending from the earth's surface at sea level to the extreme of the atmosphere, would actually have a significant weight. This weight, on an average day is approximately 10,000kg, as illustrated in Figure 16. Therefore the pressure that continuously exists at sea level due to the weight of the air above, is 100,000Pa. This is referred to as a standard atmosphere, or the atmospheric pressure on a typical day at sea level which is also known as 1 bar or 1000 millibars.

This pressure, acting on the reservoir fluid, also helps to push fluid out of the reservoir and into the inlet of a pump.

People are so accustomed to this pressure, and because it exists all the time the pressure under these conditions is considered to be 'zero'. Pressure gauges also read "zero" under these conditions, so the standard atmospheric pressure is referred to as a gauge reading. It is, of course, possible to obtain pressures below this level by removing some of the atmospheric pressure, and this is called a vacuum.


© Caterpillar of Australia Pty Ltd

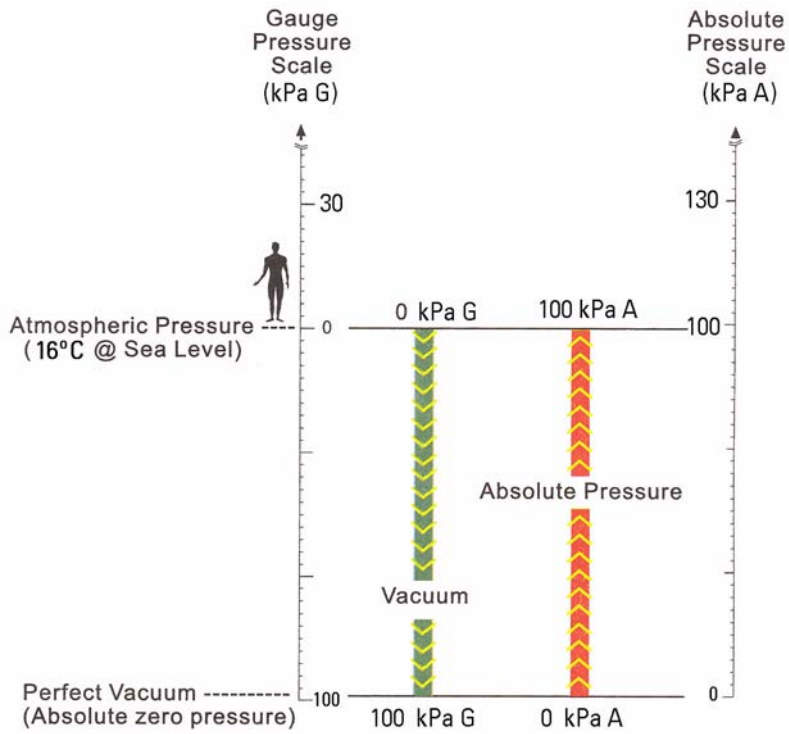


**Figure 17 - Gauge and absolute pressure**

By removing all of the atmospheric pressure, a “new” zero is derived, and this is called “absolute zero”. Absolute zero is 100 kPa below gauge zero, and is considered a perfect vacuum (Figure 17). There is no pressure below absolute zero.

To differentiate between the two pressures, gauges which read absolute values are labelled as such. This means that the zero for this pressure is absolute zero, and all positive pressure readings start from this level. If the pressure starts at atmospheric pressure as the “zero”, then it is designated gauge pressure. Gauges which read this way are not normally labelled.

## Barometric Pressure

One can see now that as we move above sea level, such as up a mountain, the column of air above us becomes shorter, and thus the weight of the air above us becomes less. The atmospheric pressure is then reduced, and the air is not compressed as much. We recognise this as “thin” air at higher altitudes, and we feel a shortness of breath; the reason being that we get less air into our lungs each time we inhale.

It is important to recognise this phenomenon; at higher altitudes, the atmospheric pressure available to help push fluid out of the bottom of a hydraulic reservoir and into the inlet of a pump is less than at lower altitudes.


© Caterpillar of Australia Pty Ltd

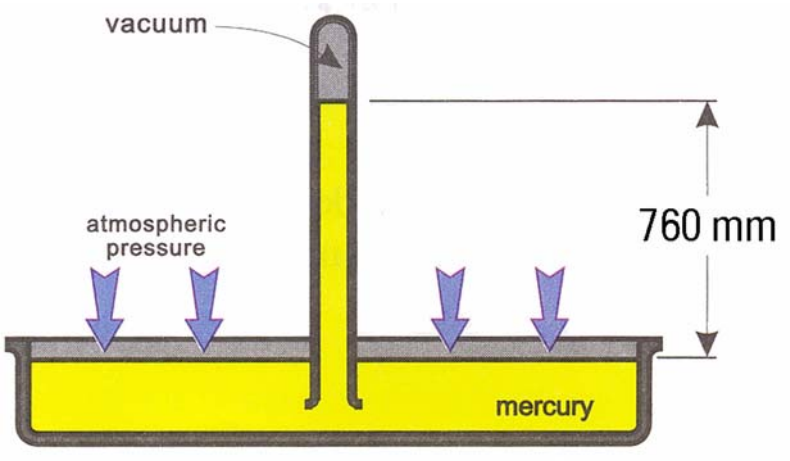


**Figure 18 - Barometer principle**

Atmospheric pressure is measured by use of a barometer, and this is illustrated in Figure 18. A tube full of mercury is inverted in a pool of mercury as shown. The mercury will fall out of the tube until it reaches a specific height. The space above the mercury in the tube will become a perfect vacuum of 0kPa. The height of the mercury in the tube will correspond to atmospheric pressure, because it is atmospheric pressure that is preventing the mercury from falling the rest of the way out of the tube.

At standard atmospheric pressure of 100 kPa mercury will fall in the tube until it reaches a height of 760mm above the pool. As the atmospheric pressure changes (due to climate or altitude change), the height of the mercury will change accordingly.

## FLOW (Q)

Flow is simply the movement of a quantity of fluid during a period of time. Fluids are confined in hydraulics, such as in hoses, tubes, reservoirs and components, so flow is the movement of a fluid through these confining elements.

Flow is normally designated by the letter “Q”, and is usually expressed in litres-per-minute, or LPM, but may also be expressed in cubic-centimetres-per-minute ($cm^3$/min) or per-second ($cm^3$/sec).

In using the above formula the correct units must be used so that they are equal on both sides of the equation. For example, if area is in sq cm, then velocity must be in cm per second or cm per minute. The flow will then be cubic centimetres (cc) per second or minute.

Flow is basically the velocity of a quantity of fluid past a given point. To visualize this, consider a cross-sectional area of fluid inside a tube. If this cross-sectional “slice” of fluid moved at the rate of one metre in one second, then it would “push” one metre of fluid ahead of it every second. The volume of that fluid is the cross sectional area times the length. The time, in this case, is one second. This gives rise to the basic formula for flow in hydraulics:

Flow = Area x Velocity, or Q = A x V.


© Caterpillar of Australia Pty Ltd

## Laminar Flow

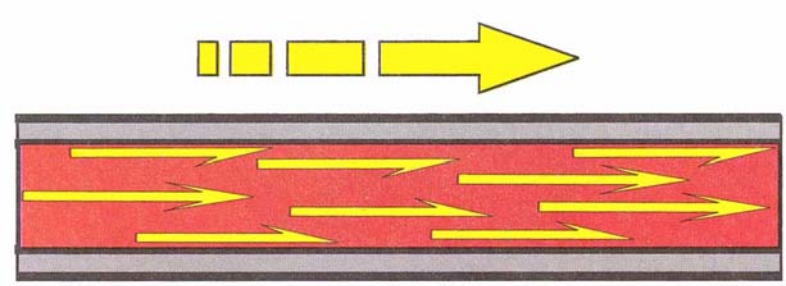

**Figure 19 - Laminar flow**

We would like to think of flow in a hydraulic system as a smooth transition of fluid from one point to another; all particles of the fluid would be moving parallel to all other particles, and there would be no turmoil within the fluid. This we would call laminar flow (Figure 19), and it is very desirable.

## Turbulent Flow

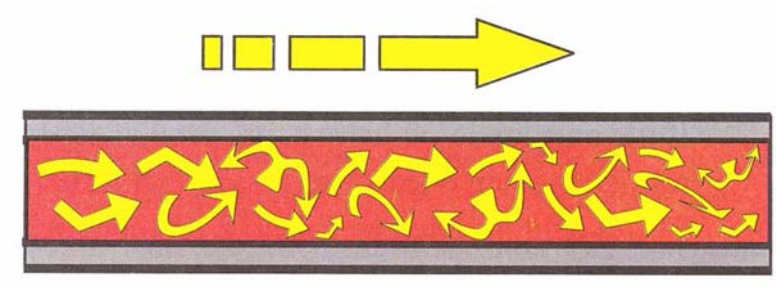

**Figure 20 - Turbulent flow**

In fact, hydraulic system flow often experiences more turmoil than is desirable. Although the fluid generally move in the direction which is required, it also travels through small conduits, across sharp-edged restrictions, through small orifices, around sharp bends, in fact, through all the places that have a tendency to cause anything but a nice, smooth transition.

Particles of the fluid are travelling helter-skelter among each other (see Figure 20), causing friction and inefficient movement. This type of flow, called turbulent flow, is undesirable and wasteful. Unfortunately, the economic and practical aspects of mobile fluid power result in most flow being in the turbulent variety.


© Caterpillar of Australia Pty Ltd

# PRESSURE DROP

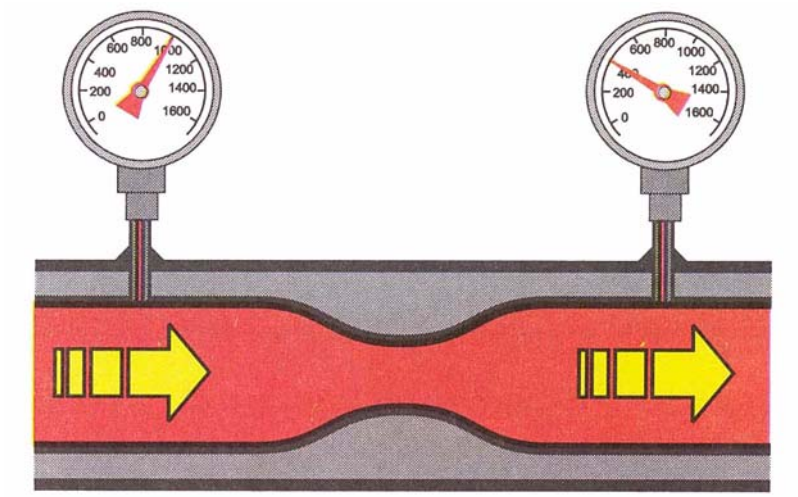


**Figure 21 - Flow past an orifice creates a pressure drop**

When fluid flows across an orifice, as in Figure 21, it loses some of its energy. This is reflected in a lower pressure at the downstream side of the orifice, as illustrated by the two gauges. The difference between the upstream and downstream pressure is called a pressure drop; it is the drop in pressure caused by the flow and the restriction (orifice).

- The magnitude of the pressure drop will vary, depending upon:
- The rate of flow passing across the orifice
- The size of the orifice
- The ease with which the fluid will flow (viscosity).

The downstream flow must be the same as the upstream flow in Figure 21, because there is nowhere for the fluid to escape. However, if the pressure in the fluid is lower, then the energy in the fluid is less. A law of physics states that energy cannot be destroyed, therefore the difference in energy must be given off in the form of heat.

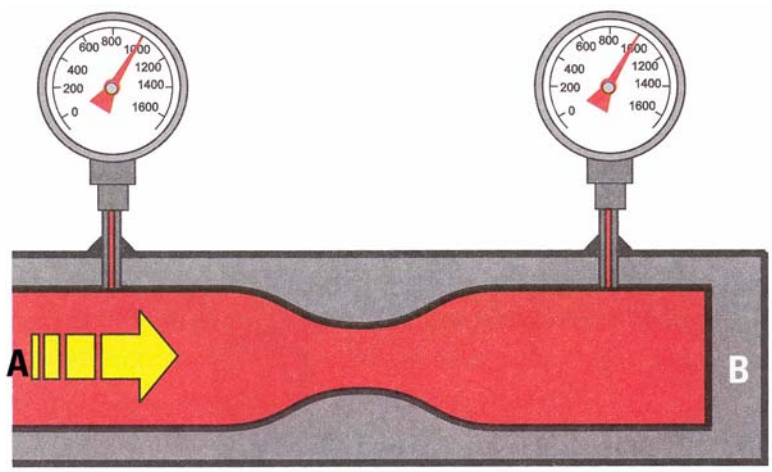


**Figure 22 - If there is no flow across an orifice, there is no pressure drop**

If the magnitude of the pressure drop is dependent on the amount of flow passing the restriction, then it stands to reason that if there is no flow, there will be no pressure drop. This is demonstrated by Figure 22; there being no flow across the orifice will result in equal pressure on both sides. With no flow and no pressure drop, there will be no heat rejected due to a drop in energy.


© Caterpillar of Australia Pty Ltd

This direct relationship between flow and pressure drop is an important consideration in hydraulics; if there is no flow between point A and point B, there will be no pressure drop. Conversely, if there is no difference in pressure between points A and B, there is no fluid flow between these two points.

## Bernoulli's Principle

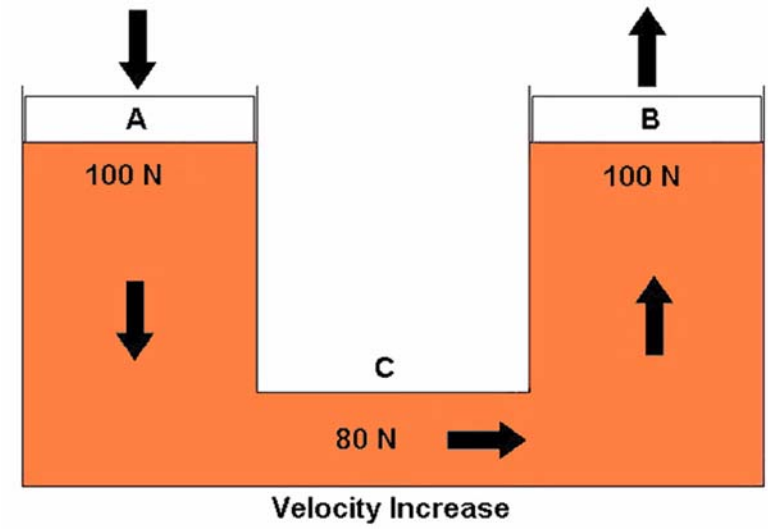


**Figure 23**

Bernoulli's Principle tells us that the sums of pressure and kinetic energy at various points in a system must be constant, if flow is constant. When a fluid flows through areas of different diameters as shown in Figure 23, there must be corresponding changes in velocity. At the left, the section is large so velocity is low. In the centre, velocity must be increased because the area is smaller. Again, at the right, the area increases to the original size and the velocity again decreases.

Bernoulli proved that the pressure component at C must be less than at A and B because velocity is greater. An increase in velocity at C means an increase in kinetic energy. Kinetic energy can only increase if pressure decrease. At B, the extra kinetic energy has been converted back to pressure and flow decreases. If there is no frictional loss, the pressure at B is equal to the pressure at A.


© Caterpillar of Australia Pty Ltd

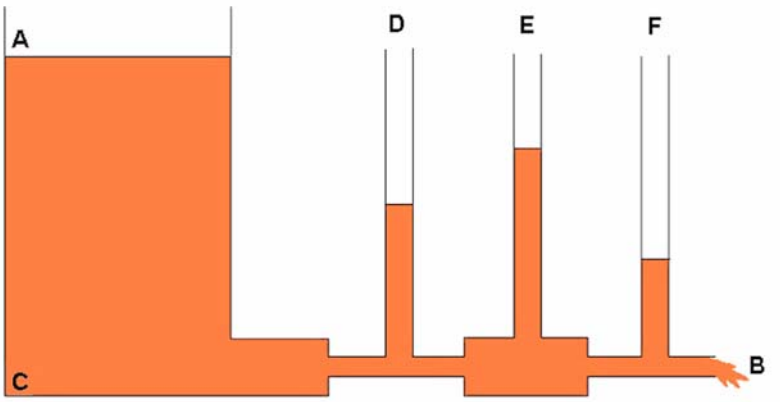


**Figure 24**

Figure 24 shows the combined effects of friction and velocity changes. Pressure drops from a maximum at C to zero at B. At D, velocity is increased, so the pressure head decreases. At E, the head increases as most of the kinetic energy is given up to pressure energy because velocity is decreased. Again, at F, the head drops as velocity increases.

Put simply, Bernoulli's Principle is indicating that:

- As flow increases, pressure decreases
- As flow decreases, pressure increases.

## Summary for some key Hydraulic principles

Hydraulic "work done" is a combination of pressure, and flow, over time.

Pressure without flow results in no action.

Flow without pressure results in no action.

Hydraulic pressure is a result of resistance to flow and in force:

- Increase in flow, decrease in pressure
- Decrease in flow, increase in pressure.

Hydraulic flow is movement.


© Caterpillar of Australia Pty Ltd

## Series & Parallel Circuits

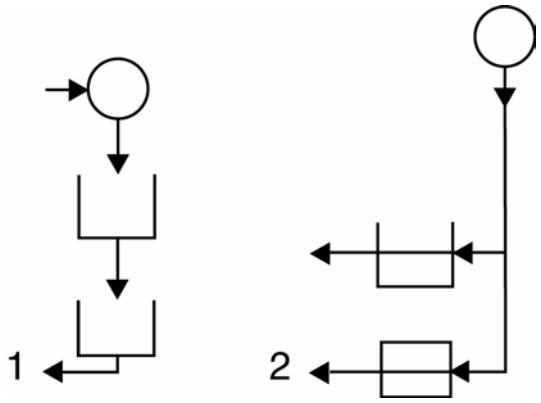


**Figure 25**

Most machines require multiple components that can be connected in series or parallel (Figure 25).

When components are connected in series (1), fluids flow from one component to the next, before returning to the tank. When components are connected in parallel (2), fluid flows through each component simultaneously.

## Restrictions in Series

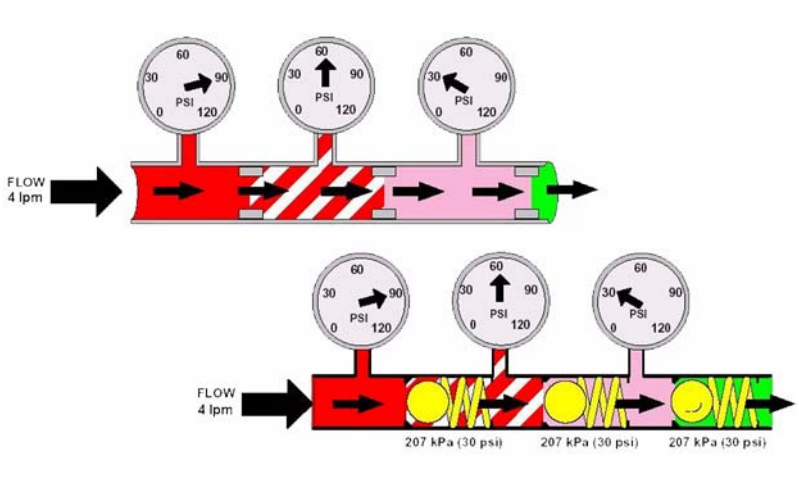


**Figure 26**

In Figure 26, a pressure of 620 kPa (90 psi) is required to send 4 litres per minute (lpm) through either circuit.

Orifices or relief valves in series in a hydraulic circuit offer a resistance that is similar to resistors in series in an electrical circuit, in that the oil must flow through each resistance. The total resistance equals the sum of each individual resistance.


© Caterpillar of Australia Pty Ltd

## Restriction in Parallel

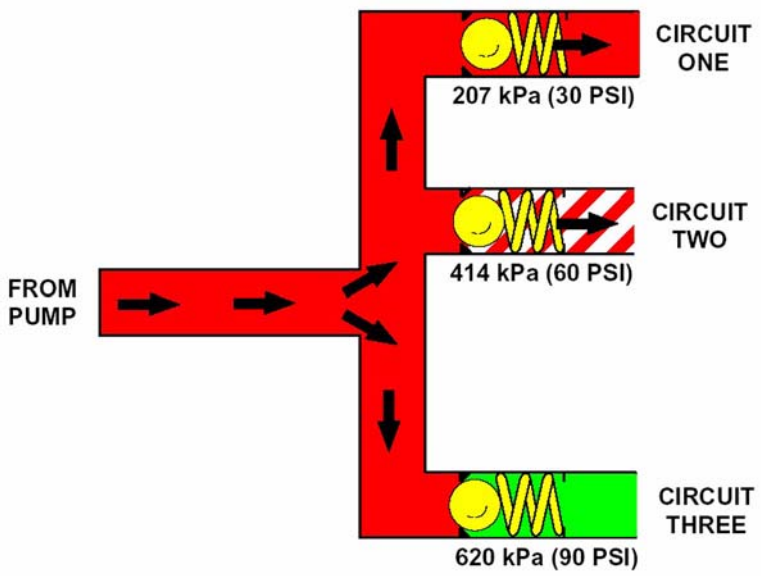


**Figure 27**

In a system with parallel circuits, pump oil follows the path of least resistance. In Figure 27, the pump supplies oil to three parallel circuits. Circuit three has the highest resistance and therefore would have the lowest priority. Circuit one has the lowest resistance and therefore would have the highest priority.

When the pump oil flow fills the passage from the pump to the valves, pump oil pressure increases to 207 kPa (30 psi). The pressure created by the restriction of oil flow, opens the valve to circuit one and oil flows into the circuit. Circuit pressure will not increase until circuit one if full. When circuit one fills, fluid pressure will increase to 414 kPa (60 psi) and opens the valve in circuit two. Again, circuit pressure will not increase until circuit two is full. Pump oil pressure must exceed 620 kPa (90 psi) to open the valve in circuit three.

There must be a system relief valve in one of the circuits or at the pump to limit the maximum pressure in the system.


© Caterpillar of Australia Pty Ltd

# HYDRAULICS DOING WORK

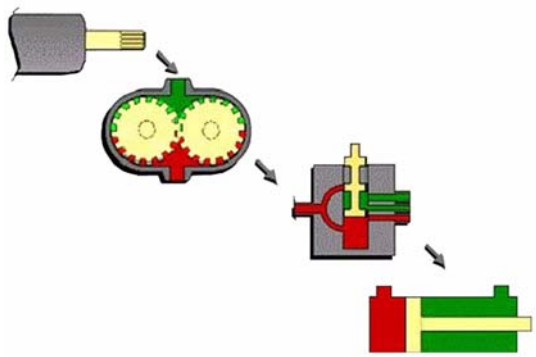

**Figure 28**

In order to perform useful work, a hydraulic system must convert and control energy as it flows from one component to the next.

Figure 28 above represents the key conversion and control points in the system.

The hydraulic system receives input energy from a source, normally from an engine or rotating gear train. The hydraulic pump converts the energy into hydraulic energy in the form of flow and pressure. Valves control the transfer of hydraulic energy through the system by controlling fluid flow and direction. The actuator (which can be either a cylinder or a hydraulic motor) converts hydraulic energy into mechanical energy in the form of linear or rotary motion, which is used to perform work.

**To perform hydraulic work, both flow and pressure are required. Hydraulic pressure is force and flow provides movement**.

## Imperial/Metric Conversion Factors

### Length

0.03937 inches (ins) = 1 millimetre (mm)

0.3937 inches (ins) = 1 centimetres (cm))

39.37 inches (ins)=1 metro (m)

1 inch (in or “) = 25.4 millimetres (mm)

1 foot (ft or ‘) = 0.3048 metres.

### Area

0.00155 ins2 = 1 $mm^2$

0.155 ins2 = 1 $cm^2$

1 square inch ($in^2$) = 6.452 square centimetres ($cm^2$).

### Volume

0.061 $in^3$ = 1 $cm^3$

61.02 $in^3$ = 1 litre (L)

0.22 Imperial gallon = 1 litre (L)

0.2642 U.S. Gallon = 1 litre (L)

1 cubic inch ($in^3$) = 16.39 cubic centimeters ($cm^3$ or cc)

1 imperial gallon (imp gal)= 4.546 litres (lt)

1 US gallon (US gal) = 3.785 litres (lt).



© Caterpillar of Australia Pty Ltd 

## Mass

2.205 pounds (lb) = 1 kilogram (kg)

0.9844 tons (t) = 1 tonne (t)

1 pound (lb) = 0.4536 kilograms (kg).

## Velocity

196.8 feet per minute (ft/min) = 1 meter per second (m/s).

## Force

0.2248 pounds force (lb.force) = 1 Newton (N)

0.1004 tons force (t.force) = 1 KiloNewton (kN).

## Pressure

0.145 pounds per square inch (psi) = 1 Kilopascal (kPa)
*Note: 101.325 kPa = 1 Atmosphere (atms)*

1 kg/sq.cm = 14.22 psi or 0.9678 atms or 100 kPa.

## Torque

0.7376 pound foot (lb.ft) = 1 Newton Meter (Nm)

7.23 (lb.ft) = 1 Kg/m.

## Temperature

Degrees Fahrenheit (°F) = °C x 1.8 + 32 (Degree Celsius°C).

## Power

1 kilowatt (kW) = 1.341 Horsepower (hp)
*Note: 1 watt (w) = 1 Nm/s.*

## Prefixes Commonly Linked to Base Units

| | | |
|---|---|---|
| Micro | = | 0.000 00 One Millionth |
| Milli | = | 0.001 One Thousandth |
| Centi | = | 0.01 One Hundredth |
| Deci | = | 0.1 One Tenth |
| 1.0 | = | One |
| Deca | = | 10.0 Ten |
| Hecto | = | 100.0 One Hundred |
| Kilo | = | 1000.0 One Thousand |
| Mega | = | 1000000.0 One Millionth. |


© Caterpillar of Australia Pty Ltd

# TOPIC 2

## Hydraulic Circuit & Components

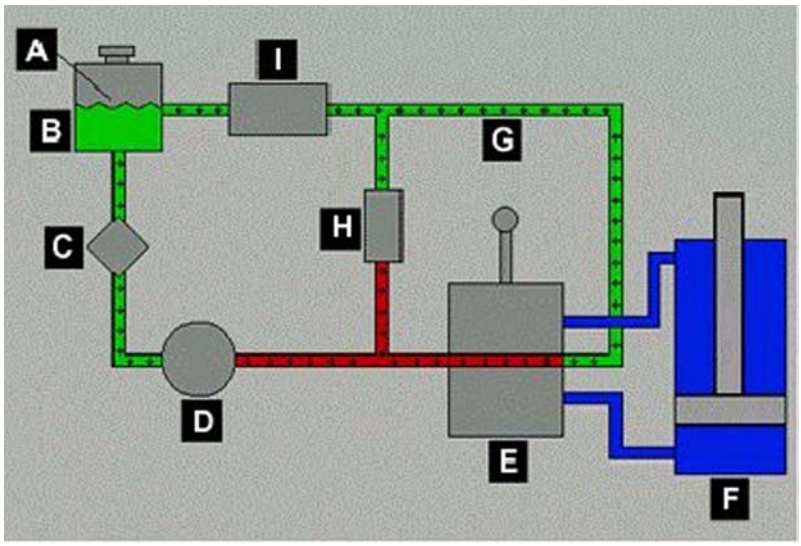


**Figure 29**

Mobile earthmoving machines are designed with hydraulic systems which use a variety of hydraulic components to provide efficient operation.

Hydraulic cylinders of various types are used to operate implements, e.g. buckets, blades, rippers, backhoes and truck beds.

Hydraulic motors drive tracks, wheels, car bodies and conveyors.

Brakes, steering, transmissions, suspensions and other vehicle systems rely on hydraulics for power and control.

Figure 29 depicts a basic hydraulic system. For a basic hydraulic system to operate (e.g. cylinder extend and retract), it must contain the following components:

- fluid (A)
- reservoir (B)
- filter (C)
- pump (D)
- directional control valve (E)
- actuator or hydraulic cylinder (F)
- lines (G)
- pressure control valve (H)
- cooler (I).

Most manufacturers use graphic symbol circuits to identify the circuit components, and to illustrate the circuit function and operation.


© Caterpillar of Australia Pty Ltd

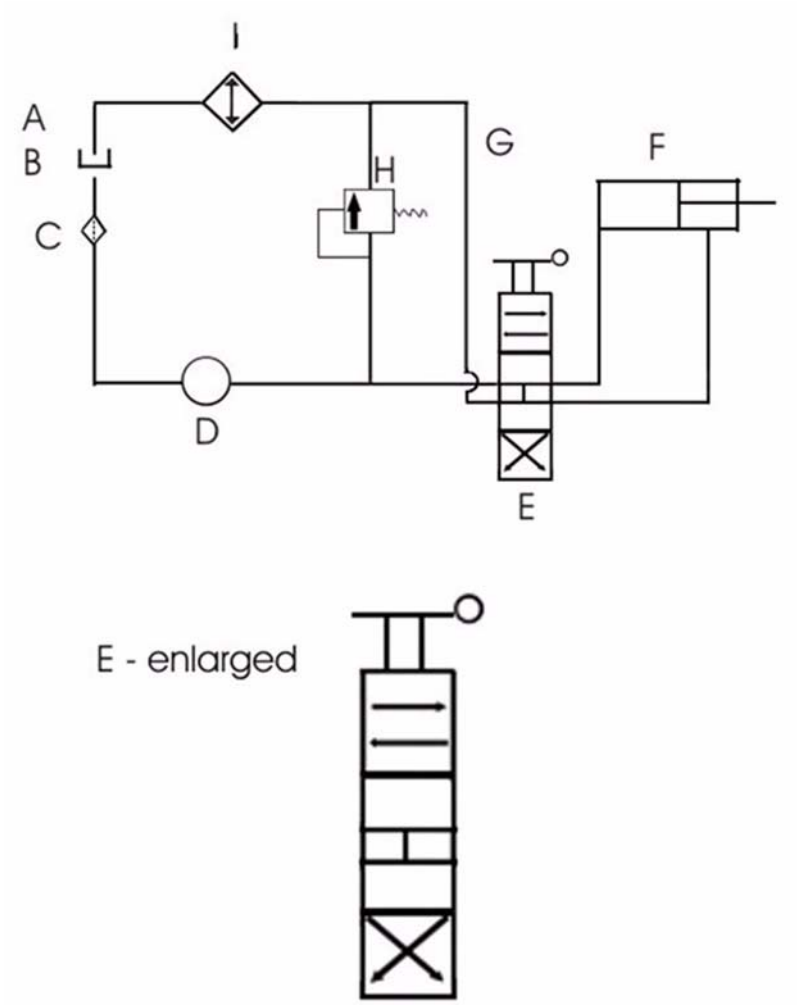


**Figure 30**

## GRAPHIC SYMBOLS

*Graphic symbols* for fluid power diagrams (Figure 30) were originally developed by the *American National Standards Institute (ANSI) and are presently adopted by the International Standards Organisation (ISO). They* provide communication standards that serve industry and education. The standards simplify design, fabrication, analysis, and servicing of fluid power systems.

The symbols describe component function rather than construction. In addition, they show how some of the fluid power components operate pneumatically, hydraulically, electrically, manually, and the like.

In order to use the graphic symbol system to its maximum potential, the following rules must be understood and followed:

1. Symbols show connections, flow paths, and functions of components. They do not indicate conditions occurring during transition from one flow 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 location of ports, shifting of spools, or position of control elements on an actual component.


© Caterpillar of Australia Pty Ltd

3. The position or size of a symbol can be altered for component emphasis in a circuit without changing its meaning.

4. Each symbol is drawn to show normal or neutral condition of a component unless multiple circuit diagrams are furnished showing various phases of circuit operation.

5. Arrows used within a symbol envelope show direction of flow in a component as used in the application represented. Double-end arrows indicate reverse flow.

The graphic symbols utilize elementary geometrical forms to depict components and circuits. These forms include: circles, squares, rectangles, triangles, arcs, arrows, lines, dots, and crosses.

## Elemental Symbols

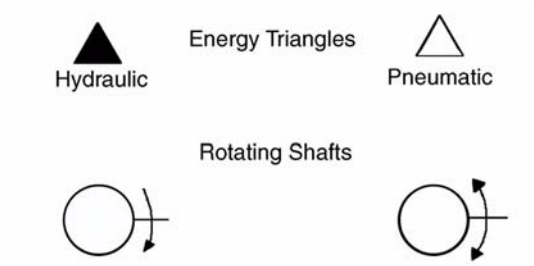


**Figure 31 - Supplemental Component Symbols**

The first elemental symbols are energy triangles (Figure 31). A triangle is used to represent a conversion point of energy and its direction of flow. A shaded or darkened triangle as seen to the left indicates the energy medium is a fluid, such as hydraulic oil. The clear triangle on the right denotes the energy medium is gaseous. Orientation of the triangle will indicate the direction of energy flow into or out of a component. A dark triangle pointing out of a component envelope would indicate the component is generating energy (such as a pump) and that the medium is a fluid. Another example might be a clear triangle pointing into the component, meaning the energy medium is pneumatic and the component is absorbing or using this energy to do work (such as a pneumatic motor). We will see examples of these later.

Rotating shafts are shown by a short solid line connected to the component outline. An arrow is used to indicate the direction of rotation. The arrow is always assumed to be on the near side of the shaft, and may denote either uni or bidirectional rotation.


© Caterpillar of Australia Pty Ltd

## Basic Components

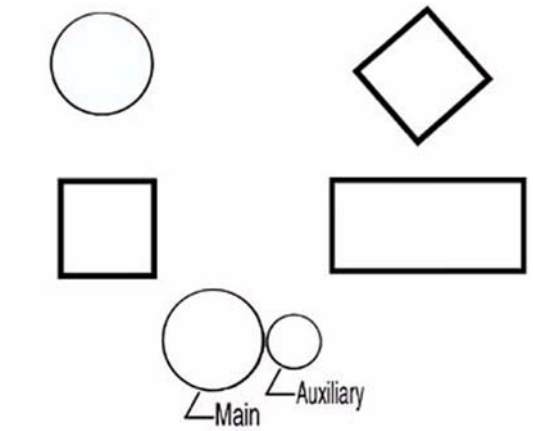


**Figure 32 - Basic Component Symbols**

The basic component symbols used are the outlines of circles, squares, diamonds, rectangles and a few other geometrical features (Figure 32). These raw component symbols or envelopes will have supplemental component symbols or elements added to them in order to create or, illustrate a specific type of component such as a valve, pump, or motor.

Size of the component's outline may be varied to emphasize certain components or indicate a difference between a main and auxiliary component. Otherwise, variations in size are not an indication of the components' physical sizes.

## Tubes, Hoses and Internal Passages

Three types of lines are used in graphic symbol illustrations to represent tubes, hoses and internal fluid passages that connect the hydraulic components.

1. **Working Line:**

   A solid line is used to show a hydraulic working line. The working line carries the major flow of oil in a hydraulic system.

2. **Pilot Line**:

   A dashed line is used to show a hydraulic pilot line. The pilot line carries a small volume of oil used as an auxiliary flow to actuate or control a hydraulic component. The length of the dash will be drawn at least ten times its width.

3. **Drain Line**:

   A dashed line is used to show a drain line that carries leakage oil back to the reservoir. The drain line will be illustrated as a dashed line with the length of the dash less than five times its width.


© Caterpillar of Australia Pty Ltd

**Some other symbols are:**

1. **Enclosure Line**:



The enclosure line is used to illustrate the boundary of the area on a machine, in which hydraulic components are contained. e.g. an operation compartment, or the front half of an articulated machine.

2. **Instrument Line**:

The instrument line is used to connect an instrument to its sensor.

## Crossing Lines

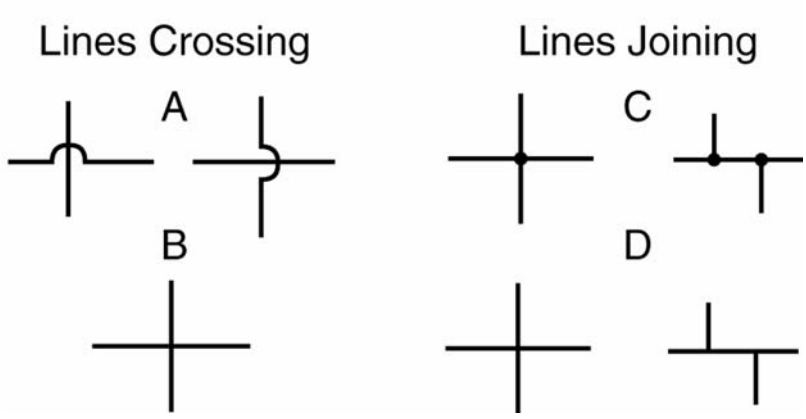


**Figure 33 Techniques for crossing and joining lines**

Here are two techniques used for representing both lines crossing and joining (Figure 33). It is important to note that graphic symbols may be drawn several different ways to represent the same thing.

First let's take a look at the techniques, where A & B are used to represent lines crossing. In method “A” a small half circular line is used to jump or cross another line. The alternative method “B” merely shows the lines crossing each other.

On the right two methods are used for joining lines. The standard and most desirable way to show lines which join is to use a solid dot at the point of junction as seen in “C.” An alternative method is seen at “D” in which the lines join without the connecting dots. This may appear confusing at first, since this is also a way in which lines crossing may be shown as in “B.” The way to determine the type of junction you have will depend on which of the other techniques is used throughout the rest of the circuit to represent line crossing or junctions.


© Caterpillar of Australia Pty Ltd

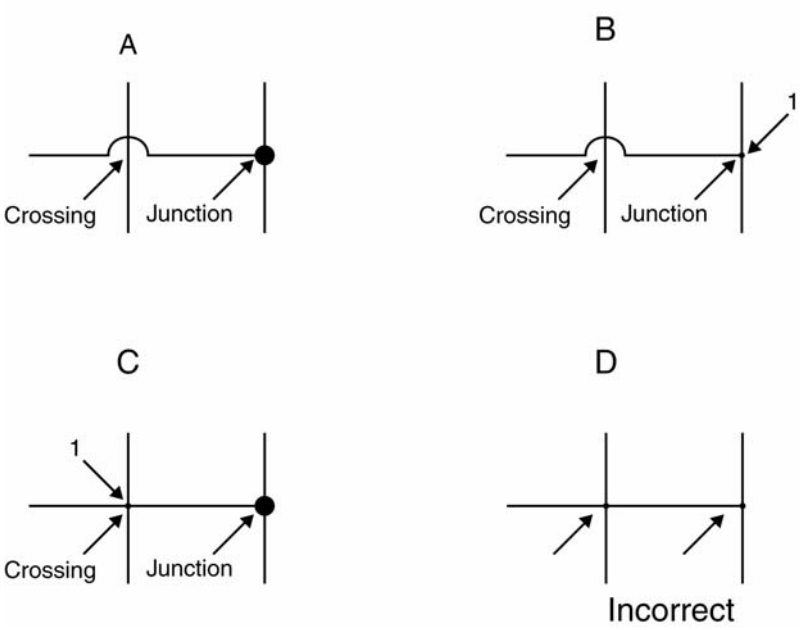


**Figure 34 - Junctions and Crossings**

The key to determining the type of line junction, seen in Figure 34 at point (1) in views “B” or “C”, will be dependent on the other technique used throughout the circuit. If a small half circular line is used to depict lines crossing, then lines joining may be drawn with or without a connecting dot, as seen in views “A” or “B”. Both methods are correct. Whichever method is chosen, it must be used consistently throughout the entire circuit. In a similar fashion when a connecting dot is used to indicate lines joining throughout the circuit, then lines crossing can be shown with the half circular line as in “A” or without it as shown in “C”. The important point to remember is that the technique chosen will be used consistently throughout the circuit.

View “D” shows what would happen if the same method was used to illustrate both line crossings and junctions in a circuit. This is incorrect because no one would be able to differentiate between the two.


© Caterpillar of Australia Pty Ltd

## HYDRAULIC LINES

Hydraulic lines are used to connect the various components together to allow transmission of fluid in the circuit. The lines can be either tubes or hoses.

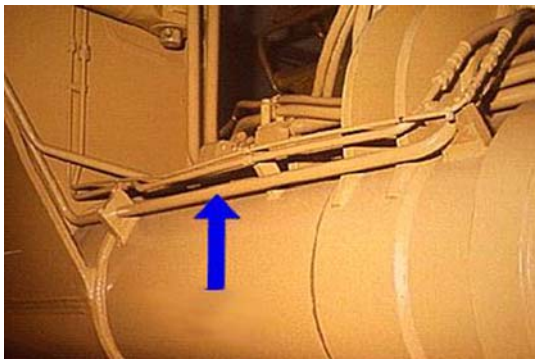

**Figure 35**

A tube (Figure 35) is a rigid hydraulic line, usually made of steel. Tubes are used to connect components that do not move in relation to each other. Tubes also generally require less space than hoses and can be firmly attached to the machine, resulting in better protection to the lines and a better overall machine appearance.

**Figure 36**

Hydraulic hoses (Figure 36) are used whenever flexibility is needed, such as when components move in relation to each other. Hoses absorb vibration and resist pressure variations.


© Caterpillar of Australia Pty Ltd

# HYDRAULIC TANK

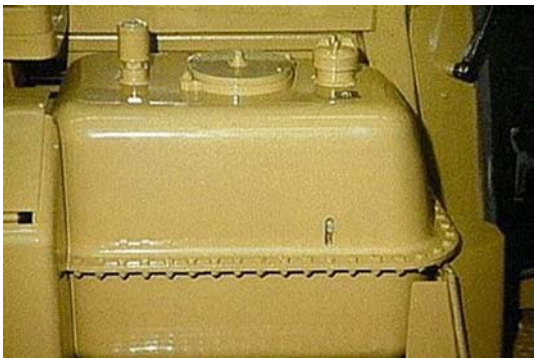

**Figure 37**

When construction machines and equipment are in the design stage, considerable thought is given to the type, size and location of the hydraulic oil tank (Figure 37). Once the machine or equipment is in operation, the hydraulic tank functions as a storage place for the hydraulic oil, a device to remove heat from the oil, a separator to remove air from the oil and allows particles to settle out of the oil.

The hydraulic oil tank main function is to store oil and ensure there is enough oil for any requirements of the system. Tanks must have sufficient strength, adequate capacity and keep dirt out. Hydraulic tanks are usually but not always sealed.

Tanks are mounted in any convenient location, sometimes as part of a major component housing.

The components of the tank are:

- Fill cap
- Sight glass
- Supply and return line
- Drain.

## Fill Cap

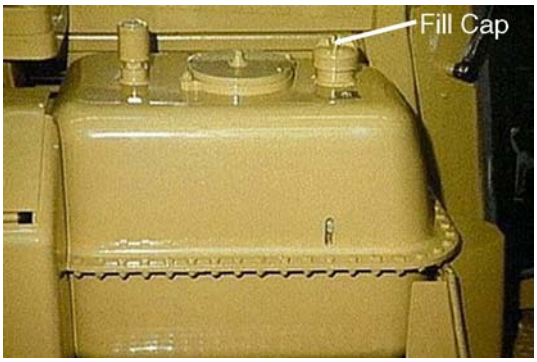


**Figure 38**

The fill cap keeps contaminants out of the opening that's used to fill and add oil to the tank and seals pressurized tanks (Figure 38).


© Caterpillar of Australia Pty Ltd

## Sight Glass

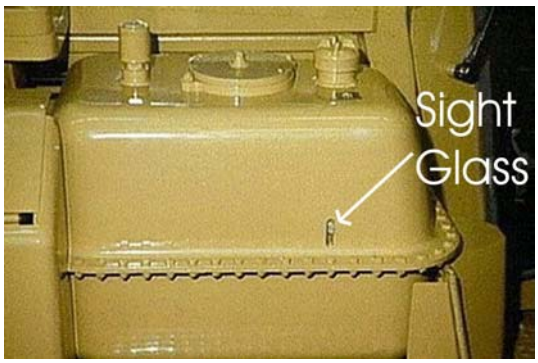


**Figure 39**

The sight glass (Figure 39) is used to check the oil level according to the operation and maintenance manual. The oil level is usually correct when the oil is in the middle of the sight glass. The oil level should be checked when the oil is cold. Refer to manufacturer's specifications for the correct procedures for reading oil level.

## Breather

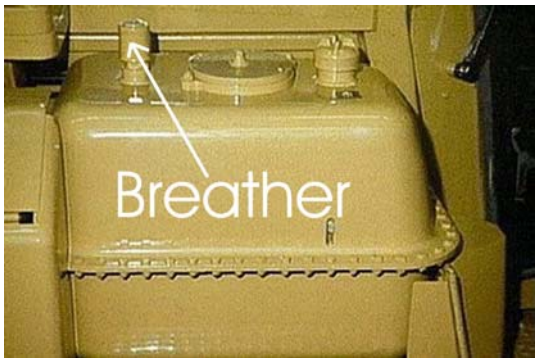


**Figure 40**

The breather (Figure 40) is fitted to unpressurised tanks and allows atmospheric pressure to flow in and out of the tank.

## Drain

Located at the lowest point in the tank, the drain is used to remove old oil from the tank. The drain also allows for the removal of water and sediment from the oil

Drain plugs often contain a strong magnet to capture particles at the bottom of the tank.

## Supply and Return Lines

The supply line allows oil to flow from the tank to the system. The return line allows oil to flow from the system to the tank.


© Caterpillar of Australia Pty Ltd

## Pressurised Tank

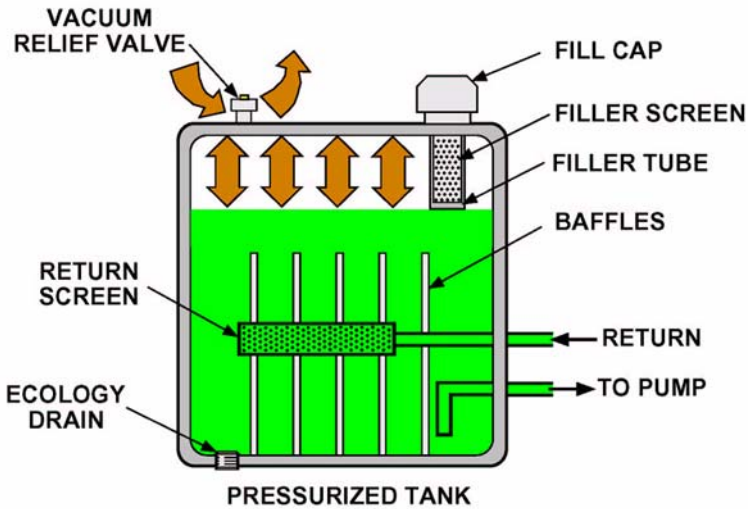


**Figure 41**

The pressurised tank is completely sealed. Atmospheric pressure does not affect the pressure in the tank. When the oil circulates through the system, it absorbs heat and expands. The expanding heated oil compresses the air in the tank and creates a positive pressure in the system.

Pressurised tanks prevent the entry of dirt and moisture and help force oil into the hydraulic pump. Air pressurised reservoirs receive air from the vehicles compressed air system although these are not used often.

Never open the reservoir when it is pressurised.

Thermally pressurised tanks rely on the expansion of the oil as it is heated to exert a slight pressure on the surface of the oil.

The pressure relief valve controls the pressure in the tank and the vacuum valve prevents negative pressures when the system cools.

### Vacuum/Relief Valve

The vacuum/relief valve serves two purposes. It prevents a vacuum and limits the maximum pressure in the tank.

The vacuum relief valve prevents a vacuum by opening and allowing air to enter the tank when the tank pressure drops to 3.45 kPa (0.5 psi). When pressure in the tank reaches the vacuum relief valve pressure setting, the valve opens and vents compressed air to the atmosphere.

The vacuum relief valve pressure setting may vary from 70 kPa (10 psi) to 207 kPa (30 psi).

### Filler Screen

Prevents large contaminants from entering the tank.

### Filler Tube

Allows the tank to be filled to the correct level, but not over-filled.


© Caterpillar of Australia Pty Ltd

### Baffles

Prevents the return oil from flowing directly to the tank outlet, allowing time for bubbles to rise to the top. It prevents the oil from sloshing which helps reduce foaming of the oil.

### Ecology Drain

Used to prevent accidental spills when removing water and sediment from the tank.

### Return Line

Returns oil from the hydraulic circuit/s to the tank.

### Return screen

Prevents larger particles from entering the tank, but does not provide fine filtering.

### Pump Pick-up Line

The pump pick-up line directs oil to the inlet side of the pump. The line does not normally touch the bottom of the tank. This prevents sediment at the bottom of the tank being directed to the pump.

## Vented Tank

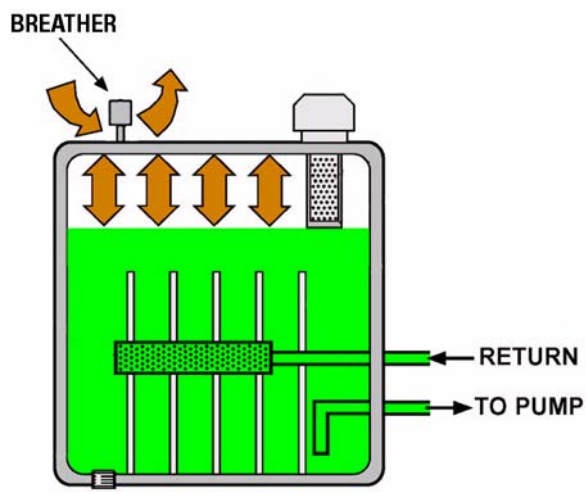


**Figure 42 - Vented tank and ISO Symbol**

The vented tank is the most common type of tank. It has a breather that allows air to enter and exit freely. Therefore, pressure inside the tank is atmospheric. An air cleaning element or screen is usually fitted in the vent to reduce the entry of airborne dust.


© Caterpillar of Australia Pty Ltd

## GRAPHIC SYMBOL - HYDRAULIC TANK

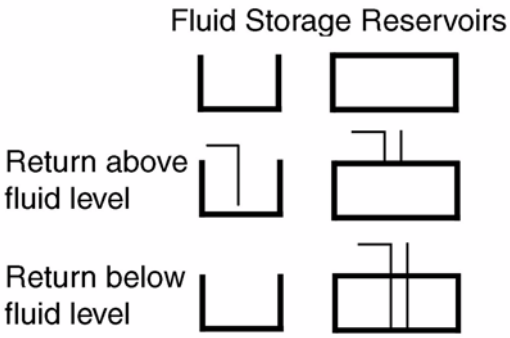


**Figure 43**

The vented reservoir symbols (Figure 43) are shown to the left and are merely an open-topped box or rectangle. A pressurised reservoir is drawn as a completely closed box. Return line connections can be either above or below the fluid level. Examples of both types are shown. The reservoir symbol is one symbol which can be drawn as many times as necessary on a circuit schematic to reduce the number of lines which must be drawn. Although the symbol may be drawn several times, it only represents one tank, unless otherwise specified.

## Fluid Filters

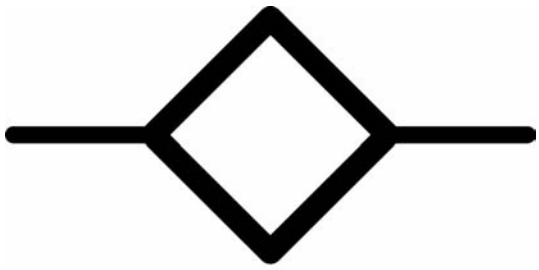

**Figure 44 - Basic Symbol**

The general symbol used for a fluid filter is an empty diamond as seen in Figure 44 above. Several different types of fluid conditioner symbols can be made by making slight changes or additions to this basic symbol.

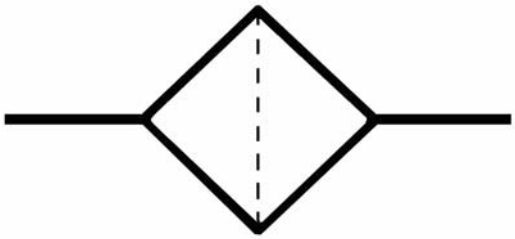

**Figure 45**

First is a filter or strainer, shown in Figure 45 above, with a dashed vertical line inside the basic symbol. This represents the filtering media which the fluid must flow through.


© Caterpillar of Australia Pty Ltd

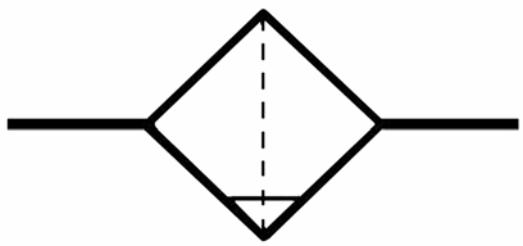

**Figure 46**

A line drawn horizontally across the bottom portion of the symbol, as shown in Figure 46, represents the separated matter that has settled to the bottom, such as water.

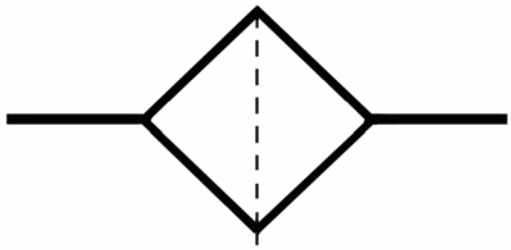

**Figure 47**

A short line extending from the bottom of the symbol, shown in Figure 47, represents a manual drain. If the short line is not on the symbol, it must be assumed to be a manual drain. Nothing on the symbol will indicate

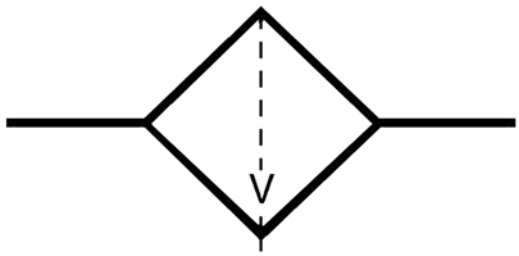


**Figure 48**

Automatic drains will be represented by a small ‘V’ placed below the horizontal separation line as shown in Figure 48.

## HYDRAULIC PUMPS

The hydraulic pump transfers mechanical energy into hydraulic energy. It is a device that takes energy from one source (i.e. engine, electric motor, etc.) and transfers that energy into a hydraulic form.

The function of the pump is to supply the hydraulic system with a sufficient flow of oil to enable the circuits to operate at the correct speed.

Pumps can generally be classified into two types:

- non-positive displacement
- positive displacement.


© Caterpillar of Australia Pty Ltd

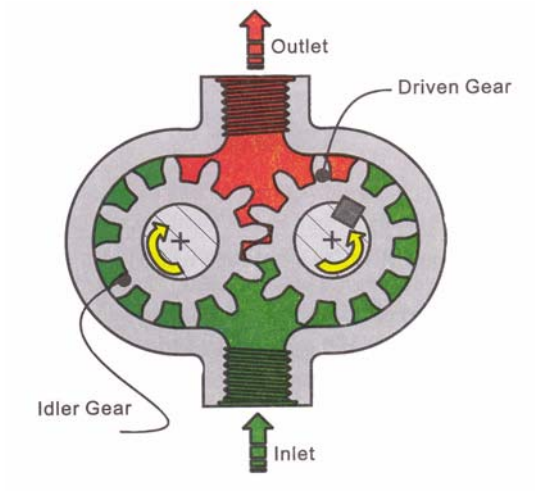


**Figure 49**

Figure 49 is showing a gear type pump. The gears are in mesh and rotated by a power source. The pump takes oil from a storage container (i.e. tank) and pushes it into a hydraulic system.

All pumps produce oil flow in the same way. A partial vacuum is created at the pump inlet and outside pressure (tank pressure and/or atmospheric pressure) forces the oil to the inlet passage and into the pump inlet chambers. The pump idler gears carry the oil to the pump outlet chamber.

With each element of fluid that is discharged from a hydraulic pump, an equal amount must be available at the inlet side to replace it. The availability of the fluid at the inlet is entirely dependent upon the reservoir pressures that force the fluid into the pump.

The larger the pump, or the faster the pump runs, the more fluid is needed to replace the amount that is discharged. This will depend upon there being adequate pressure in the reservoir to force fluid into the pump. Without sufficient pressure, “starvation” of the pump will occur, and this will cause severe damage to the pump components, and ultimately cause pump failure.

There are many factors that can hinder the flow of fluid between the reservoir and the pump:

- A fluid line that is too small for the volume of fluid going through it.
- A clogged outlet on the reservoir.
- A pump that is located too far away from the reservoir, or too far above it.
- A fluid that is too viscous to flow easily.

When one or more of these conditions exist to the point that "starvation" of the pump begins to occur, they must be corrected immediately.

**Pumps DO NOT produce or cause ‘pressure’.** The resistance to the flow causes pressure. Resistance can be caused by flow through hoses, orifices, fittings, cylinders, motors, or anything in the system that hinders free flow to the tank. Pumps create flow only.


© Caterpillar of Australia Pty Ltd

## Positive Displacement Pump

A positive displacement pump will discharge a specified amount of fluid during each revolution or stroke, almost regardless of the restriction on the outlet side. Because of this characteristic, positive displacement pumps are nearly always the pump of choice in hydraulic systems.

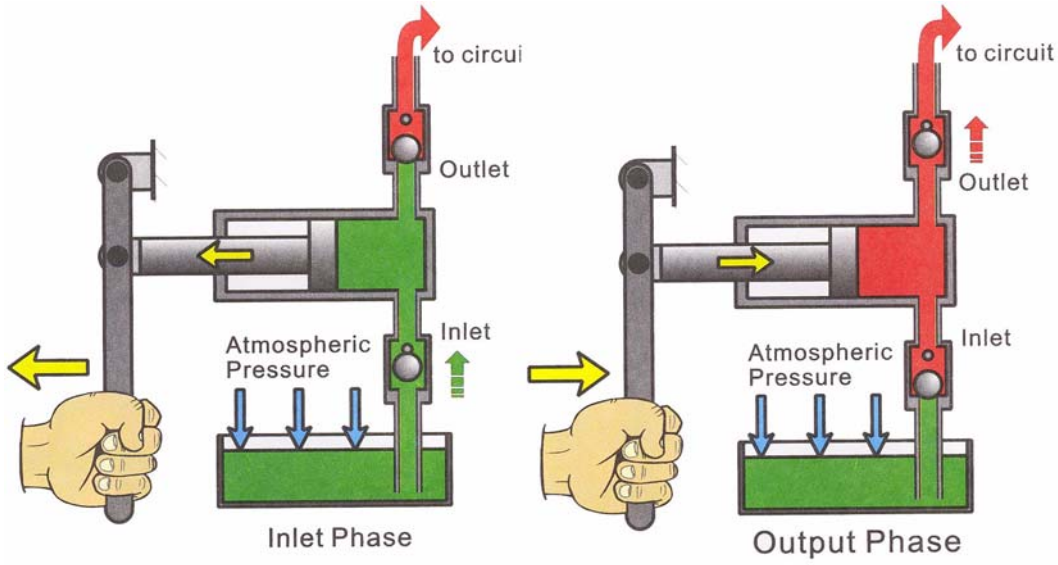


**Figure 50**

The hand pump illustrated in Figure 50 provides an example of the operation of a positive displacement pump.

Positive displacement hydraulic pumps are designated by their volume of displacement, such as gallons per minute, litres per minute, cubic inches or cubic centimeters per revolution. This designation is usually a theoretical displacement, and does not allow for any losses that may occur within the pump due to internal leakage.

Positive displacement pumps have small clearances between components. This reduces leakage and provides a much higher efficiency when used in a high-pressure hydraulic system. The output flow in a positive displacement pump is basically the same for each pump revolution. Both the control of their output flow and the construction of the pump classify positive displacement pumps.

Positive displacement pumps are rated in two ways. One is by the maximum system pressure (21,000 kPa or 3000 psi) at which the pump is designed to operate. The second is by the specific output delivered either per revolution or at a given speed against a specified pressure. As an example a pump maybe rated in lpm @ rpm @ kPa (i.e.380 lpm @ 2000 rpm @ 690 kPa).

When expressed in output per revolution, the flow rate can be easily converted by multiplying by the speed, in rpm, (i.e. 2000 rpm) and dividing by a constant. For example, we will calculate the flow of a pump that rotates 2000 rpm and has a flow of 11.55 $in^3$ /rev or 190 cc/rev.

| | | | | | |
|---|---|---|---|---|---|
| GPM | = | $in^3$ /rev X rpm/231 | LPM | = | cc/rev X rpm/1000 |
| GPM | = | 11.55 X 2000/231 | LPM | = | 190 X 2000/1000 |
| GPM | = | 100 | LPM | = | 380. |


© Caterpillar of Australia Pty Ltd

## Non Positive Displacement Pump

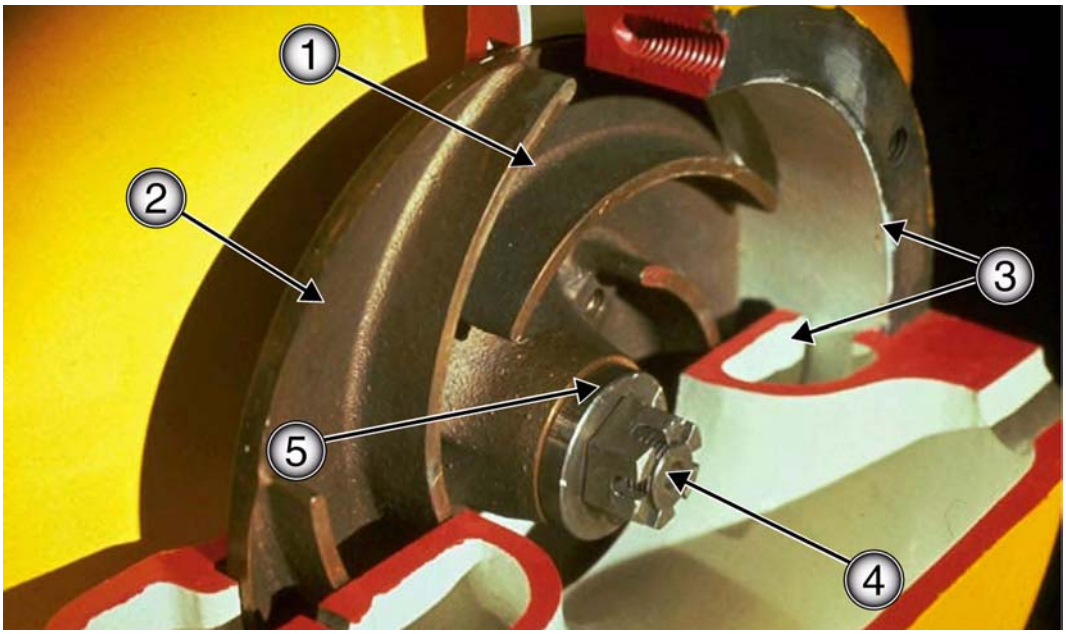


**Figure 51**

The outlet flow of a non-positive displacement pump is dependent on the inlet and outlet restrictions. The greater the restriction on the outlet side, the less flow the pump will discharge. An example of a non-positive displacement pump is the water pump rod on an engine (Figure 51).

The centrifugal impeller is an example of a non-positive displacement pump and consists of two basic parts; the impeller (2) that is mounted on an input shaft (4) and the housing (3). The impeller has a solid disc back with curved blades (1) moulded on the input side.

Fluid enters the centre of the housing (5) near the input shaft and flows into the impeller. The curved impeller blades propel the fluid outward against the housing. The housing is shaped to direct the oil to the outlet port.


© Caterpillar of Australia Pty Ltd

## GEAR PUMPS

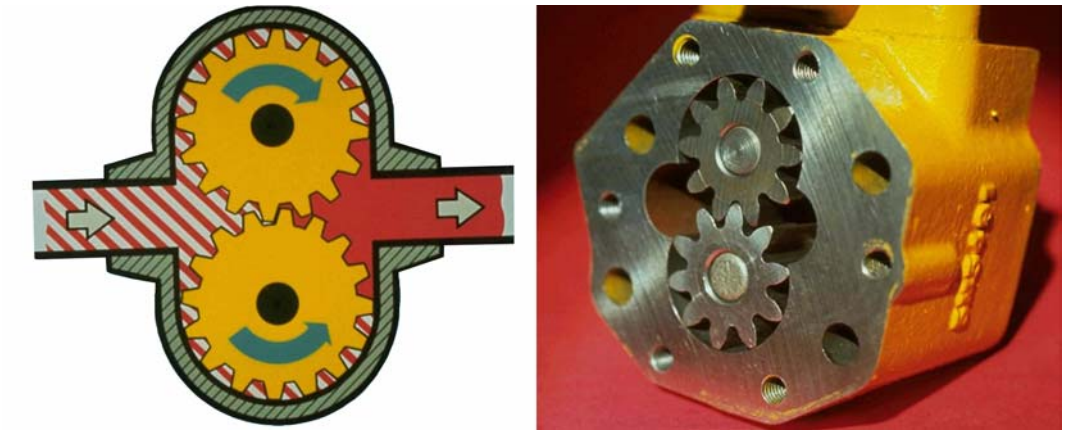

**Figure 52**

Gear pumps (Figure 52) are positive displacement pumps. They deliver the same amount of oil for each revolution of the input shaft. Changing the speed of rotation controls the pump's output. The maximum operating pressure for gear pumps is limited to 27,579 kPa (4000 psi). This pressure limitation is due to the hydraulic imbalance that is inherent in the design. The hydraulic imbalance produces a side load on the shafts that is resisted by the bearings and the gear teeth to housing contact. The gear pump maintains a 'volumetric efficiency' above 90% when pressure is kept within the designed operating pressure range.

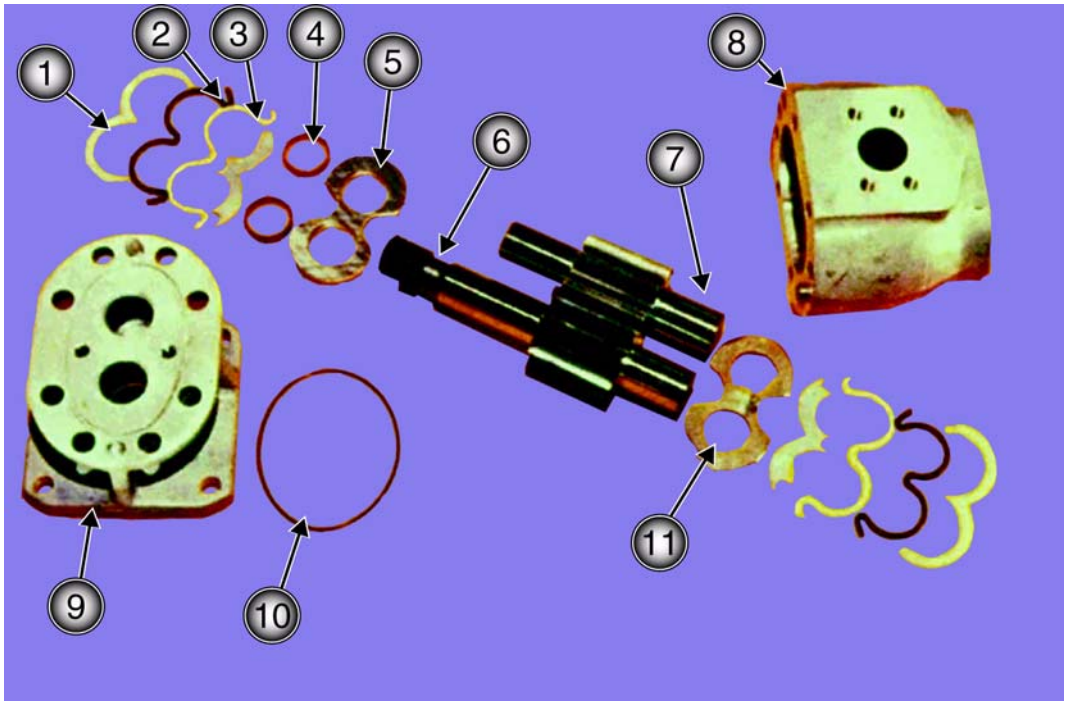


**Figure 53**

Figure 53 shows the components of the gear pump: seal retainers (1), seals (2), seal back- ups (3), isolation plates (4), spacers (5), a drive gear (6), an idler gear (7), a housing (8), a mounting flange (9), a flange seal (10) and pressure balance plates (11) on either side of the gears.

Bearings are mounted in the housing and mounting flange on the sides of the gears to support the gear shafts during rotation.


© Caterpillar of Australia Pty Ltd

### Pressure Balance Plates

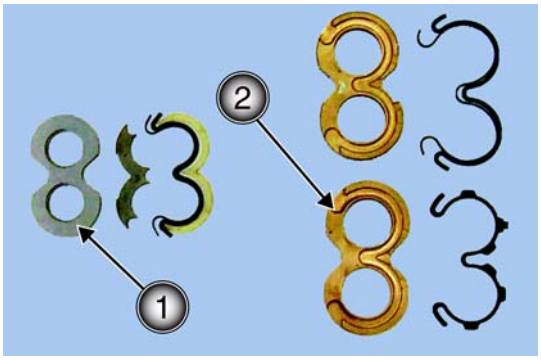


**Figure 54**

There are two different types of pressure balance plates used in gear pumps (Figure 54). The earlier type (1) has a flat back. This type uses an isolation plate, a back up for the seal, a seal shaped like a 3 and a seal retainer. The later type (2) has a groove shaped like a 3 cut into the back and is thicker than the earlier type. Two different types of seals are used with the later type of pressure balance plates.

## Gear Pump Flow

The output flow of the gear pump is determined by the tooth depth and gear width. Most manufacturers standardised on a tooth depth and profile determined by the centreline distance (1.6", 2.0", 2.5", 3.0", etc.) between gear shafts. With standardised tooth depths and profiles, the tooth width totally determines flow differences within each centreline classification.

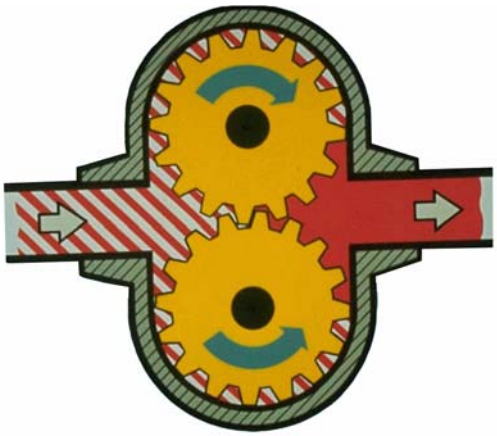

**Figure 55**

As the pump rotates (Figure 55), the gear teeth carry the oil from the inlet to the outlet side of the pump. The direction of rotation of the drive gear shaft is determined by the location of the inlet and outlet ports and drive gear will always move the oil around the outside of the gears from inlet to outlet port. This is true on both gear pumps and gear motors. On most gear pumps the inlet port is larger in diameter than the outlet port too ensure that there is always an ample supply of oil for the demand of the system and to ensure pump starvation does not occur. On bi-directional pumps and motors, the inlet port and outlet port will be the same size.


© Caterpillar of Australia Pty Ltd

## Gear Pump Forces

The outlet flow from a gear pump is created by pushing the oil out of the gear teeth as they come into mesh on the outlet side. The resistance to oil flow creates the outlet pressure. The imbalance of the gear pump is due to outlet port pressure being higher than inlet port pressure. The higher pressure oil pushes the gears toward the inlet port side of the housing.

The shaft bearings carry the majority of the side load to prevent excessive wear between the tooth tips and the housing. On the higher pressure pumps, the gear shafts are slightly tapered from the outboard end of the bearings to the gear. This allows full contact between the shaft and bearing as the shaft bends slightly under the unbalanced pressure.

The pressurised oil is also directed between the sealed area of the pressure balance plates and the housing and mounting flange to seal the ends of the gear teeth. The size of the sealed area between the pressure balanced plates and the housing is what limits the amount of force that pushes the plates against the ends of the gears.

## VANE PUMP

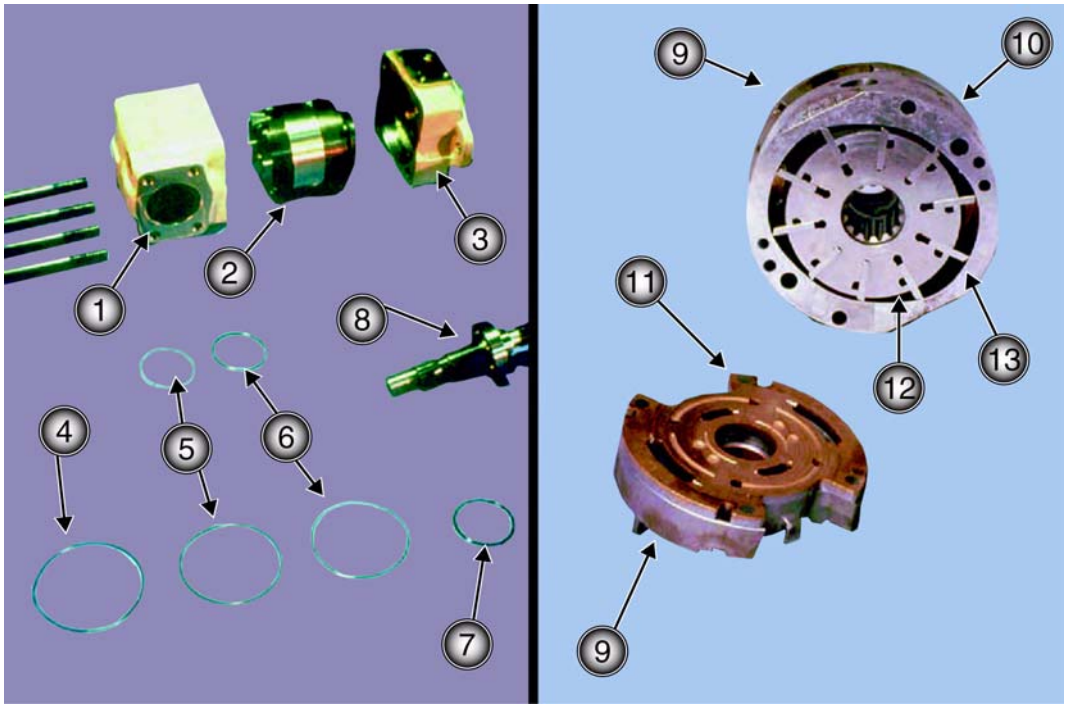


**Figure 56**

As shown in Figure 56, vane pumps are positive displacement pumps. The pump output can be either fixed or variable.

Both the fixed and variable vane pumps use common part nomenclature. Each pump consists of the housing (1), cartridge (2), mounting plate (3), mounting plate seal (4), cartridge seals (5), cartridge backup rings (6), snap ring (7), and input shaft and bearing (8).

The cartridge consists of the support plates (9) displacement ring (10), flex plates (11), slotted rotor (12) and the vanes (13).

The input shaft turns the slotted rotor. The vanes move in and out of the slots in the rotor and seal on the outer tips against the cam ring.

The inside of the fixed pump displacement ring is elliptical in shape.


© Caterpillar of Australia Pty Ltd

The inside of the variable pump displacement ring is round in shape.

The flex plates seal the sides of the rotor and the ends of the vanes. In some lower pressure designs, the support plates and housing seal the sides of the rotating rotor and the ends of the vanes.

The support plates are used to direct the oil into the proper passages in the housing. The housing, in addition to providing support for the other parts of the vane pump, directs the flow in and out of the vane pump.

## Vanes

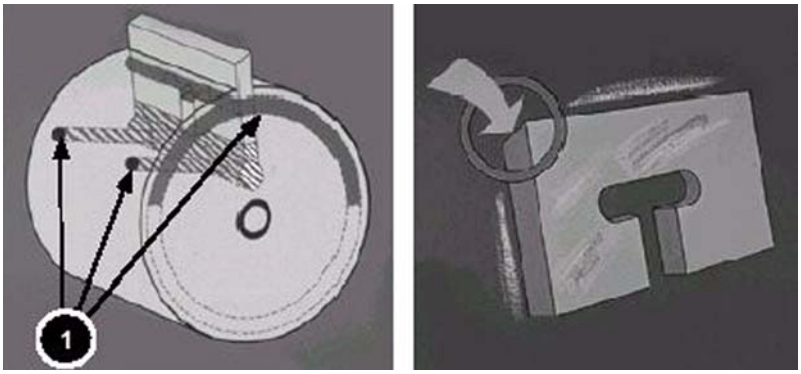


**Figure 57**

The vanes (Figure 57) are initially held against the displacement ring by centrifugal force created by the rotation of the rotor. As flow increases, the resultant pressure that builds from the resistance to that flow is directed into passages in the rotor beneath the vanes (1).

This pressurised oil beneath the vanes keep the vane tips pushed against the displacement ring to form a seal. To prevent the vanes from being pushed too hard against the displacement ring, the vanes are bevelled back (arrow) to permit a balancing pressure across the outer end.

### Flex Plates

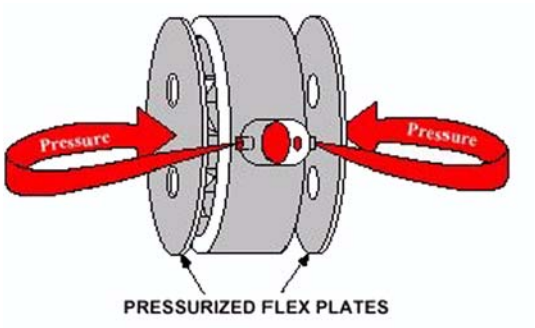


**Figure 58**

The same pressurised oil is also directed between the flex plates and the support plates to seal the sides of the rotor and the end of the vanes (Figure 58). The size of the seal area between the flex plate and the support plates is what controls the force that pushes the flex plates against the sides of the rotor and the end of the vanes. The kidney shaped seals must be installed in the support plates with the rounded o-ring side into the pocket and the flat plastic side against the flex plate.


© Caterpillar of Australia Pty Ltd

## Vane Pump Operation

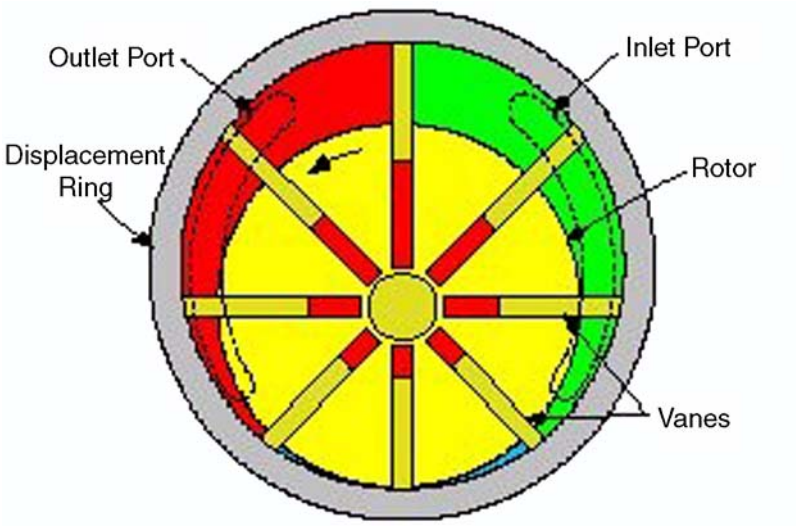


**Figure 59**

When the rotor rotates around the inside of the displacement ring Figure 59, the vanes slide in and out of the rotor slots to maintain the seal against the displacement ring. As the vanes move out of the slotted rotor, the volume between the vanes changes. An increase in the distance between the displacement ring and the rotor causes an increase in the volume. The increase in volume creates a slight vacuum that allows the inlet oil to be pushed into the space between the vanes by atmospheric or tank pressure. As the rotor continues to rotate, a decrease in the distance between the displacement ring and the rotor causes a decrease in the volume. The oil is pushed out of that segment of the rotor into the outlet passage of the pump.

The vane pump just described is known as the “unbalanced” vane pump.

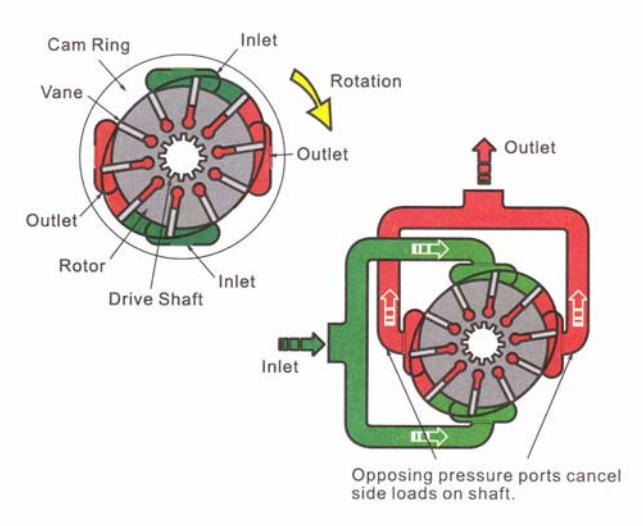


**Figure 60**

Figure 60 shows the balanced design principle. This design has opposing sets of inlet and outlet ports. Since the ports are positioned exactly opposite each other, the high forces generated at the outlet ports cancel each other out. This prevents side-loading of the pump shaft and bearings and means that the shaft and bearings only have to carry the torque load and external loads. Since there are two lobes to the cam ring per revolution, the displacement of the pump is equal to twice the amount of fluid which is pumped by the vanes moving from one inlet to its corresponding outlet.


© Caterpillar of Australia Pty Ltd