

**Hydraulic Systems**

Chapter 11

Material taken from Goering, 2003, Off-Road Vehicle Engineering Principles

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**Hydraulic Actuators**

- A hydraulic actuator is a device for converting hydraulic power into mechanical power.
- There are two types of actuators: rotary and linear.
- Rotary actuators are called hydraulic motors, while linear actuators are called hydraulic cylinders.

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**Hydraulic Motors**

- Hydraulic motors are similar in appearance to hydraulic pumps.
- If care is taken to avoid damaging the seal, pumps and motors can often be used interchangeably.

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## Hydraulic Motors con't

• The theoretical speed of a hydraulic motor is calculated using:

- $N_{mt} = (1000Q_{ma}) / D_m$
- Where  $N_{mt}$  = theoretical motor speed, rpm
- $Q_{ma}$  = liquid flow rate into the motor, L/min
- $D_m$  = motor displacement, cm<sup>3</sup>/rev

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## Hydraulic Motors con't

• Internal leakage from the inlet port to the outlet port causes the actual motor speed to be less than the theoretical speed.

• The volumetric efficiency of a motor is defined as:

- $e_{mv} = N_{ma} / N_{mt} = Q_{ma} / (Q_{ma} + Q_{ml})$
- Where  $e_{mv}$  = motor volumetric efficiency, decimal
- $N_{ma}$  = actual speed of motor, rev/min
- $Q_{ml}$  = internal leakage in motor, L/min

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## Hydraulic Motors con't

• The equation for calculating the theoretical torque produced by a motor is similar to  $T_{pt} = \Delta p D_p / 2\pi$ , except that the p-subscripts are replaced by m:

- $T_{mt} = \Delta p D_m / 2\pi$
- Where  $T_{mt}$  = theoretical torque from motor, N\*m
- $\Delta p$  = pressure drop across motor, Mpa
- $D_m$  = motor displacement

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## Hydraulic Motors con't

- Internal friction causes the actual torque production to be less than the theoretical torque. Motor torque efficiency is:
  - $e_{mt} = T_{ma} / T_{mt} = (T_{mt} - T_{mf}) / T_{mt}$
  - Where  $e_{mt}$  = motor torque efficiency, decimal
  - $T_{ma}$  = actual motor torque, N\*m
  - $T_{mf}$  = motor friction torque, N\*m

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## Hydraulic Motors con't

- $P_h = Q\Delta p / 60$  calculates the hydraulic power into a motor, given the actual flow into the motor and the pressure drop across the motor.
- The power efficiency of a hydraulic motor is:
  - $e_{mp} = P_{ms} / P_{mh} = e_{mv}e_{mt}$
  - Where  $e_{mp}$  = power efficiency of motor, decimal
  - $P_{ms}$  = shaft power out of motor, kW
  - $P_{mh}$  = hydraulic power into motor, kW
- The volumetric, torque, and power efficiencies of a hydraulic motor vary in a manner similar to the next figure for hydraulic pumps.

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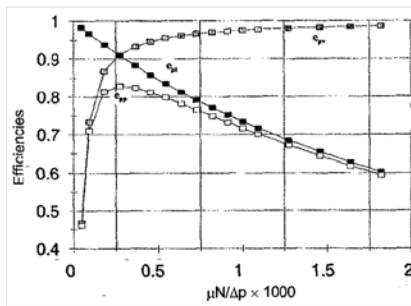
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## Motor Efficiencies



- $e_{pp}$  = pump power efficiency
- $e_{pt}$  = pump torque efficiency
- $e_{pv}$  = pump volumetric efficiency

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## Hydraulic Cylinders

- When oil is forced into the port on the left, the cylinder is forced to extend while expelling oil from the port on the right.
- Conversely, the cylinder retracts and expels oil from the port on the left when oil is forced into the port on the right.

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## Hydraulic Cylinders con't

- The force generated by a cylinder is:
  - $F_c = (p_1 A_1 - p_2 A_2) / 10$
  - Where  $F_c$  = force exerted by the cylinder rod, kN
  - $A_1$  = area of piston face,  $cm^2$
  - $A_2$  = area of piston face minus area of rod,  $cm^2$
  - $p_1$  = pressure acting on  $A_1$ , MPa
  - $p_2$  = pressure acting on  $A_2$ , MPa

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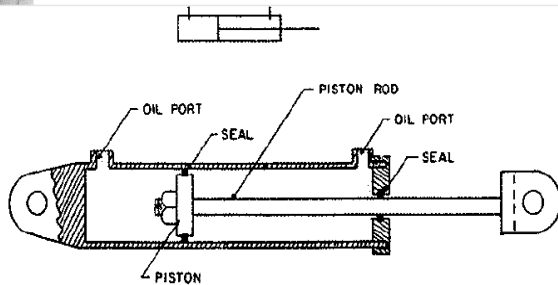
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## Double-Acting Hydraulic Cylinder



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## Hydraulic Cylinders con't

- When  $p_1A_1 > p_2A_2$ , the cylinder extends and  $F_c$  is positive. When  $p_1A_1 < p_2A_2$ ,  $F_c$  is negative and the cylinder retracts.
- The cylinder speed can be calculated using:
  - $V_c = Q / 6A$
  - Where  $v_c$  = cylinder speed, m/s
  - A = area on which inflowing oil acts,  $\text{cm}^2$

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## Hydraulic Cylinders con't

- Because  $A_1 > A_2$ , the cylinder can lift less force but moves faster while retracting and returns more oil to the reservoir than it receives from the pump.
- The difference in extension and retraction speeds can cause difficulties in applications such as power steering.
- If a single cylinder were used, the vehicle steering response would not be the same to both the left and right. In such applications, a double-rod cylinder may be used (the rod extends from both ends of the cylinder).
- The effective area of both sides is the piston area minus the rod area.

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## Hydraulic Orifices

- In hydraulic circuit design it is often necessary to restrict flow to some segment of the circuit and/or to create a pressure difference. These goals can be achieved by use of a hydraulic orifice.

$$Q = 2.68C_dA_o\sqrt{(\Delta p / \rho)}$$

- Where Q = flow through orifice, L/min
- $C_d$  = orifice coefficient, dimensionless
- $A_o$  = cross sectional area of orifice,  $\text{mm}^2$
- $\Delta p$  = pressure drop across orifice, MPa
- $\rho$  = fluid density, kg/L

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## Hydraulic Orifices con't

- The orifice coefficient varies with the Reynolds number, which is for flow through an orifice, is defined as:
  - $Re = (10^3 \rho V_o d_o) / \mu$
  - Where Re = Reynolds number, dimensionless
  - $\rho$  = fluid density, kg/L
  - $v_o$  = fluid velocity through orifice, m/s
  - $d_o$  = orifice diameter, mm
  - $\mu$  = dynamic viscosity of fluid, mPa\*s

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## Hydraulic Orifices con't

- The following graph shows an approximate relationship between orifice coefficient and Reynolds number for a sharp-edged orifice. For high Reynolds numbers, ( $Re > 2500$ ) the orifice coefficient is often assumed to be equal to 0.6.
- Many practical orifices are not circular. For such orifices, the effective diameter can be calculated using the following equation:
  - $d_{eff} = A_o / L_{co}$
  - Where  $d_{eff}$  = effective orifice diameter, mm
  - $A_o$  = cross sectional area of orifice, mm<sup>2</sup>
  - $L_{co}$  = length of orifice circumference, mm

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## Hydraulic Orifices con't

- Many valves form orifices that are used to control flow and the orifices are not ideal.
  - This figure does not describe their orifice coefficients.
- In such cases, the equation can be used with experimental data to calculate  $C_d$  values.

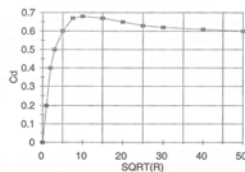


Figure 11.18. Sharp-edged orifice coefficient as affected by Reynolds number.  
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## Hydraulic Valves

- Valves are used in hydraulic circuits to control pressure, volume flow rate, and direction of flow.
- The most common type of pressure control valve is the pressure relief valve, which is used to limit the pressure in a hydraulic circuit to a safe level.
- In a hydraulic circuit in which flow is supplied by a fixed-displacement pump, for example, the pump may continue to produce flow even when an actuator is stalled and incapable of accepting flow.

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## Hydraulic Valves con't

- In the absence of a pressure relief valve, the pressure would climb rapidly until the circuit ruptured at some point and provided an escape path for the flow.
- A direct-acting pressure relief valve is illustrated here.

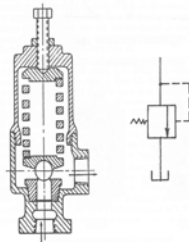


Figure 13.13. A direct-acting pressure relief valve.  
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## Hydraulic Valves con't

- When the cracking pressure is reached, or when the pressure is high enough to lift the ball from the seat and compress the spring, oil can flow from the inlet port to the outlet port.
- The increase in pressure drop from the cracking pressure to the full-flow pressure is called pressure override.
- Because the lost power is converted to heat, it is important to minimize such power losses.

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## Relief Valve Flow

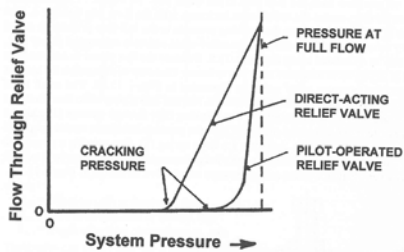


Figure 11.12. Typical characteristics of pressure relief valves.

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## Hydraulic Valves con't

- One way of doing so is by use of a pilot-operated pressure relief valve, as shown below.
- The pilot-operated pressure relief valve has a much smaller pressure override than a direct-acting pressure relief valve.

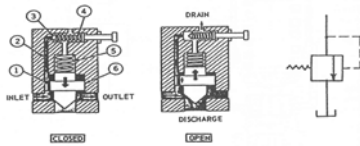


Figure 11.13. A pilot-operated pressure relief valve.

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## Pressure Relief Valves

- Relief valve is set to a specific pressure at which it will open and begin to dump flow to the tank. Until system pressure reaches the cracking pressure the valve is closed.

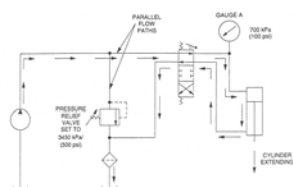


Figure 2-4. Oil flows through the circuit.  
Lab-Vol, Hydraulic Trainer Manual

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## Pressure Relief Valves

- Once the line pressure reaches the cracking pressure, the relief valve opens and begins to dump pressure back to tank

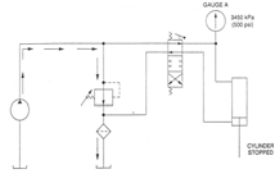


Figure 2-6. Oil flows through the relief valve.  
Lab-Volt, Hydraulic Trainer Manual

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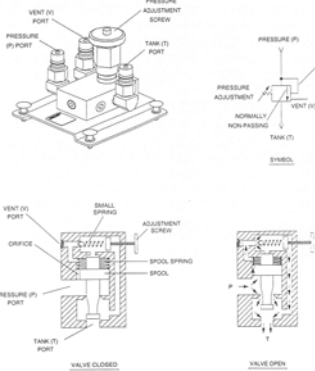
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## Pressure Relief Valve



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## Hydraulic Valves con't

- An unloading valve is used to unload the pump when the pressure at some point in a hydraulic circuit reaches a desired level.

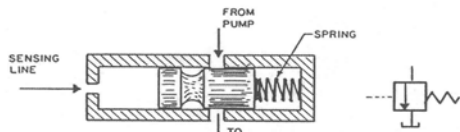


Figure 11.14. An unloading valve.  
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## Volume Control Valves

- The pressure-compensated throttling valve regulates flow to the outer port regardless of pressure variations in the downstream circuit.
- The head knob permits the user to adjust the orifice size to set the metered flow rate.
- A simple hand valve could also meter flow but it would not be pressure compensated (the flow rate would be affected by pressure variations in the circuit).

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## Pressure Compensated Throttling Valve

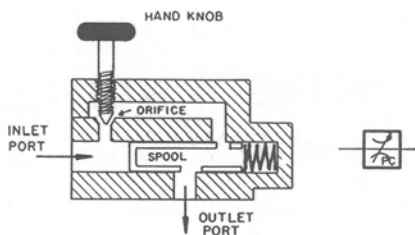


Figure 11.15. An adjustable pressure-compensated throttling valve.

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## Volume Control Valves con't

- The flow divider valve shown can be used with a fixed-displacement pump.
- The flow divider valve, or priority valve, is also pressure compensated .

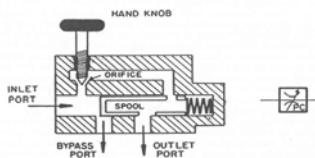


Figure 11.16. An adjustable pressure-compensated flow divider valve.

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## Volume Control Valves con't

- For example, if 20 L/min of flow is needed for the vehicle power steering system.
- The pump is supplying 70 L/min, then 50 L/min would be routed to the bypass port to be used for other hydraulic functions.
- If the pump speed decreased until the pump was supplying only 25 L/min, the power steering system would still receive 20 L/min, but the bypass port would pass only 5 L/min.

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## Basics of Directional Valves

- The valves in the next figures control the direction of the oil flow and are called directional control valves (DCVs).
- Each of the valves shown is a four-port device (has 4 connections to the hydraulic circuit).
- Ports P and T provide pressure and return, while A & B are for connection to the actuator or circuit to be controlled by the valve.

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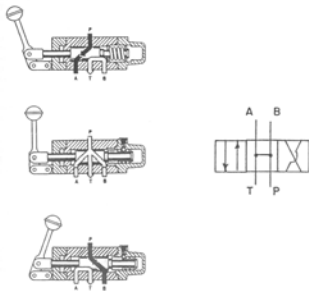
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## Directional Control Valve



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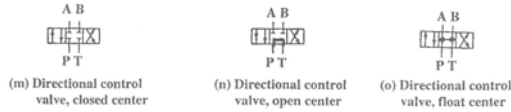
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## 4 Way – 3 Position Valve Center Conditions



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- Closed Center: has not flow when valve centered
- Open Center: relieves pressure to tank when centered
- Float Center: relieves pressure from load and pump

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## Valve Basics, con't

- These DCV's are three-position valves with the valve spool shown in the centered position.
- The valve spool can be slid to the right to align the left-most box with the external ports, or to the left to align with the right-most box with external ports.

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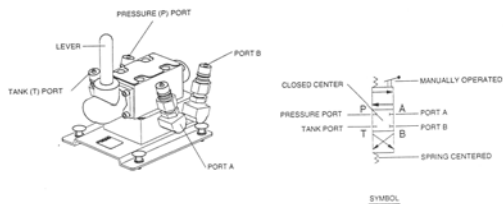
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## 4 Way – 3 Position Valve



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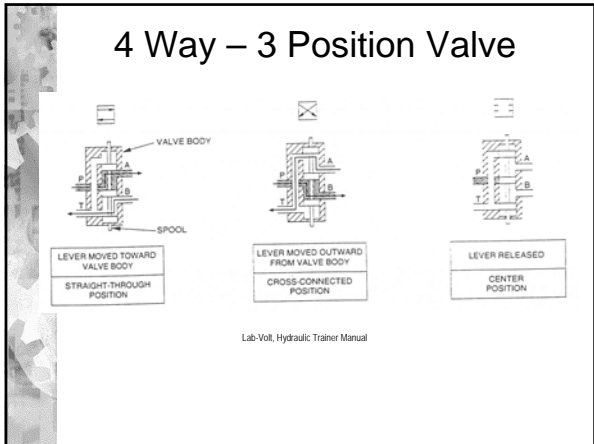
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### Hydraulic Lines

- Hydraulic lines, or conduits, are used to transfer hydraulic fluid between components.
- Rigid lines are made from steel, while flexible lines are made from wire-reinforced rubber.
- The line must be strong enough to withstand the maximum pressure to which it will be subjected, and large enough to convey the hydraulic fluid without excessive pressure drop.

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### Hydraulic Lines con't

- Manufacturers of hydraulic hoses normally specify the limiting pressure rating of their hoses.
- For a line made of steel or other homogeneous material, the maximum allowable pressure is limited by the hoop stress.

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## Hydraulic Lines con't

• The allowable pressure is:

$$• p_{\max} = 2 \cdot t \cdot S_{\text{des}} / d$$

• Where  $p_{\max}$  = maximum allowable pressure, MPa

•  $t$  = wall thickness of conduit, mm

•  $d$  = conduit diameter, mm

•  $S_{\text{des}}$  = design stress for conduit material, MPa

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## Hydraulic Lines con't

• The Hagen-Poiseuille law is used to calculate the pressure drop for laminar flow in conduits:

$$• \Delta p / L = (2.13 \mu Q) / \pi d^4$$

• Where  $L$  = length of conduit, m

• And  $\mu$  = dynamic viscosity of fluid, mPa-s

• And  $Q$  = Flow rate, L/min

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## Hydraulic Lines con't

• For fully turbulent flow, the pressure drop can be calculated as:

$$• \Delta p / L = (5.92 \mu^{0.25} \rho^{0.75} Q^{1.75}) / d^{4.25}$$

• Flow is laminar for Reynolds numbers below 2500 and fully turbulent for Reynolds numbers above 4000.

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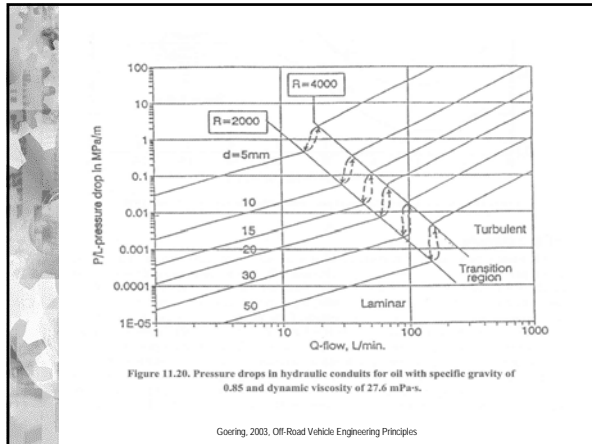
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### Hydraulic Lines con't

- The following equation can be used to calculate pressure drops in bends:
  - $\Delta p = 0.139K \rho (Q^2 / A^2)$
  - Where  $\Delta p$  = pressure drop, Mpa
  - $A$  = cross sectional area of conduit, mm<sup>2</sup>
  - $K$  = dimensionless factor from Figure 11.21.

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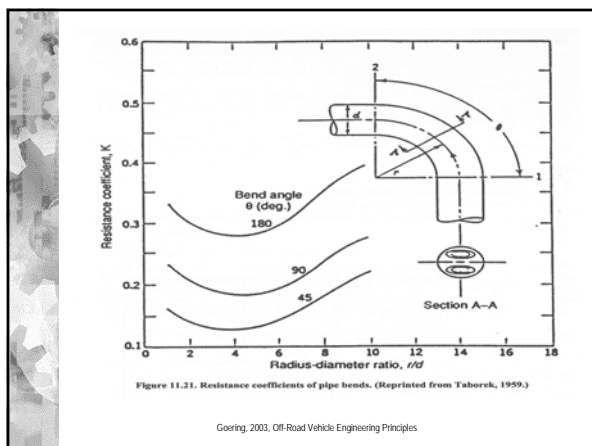
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### Filters

- Clearances between mating parts in some hydraulic components are 10  $\mu\text{m}$  or less, and if particles of that size or larger pass between mating parts, severe damage can result.
- Filters are used to remove solid particles just upstream of the reservoir return port.

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### Filters con't

- To prevent large particles (150  $\mu\text{m}$  or larger) from entering the pump, a strainer or porous filter is usually placed on the reservoir withdrawal tube.

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### Reservoirs

- Every hydraulic system includes a reservoir to supply hydraulic fluid to the pump and to provide storage for fluid returning from the hydraulic circuit.
- The reservoir must have sufficient volume to allow the returning fluid sufficient resident time to cool and to allow air to escape before the fluid re-enters the pump.
- If the reservoir can't provide sufficient cooling, an oil cooler may be needed.

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## Reservoirs con't

- The return line is normally below fluid level in the reservoir to prevent air entrainment and foaming of the fluid.
- The reservoir designer can use careful placement of the two reservoir ports and baffles to prevent the returning fluid from immediate entry into the pump port; otherwise, the fluid would not have time to cool.

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## Reservoirs con't

- Finally, reservoirs normally operate at atmospheric pressure and thus are vented to the atmosphere.

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## Hydraulic Accumulators

- An inert gas above the diaphragm is compressed when hydraulic fluid is forced into the space below the diaphragm.
- The compressed gas represents potential energy that can be reconverted into hydraulic energy when needed.
  - For example, the stored energy can be used for emergency powering of power brakes or power steering during engine failure.

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## Accumulators

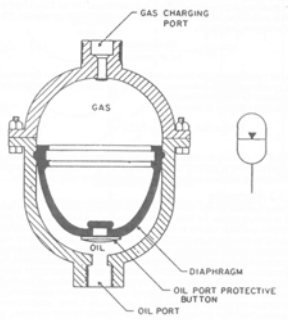


Figure 11.22. A hydraulic accumulator.

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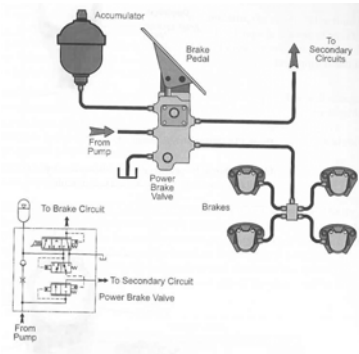
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## Accumulators



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## Hydraulic Accumulators con't

- Because the compressed gas provides cushioning, an accumulator can also be used as a shock absorber to reduce maximum stresses when the system is subjected to unusual loads.

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## Oil Coolers

- If the reservoir volume is too small to allow sufficient cooling of the hydraulic fluid, an oil cooler may be used.
- Typically, the oil cooler is a liquid-to-liquid heat exchanger that transfers heat from the hydraulic fluid to the engine coolant.

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## Hydraulic Fluids

- The most important property of a hydraulic fluid is its viscosity.
- Manufacturers generally recommend fluid viscosities between 12 and 48 mPa\*s at operating temperature.
- Oil viscosity is highly dependent on temperature, but the reduction in viscosity at high temperatures is less for oils with a high viscosity index.

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## Hydraulic Fluids con't

- Viscosity control is important because pump and motor efficiencies depend on viscosity.
- The density of a hydraulic fluid varies with both temperature and pressure, according to:

$$\frac{\rho}{\rho_s} = 1 + \frac{1}{\beta_c} (p - p_s) - \alpha (T - T_s)$$

- Where  $\rho$  = fluid density, kg/L
- P = pressure, MPa
- T = temperature, °C
- $\rho_s, p_s, T_s$  = reference values at some standard condition

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## Hydraulic Fluids con't

- The bulk modulus,  $\beta_f$ , of hydraulic fluid is defined as:

$$\beta_f = \rho_s \left( \frac{\partial p}{\partial \rho} \right)_T$$
$$\alpha = \frac{1}{\rho_s} \left( \frac{\partial \rho}{\partial T} \right)_p$$

- The thermal expansion coefficient is defined as:

$$\alpha = \frac{1}{\rho_s} \left( \frac{\partial \rho}{\partial T} \right)_p$$

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## Hydraulic Fluids con't

- The effective bulk modulus of petroleum is the change in pressure associated with a change in volume of a given mass of fluid; its value is above 1500 MPa for petroleum-based hydraulic fluids (the fluid is virtually incompressible).

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