

FLUIDS 2: BASIC HYDRAULICS



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CHAPTER OVERVIEW

1: Introduction to Hydraulics

- 1.1: Definition and Applications of Hydraulics
- 1.2: Five Basic Components of a Hydraulic System and Their Functions
- 1.3: Definition of Hydraulic Pressure and Its Units of Measure

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1.1: Definition and Applications of Hydraulics

Hydraulic power technology plays a crucial role in modern manufacturing, providing the force needed to operate machinery across industries worldwide. Its versatility and efficiency have led to its widespread adoption, making it an essential subject for anyone working in technical fields.

In this chapter, you will develop foundational skills in hydraulics, including assembling and operating basic components, interpreting circuit diagrams, monitoring system performance, and designing circuits. These skills are highly valuable, as hydraulic systems are found in nearly every sector of industry. Regardless of your career path, there is a strong chance you will work with or around hydraulically powered equipment.

Common Applications of Hydraulics

Hydraulic systems are widely used in various industries, including manufacturing, transportation, and construction.

Manufacturing

- Many industrial robots rely on hydraulics for movement and precision.
- Hydraulic systems power numerous types of industrial machinery.
- Plastic injection molding machines utilize hydraulics to clamp molds shut.
- Lifting equipment, such as forklifts, depends on hydraulic power.

Transportation

- Commercial aircraft use hydraulic systems to control flight surfaces and landing gear.
- Hydraulic shock absorbers improve vehicle stability and ride comfort.
- Automotive braking systems operate using hydraulic pressure.

Construction

- Excavation equipment, such as backhoes, relies on hydraulic actuators.
- Heavy machinery like bulldozers, graders, and dump trucks use hydraulics for movement and load handling.

One of the key reasons for hydraulics' popularity is its ability to generate immense force while providing smooth and precise control. Additionally, hydraulic systems function effectively in demanding environments, including underwater operations. However, they are not suitable for all applications—for example, cleanroom environments, where oil leaks could cause contamination, may require alternative power solutions.

To gain hands-on experience, you will work with a hydraulic training system designed to replicate real-world industrial conditions. This system features industry-standard components, allowing you to build and test actual circuits. You will start by learning how to operate a hydraulic power unit and progressively move on to constructing and analyzing functional circuits.

Understanding Hydraulics and Its Applications

Every machine requires a power source and a means of transmitting energy to perform work. The three primary methods of power transmission are:

1. **Mechanical:** Using gears, belts, chains, and linkages.
2. **Electrical:** Using electric motors, generators, and wiring systems.
3. **Fluid Power:** Using pressurized fluids to generate force and motion.

Fluid power encompasses two main branches:

1. **Hydraulics:** Utilizes a liquid, typically oil, to transmit power.
2. **Pneumatics:** Uses compressed gas, usually air, for energy transfer.

In this chapter, you will explore the principles of hydraulic power, its advantages, and its limitations, while gaining practical skills in assembling and troubleshooting hydraulic circuits.

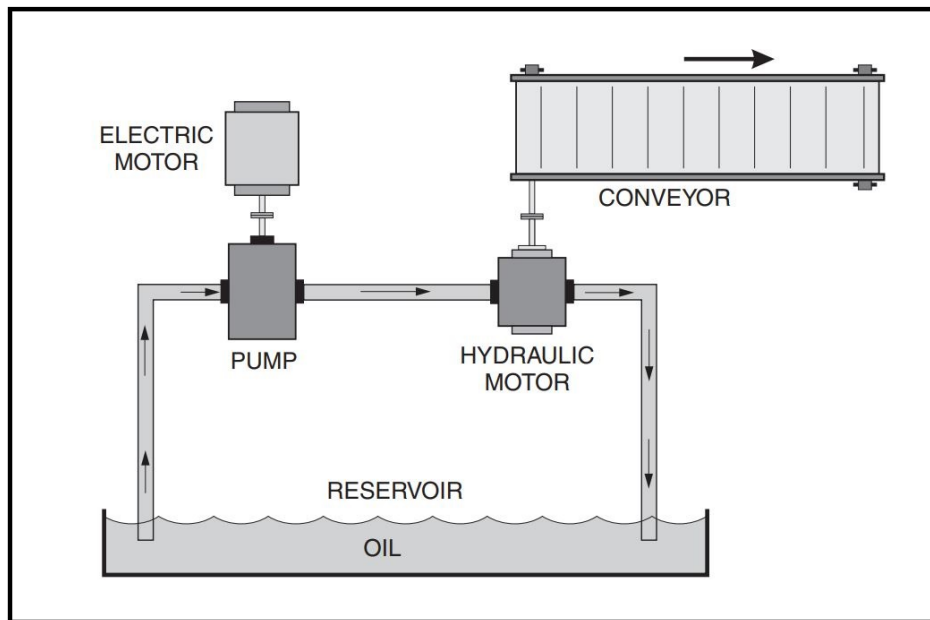


Figure 1.1.1: A hydraulic circuit.

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1.2: Five Basic Components of a Hydraulic System and Their Functions

A hydraulic system is made up of five fundamental components, each playing a crucial role in its operation:

1. **Power Input Device (Pump)** – The pump is responsible for generating hydraulic power. It draws oil from the reservoir and pressurizes it, sending it through the system.
2. **Control Devices (Valves)** – Valves regulate the direction, pressure, and flow rate of the hydraulic fluid, ensuring proper system operation. These valves can be pressure regulating devices, flow control valves, or directional control valves.
3. **Power Output Device (Actuators)** – Actuators convert hydraulic energy back into mechanical motion. There are two main types:
 - **Hydraulic motors** produce rotary motion.
 - **Hydraulic cylinders** create linear motion when pressurized oil is introduced.
4. **Conductors (Pipes, Tubing, or Hoses)** – These components transport hydraulic fluid through the system. There are typically two main lines:
 - **Supply line** – Delivers pressurized oil to the actuators.
 - **Return line** – Carries used oil back to the reservoir.
5. **Hydraulic Fluid (Liquid Medium)** – The fluid serves as the medium for energy transfer. Oil is the most commonly used hydraulic fluid, but other liquids may be used depending on the application.

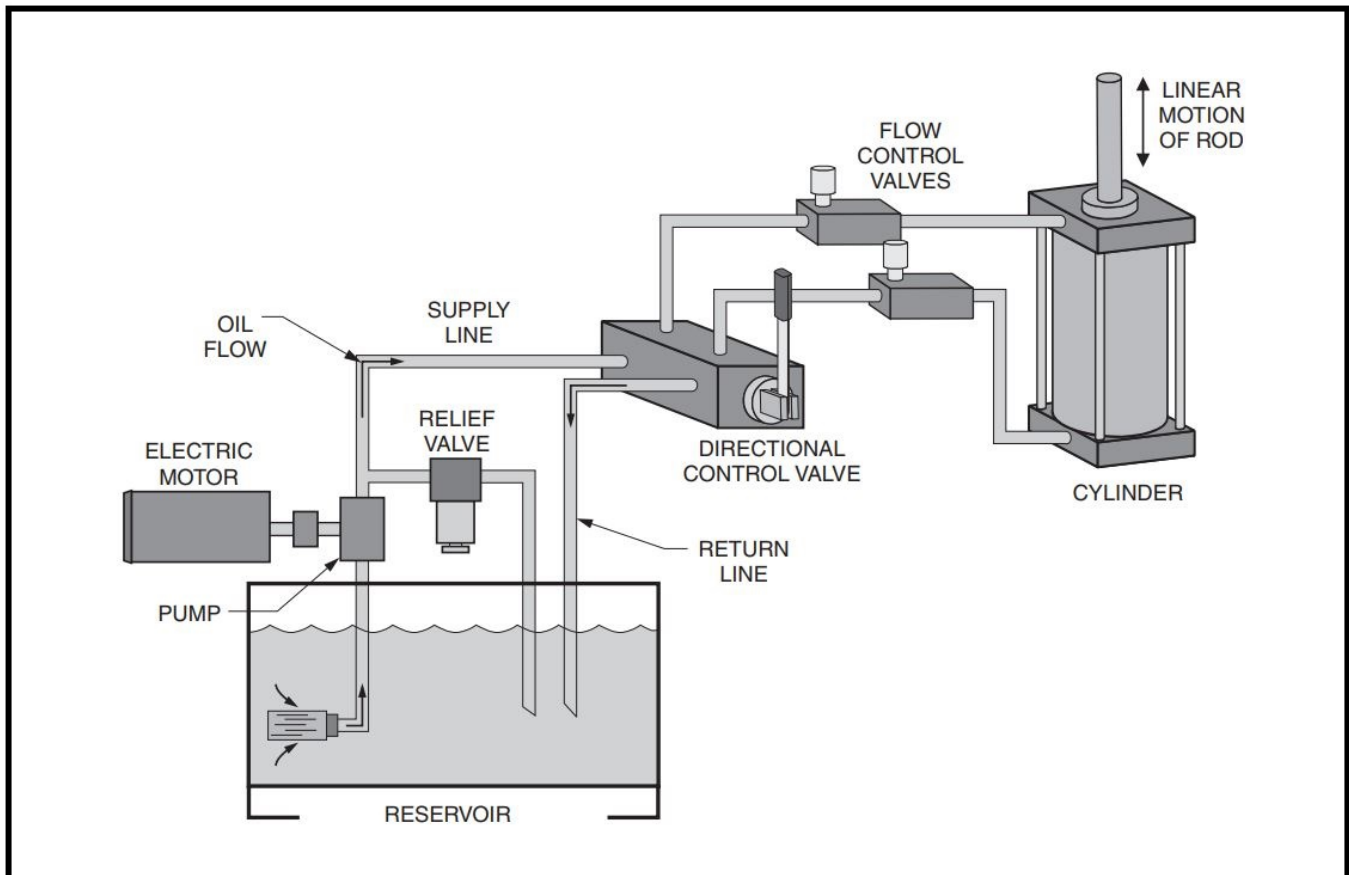


Figure 1.2.1: A hydraulic system.

Each of these components must work together efficiently to ensure reliable operation in hydraulic systems. Understanding their functions will help you design, troubleshoot, and maintain hydraulic equipment effectively.

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1.3: Definition of Hydraulic Pressure and Its Units of Measure

One of the fundamental concepts in hydraulics is **pressure**. Pressure is the intensity of force applied over a given area. It is created when a force is exerted by one object onto the surface of another.

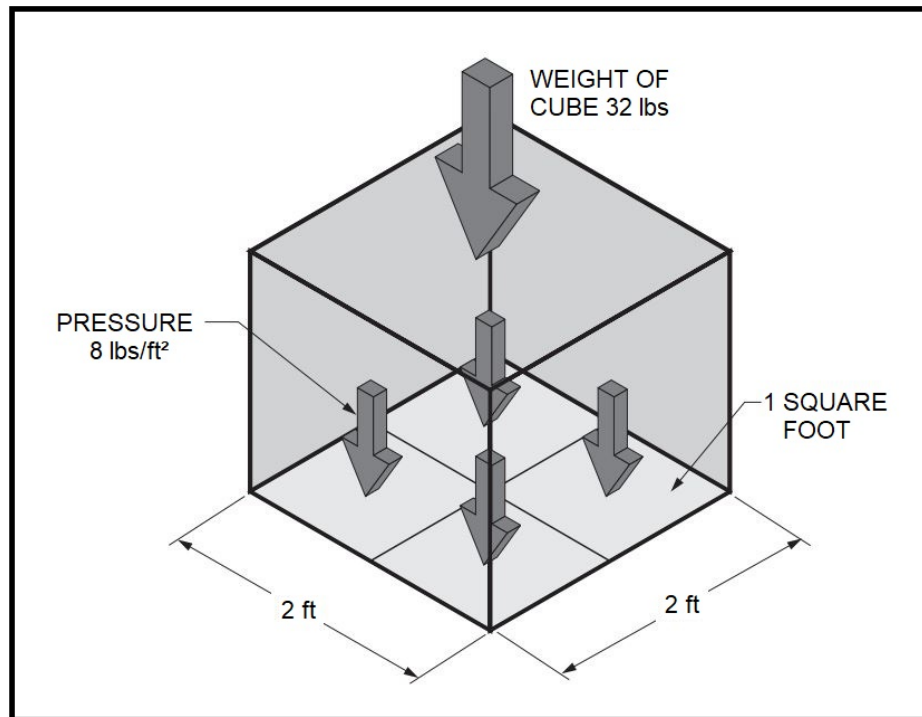


Figure 1.3.1: A 32-pound box on a surface area of 4 square feet results in 8 pounds of pressure per square foot (8 lbs/ft²).

✓ Measuring Pressure Example

Imagine a box weighing **32 pounds** resting on a surface with an area of **4 square feet**. Since the force is evenly distributed, each square foot supports a portion of the total force. In this case, the pressure exerted on the surface is:

$$32 \text{ pounds} / 4 \text{ square feet} = 8 \text{ lbs/ft}^2$$

This means the pressure exerted by the box is **8 pounds per square foot (8 lbs/ft²)**.

Calculating Pressure

Pressure is determined using the following formula:

$$P = F \times A$$

Where:

- **P** = Pressure
- **F** = Force (measured in Newtons or pounds)
- **A** = Area over which the force is applied (measured in square meters or square inches)

Units of Measurement

The units used for pressure depend on the measurement system:

- In the **English system**, pressure is commonly measured in **pounds per square inch (psi)**, which is written as **lb/in²**.
- In the **SI (International System) of units**, pressure is measured in **Pascals (Pa)**, where **1 Pascal (Pa) = 1 N/m²**.

Understanding the Relationship Between Force, Area, and Pressure

Although force and pressure are closely related, they are not the same. A single force can produce different pressures depending on the area over which it is applied.

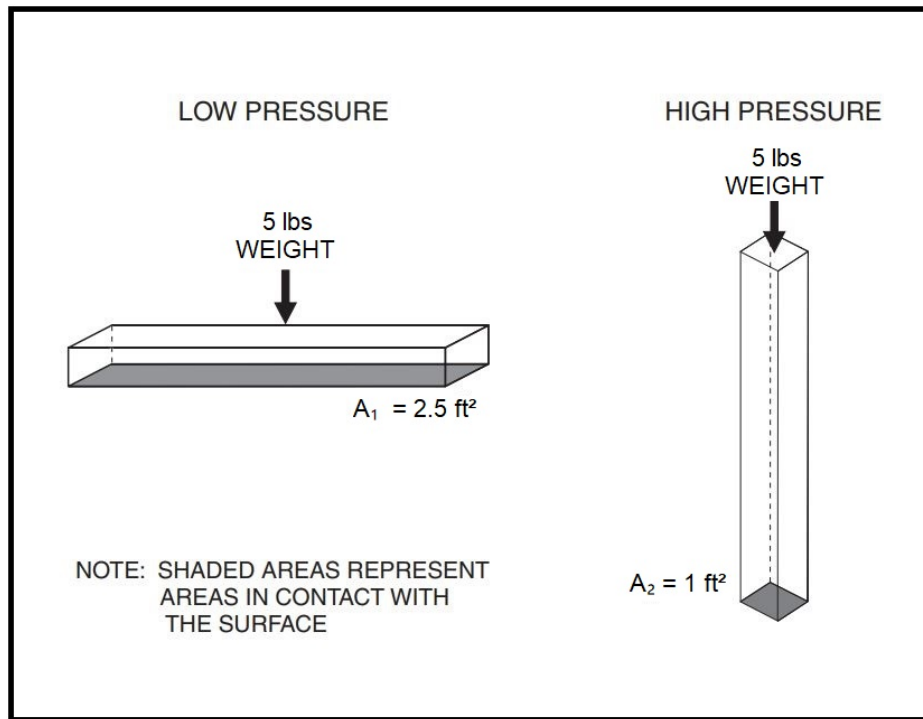


Figure 1.3.2: An object can exert different amounts of pressure depending on how much area it is in contact with.

✓ The Relationship Between Force, Area, and Pressure Example

If the same **5 lbs** weight is placed on a **2.5 ft²** surface, the pressure exerted is:

$$5 \times 2.5 = 2 \text{ lbs/ft}^2$$

If the same weight is placed on a **1 ft²** surface, the pressure increases:

$$5 \times 1 = 5 \text{ lbs/ft}^2$$

This principle explains why a person wearing high heels exerts more pressure on the ground than someone wearing flat-soled shoes. The smaller the contact area, the greater the pressure applied.

Fluid Pressure and Pascal's Law

In hydraulics, pressure is also created within a **fluid**. One way to generate **fluid pressure** is by placing a weight on a container filled with liquid. The fluid must exert pressure against the container walls to support the weight.

If the liquid inside the container is **at rest**, the pressure at every point within the fluid remains equal. This concept was first described in the seventeenth century by the French scientist **Blaise Pascal** and is known as **Pascal's Law**.

Using the same $P = F/A$ formula, the pressure in a hydraulic system can be calculated.

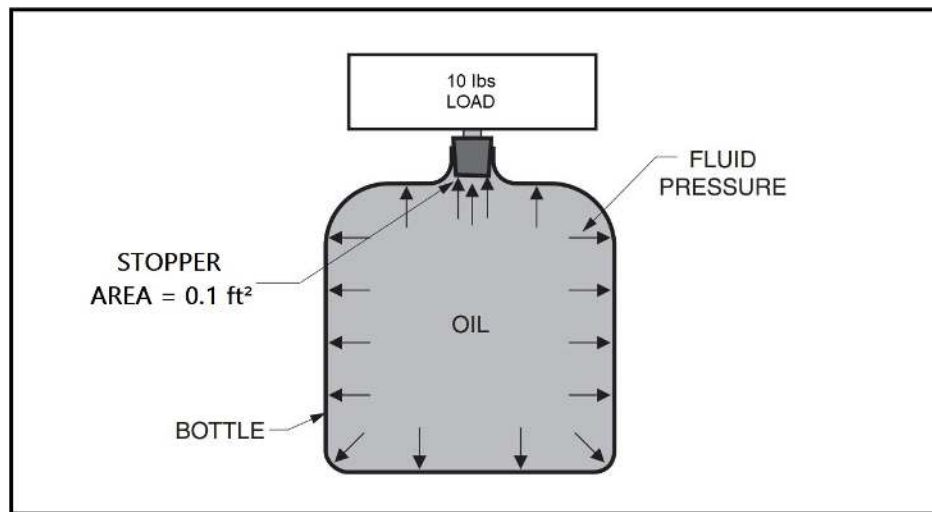


Figure 1.3.3: When a weight is placed in a container of liquid, fluid pressure pushes against the container.

✓ Calculating Pressure in a Hydraulic System Example

If a **10-pound** force is applied to an area of **0.1 ft²**, the pressure inside the system is:

$$10 \text{ pounds} / 0.1 \text{ ft}^2 = 100 \text{ lbs/ft}^2$$

Understanding these principles is essential for working with hydraulic systems, as pressure determines how effectively hydraulic machinery can operate.

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CHAPTER OVERVIEW

2: Power Units

[2.1: Operation of a Hydraulic Power Unit](#)

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2.1: Operation of a Hydraulic Power Unit

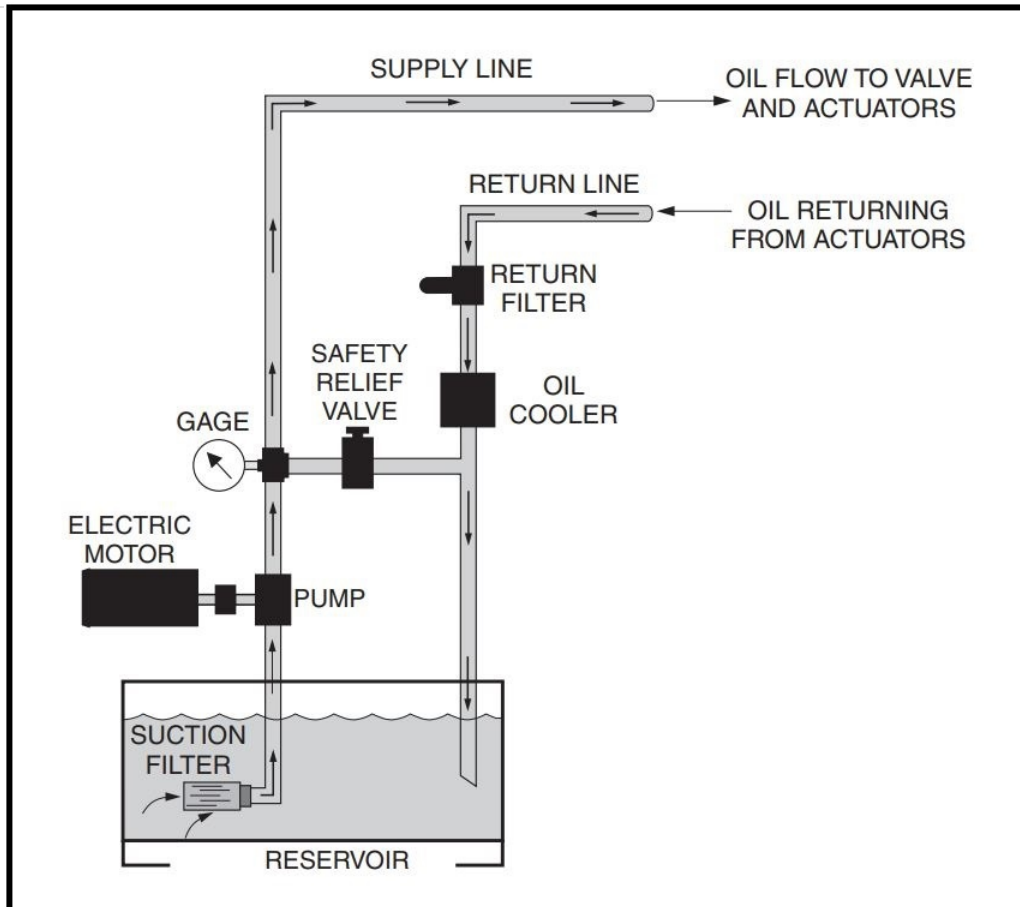


Figure 2.1.1: Hydraulic system

In most hydraulic systems, components are divided into two main sections:

1. **The actuator and control valves** are mounted on the machine structure
2. **The power unit**, which supplies hydraulic energy to the system

The **hydraulic power unit** consists of several key components, including:

- A **pump** to generate fluid flow.
- A **reservoir** to store hydraulic fluid.
- A **prime mover**, typically an **electric motor**, to drive the pump.

In addition to these primary components, most hydraulic power units include additional elements for monitoring and safety, such as:

- **Pressure gauges** to track system pressure.
- **Filters** to remove contaminants from the oil.
- **Relief valves** to prevent overpressure conditions.
- **Cooling mechanisms** to maintain optimal fluid temperature.

How a Hydraulic Power Unit Works

When the **prime mover** (electric motor) starts, it rotates the pump shaft. This movement causes the pump to draw oil from the **reservoir** through a **suction filter** and push it into the hydraulic system via the **supply line**.

Once the oil has completed its work within the actuators, it returns to the **reservoir** through the **return line**. This process ensures a continuous flow of hydraulic fluid to power the system.

Beyond supplying fluid, the power unit must also ensure the **oil remains clean and within a safe temperature range**. To accomplish this, most power units incorporate:

- **Filtration systems**, including suction and return filters, to remove contaminants.
- **Cooling systems**, such as heat exchangers using air or water, to dissipate excess heat. Some units rely on **large reservoirs** to allow oil to cool naturally before recirculating.

Key Components of a Hydraulic Power Unit

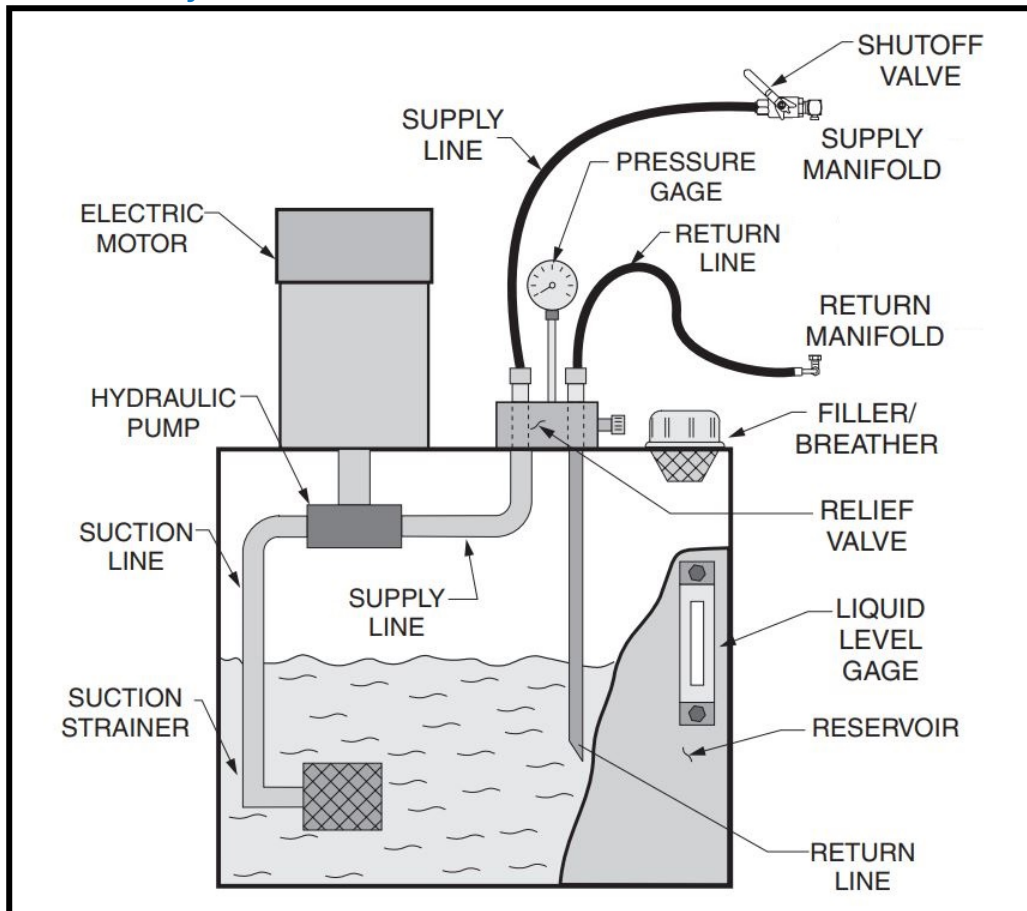


Figure 2.1.2: Hydraulic power unit

Electric Motor

Most industrial hydraulic systems use a **constant-speed electric motor** to drive the pump. The motor's shaft is connected to the pump shaft through a **coupling**, allowing efficient transfer of mechanical power.

Hydraulic Pump

The **hydraulic pump** generates fluid flow. As the electric motor drives the pump, it, in a way, pulls oil from the **reservoir** through its **inlet** and forces it into the system via its **outlet**.

Reservoir

The **reservoir** serves multiple functions:

- It **stores hydraulic fluid** when not in use.
- It allows **dirt and contaminants to settle** before re-entering the system.
- It helps **dissipate heat**, keeping the fluid at an appropriate temperature.

Suction Line

The **suction line** connects the **pump inlet** to the reservoir, allowing the pump to draw in oil.

Supply Line (Pressure Line)

The **supply line** connects to the **pump outlet** and delivers pressurized oil to the hydraulic system. This line runs through the **relief valve manifold block** and exits through a port usually labeled “P”.

Sometimes, a supply line will distribute oil to a **supply manifold**, a machined block with multiple ports that provide hydraulic fluid to various system components.

Return Line

The **return line** is responsible for directing oil from the hydraulic system back to the reservoir. This ensures continuous circulation of hydraulic fluid, allowing it to be reused in the system.

Relief Valve

The **relief valve** is a crucial safety component that prevents excessive pressure from building up in the system. It is designed to open when system pressure exceeds a preset limit, allowing excess fluid to return to the reservoir and maintain safe operating conditions. The pressure setting can be adjusted using a control knob located on the valve body.

Suction Strainer

Located within the **suction line** at the pump inlet and submerged in hydraulic fluid, the **suction strainer** plays a critical role in protecting the pump from contaminants. It acts as a first line of defense, preventing large dirt particles from entering the pump and causing damage.

Filler/Breather

The **filler/breather** serves two essential functions in a hydraulic power unit:

1. **Reservoir Filling** – The unit features a removable cap that allows hydraulic oil to be added to the reservoir. A protective screen is often included to prevent large contaminants from entering during filling.
2. **Airflow Regulation** – Since the fluid level fluctuates during system operation, the **filler/breather** ensures that air can enter or exit the reservoir, maintaining a pressure balance close to atmospheric levels. Air passes through filtered openings in the breather cap to prevent dust and debris from contaminating the fluid.

Liquid Level Gauge

Often, there is a **liquid level gauge** that provides a visual indication of the amount of oil in the reservoir. There are two common types:

1. **Oil level gauge** – This gauge is mounted externally on the reservoir and is connected to the oil inside, providing an accurate reading.
2. **Sight glass** – A small, circular glass window mounted at the correct oil level on the reservoir, allowing operators to verify the fluid level at a glance.

Return Filter

Sometimes, a **return filter** is installed in the return line to remove contaminants that may have been picked up as the oil circulated through the system. By filtering the returning fluid before it re-enters the reservoir, it helps maintain hydraulic fluid cleanliness and prolongs the lifespan of system components.

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CHAPTER OVERVIEW

3: Connections of the Circuits

3.1: Functions of a Hydraulic Schematic

3.2: Function and Schematic Symbol of a Hydraulic Quick Disconnect Fitting

3.3: Function and Schematic Symbol of a Tee

3.4: Operation and Schematic Symbol of a Pressure Gage

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3.1: Functions of a Hydraulic Schematic

Purpose of Hydraulic Schematics

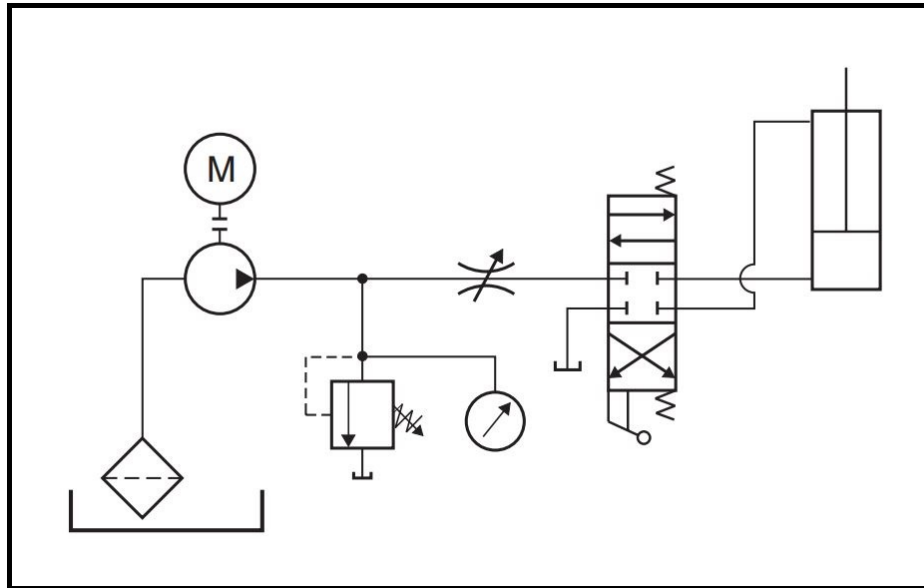


Figure 3.1.1: Hydraulic schematic diagram.

Before diving into more advanced hydraulic circuits, it is essential to understand how hydraulic components are represented in diagrams. A **fluid power schematic** is a visual representation of how components are interconnected within a system. These diagrams allow us to analyze circuit functions and troubleshoot issues efficiently.

Early diagrams often use **pictorial representations**, where actual images of components are displayed. While these can be helpful for beginners, they are impractical for complex systems due to their time-consuming nature and lack of standardization. Instead, **schematic diagrams** are used to provide a clear and efficient way to communicate hydraulic circuits.

SYMBOL	SYMBOL
 ROTATING DEVICE	 VARIABLE
 VALVE	 RESTRICTION
 CONDITIONING DEVICE	 LINES CONNECTED
 CYLINDER	 SPRING
 ACCUMULATOR	 BLOCKED LINE
 CONDUCTOR	 BLOCKED LINE
 FLOW DIRECTION	

Figure 3.1.2: Schematic symbols.

What is a Schematic Diagram?

A **schematic diagram** is a standardized way of illustrating a hydraulic circuit using universally recognized symbols. These symbols represent system components and their connections without showing physical appearances. Schematics show components typically drawn in the **normal or de-energized state**, meaning they depict how the system is configured when no external force is applied.

Each hydraulic symbol consists of simple geometric shapes such as circles, squares, rectangles, triangles, arcs, arrows, lines, dots, and ovals. These elements are combined to create distinct symbols for different components.

Additionally, **flow direction arrows** (represented as triangles) are often used to indicate fluid movement. In some cases, partial schematics are drawn using shortcut notations to illustrate only the relevant portions of a system without displaying the entire circuit.

Standardization of Hydraulic Symbols

Several organizations have developed standards for hydraulic symbols to ensure consistency across industries. The three most commonly referenced standards are:

- **National Fluid Power Association (NFPA)**
- **American National Standards Institute (ANSI)**
- **International Organization for Standardization (ISO)**

The United States primarily follows **NFPA** and **ANSI** standards, while **ISO** is widely used internationally.

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3.2: Function and Schematic Symbol of a Hydraulic Quick Disconnect Fitting

Hydraulic Quick Connect Fittings

Many hydraulic systems incorporate **flexible hoses**, which allow movement and adaptability in various applications. In situations where hoses need to be frequently connected and disconnected, **quick connect fittings** provide a practical solution.

As the name suggests, these fittings enable **fast and tool-free assembly and disassembly** of hydraulic circuits. They consist of two main parts:

- **Male-end fitting**
- **Female-end fitting**

When pressed together, these fittings snap into place, creating a secure connection. No special tools are required, making them ideal for applications requiring frequent hose changes, such as auxiliary power units on jet aircraft.

Schematic Representation

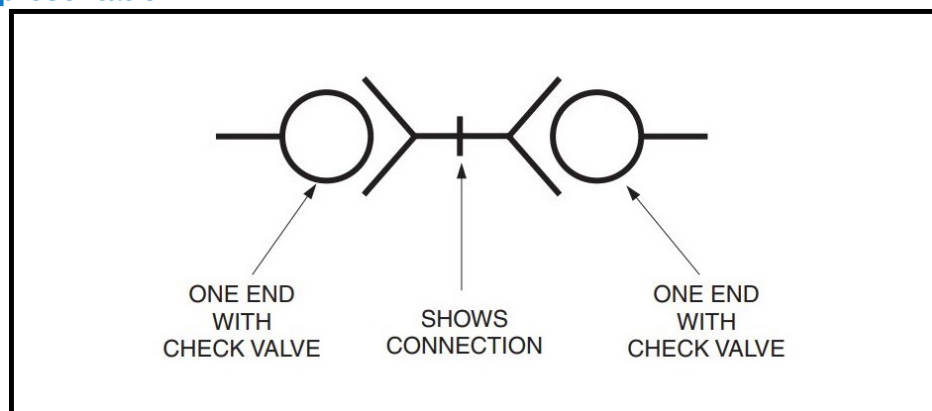


Figure 3.2.1: Schematic representation of quick connect fittings.

In hydraulic schematics, **quick connect fittings** are represented similarly to **two opposing check valves**. Each fitting contains a check valve that automatically closes when the connection is disengaged, preventing hydraulic fluid from leaking out of the system.

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3.3: Function and Schematic Symbol of a Tee

Tee Fittings and Their Function

Purpose of a Tee Fitting

In many hydraulic systems, it is necessary to connect multiple circuits to the same supply line. A **tee fitting** provides this capability in a simple and efficient manner. Named for its "**T**" **shape**, this fitting allows fluid to flow into one inlet and split into two separate paths.

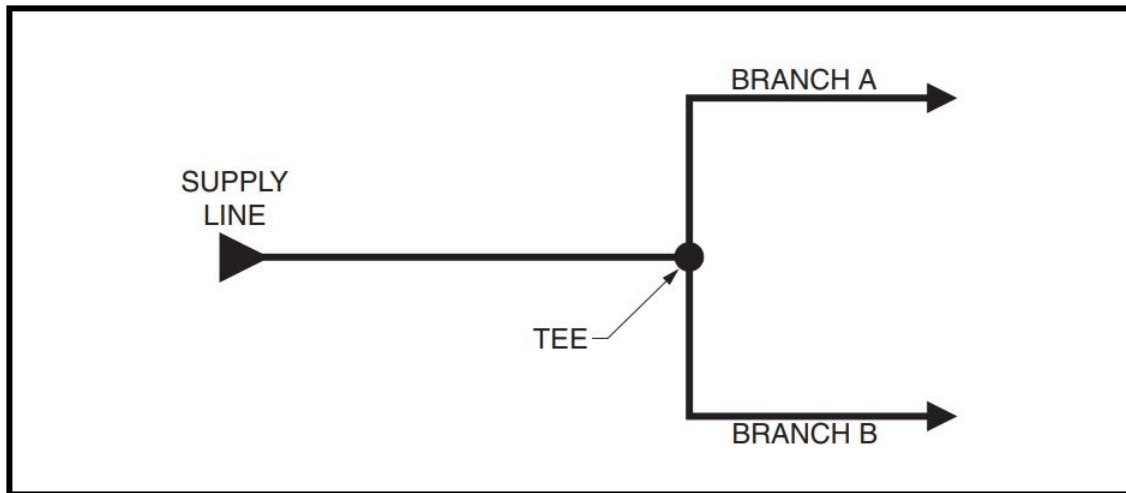


Figure 3.3.1: Schematic representation of a tee fitting.

Hydraulic trainers often include **three-fitting tees** equipped with **quick-connect fittings**, which simplify system assembly. These tees typically have **two male ends and one female end**, making it easy to connect components quickly and securely.

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3.4: Operation and Schematic Symbol of a Pressure Gage

Operation of a Bourdon Tube Pressure Gauge in Hydraulic Systems

The most widely used type of hydraulic pressure gauge is the **Bourdon tube gauge**. Its operation is based on the principle of mechanical deformation.

At its core, a Bourdon tube gauge contains a **curved, hollow tube** that behaves similarly to a party horn that unrolls when air is blown through it. As hydraulic fluid enters the gauge, **increasing pressure causes the tube to straighten slightly**. This motion is transferred through a **mechanical linkage**, moving a pointer on the gauge face to indicate pressure. The higher the fluid pressure, the more the tube straightens, resulting in a greater pointer movement.

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CHAPTER OVERVIEW

4: Basic Cylinder Circuits

4.1: Function and Application of a Hydraulic Cylinder

4.2: Operation and Schematic Symbol of a Double-Acting Hydraulic Cylinder

4.3: Function and Application of a 4/3 DCV

4.4: Operation and Schematic Symbol of a 4/3 DCV

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4.1: Function and Application of a Hydraulic Cylinder

Function of a Hydraulic Cylinder

A **hydraulic cylinder** is a type of actuator designed to convert hydraulic energy into **mechanical force and motion** in a straight line. This linear motion makes hydraulic cylinders essential in applications that require **high force and precise movement**.

Common Applications

Hydraulic cylinders are widely used in industrial and manufacturing settings. Some common examples include:

- **Plastic Injection Molding Machines** – Cylinders apply force to inject molten plastic into molds.
- **Hydraulic Presses** – Used in metal forming, forging, and shaping operations where high pressure is required.

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4.2: Operation and Schematic Symbol of a Double-Acting Hydraulic Cylinder

How a Double-Acting Cylinder Works

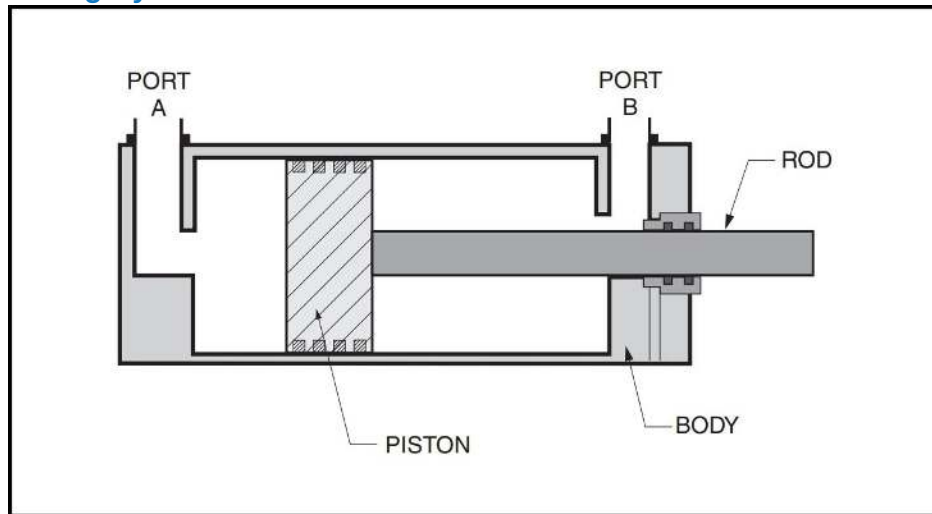


Figure 4.2.1: Diagram of a double-acting cylinder.

A **double-acting cylinder** consists of a **piston and rod assembly** housed within a **barrel-shaped body**. Unlike single-acting cylinders, which rely on external forces such as gravity or springs for movement in one direction, a double-acting cylinder can extend and retract under hydraulic power.

- When **oil enters the cap end**, it **forces the rod to extend**.

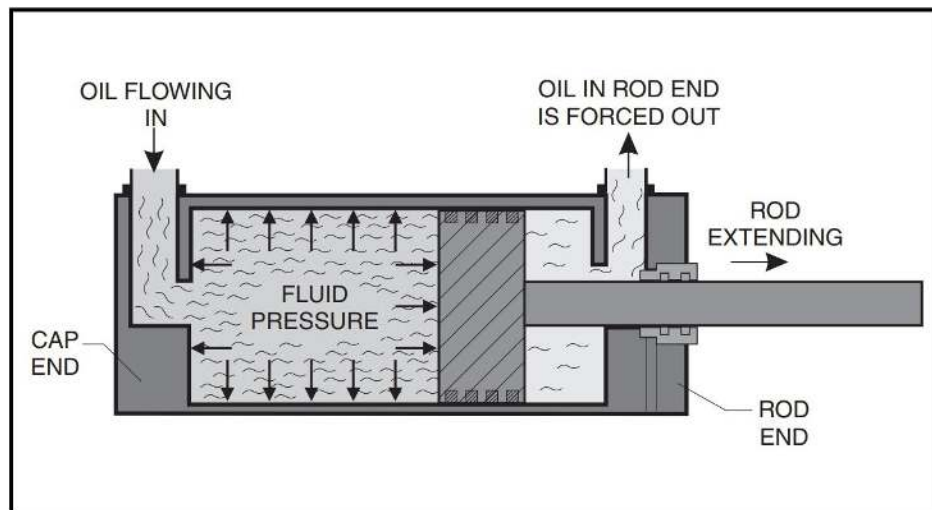


Figure 4.2.2: Diagram of a double-acting cylinder. As oil enters the cap end, fluid pressure forces the rod to extend.

- When **oil enters the rod end**, it **causes the rod to retract**.

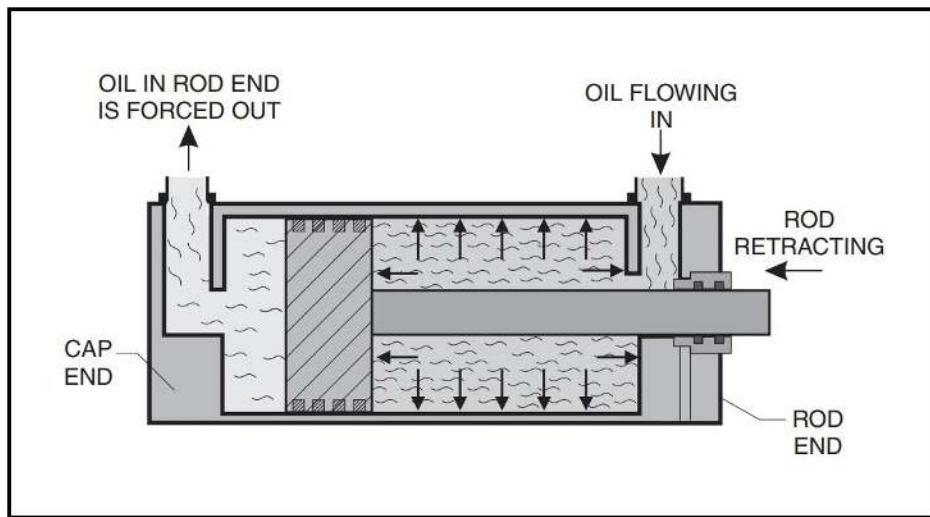


Figure 4.2.3: Diagram of a double-acting cylinder. As oil enters the rod end, fluid pressure forces the rod to retract. This bidirectional control allows for greater versatility and precision in hydraulic systems.

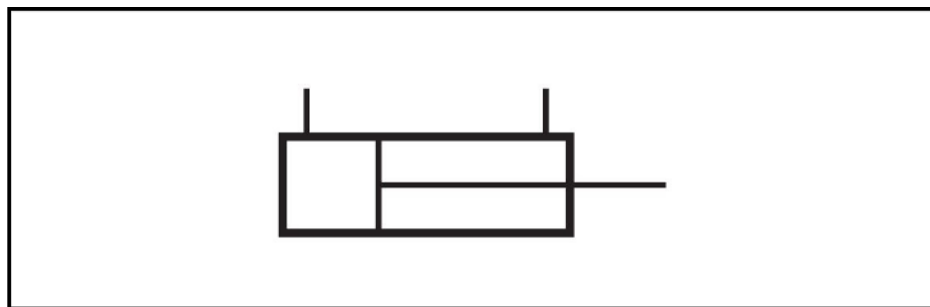


Figure 4.2.4: Schematic symbol for a double-acting cylinder.

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4.3: Function and Application of a 4/3 DCV

Directional Control Valves: 3-Position, 4-Way DCVs: Function and Purpose

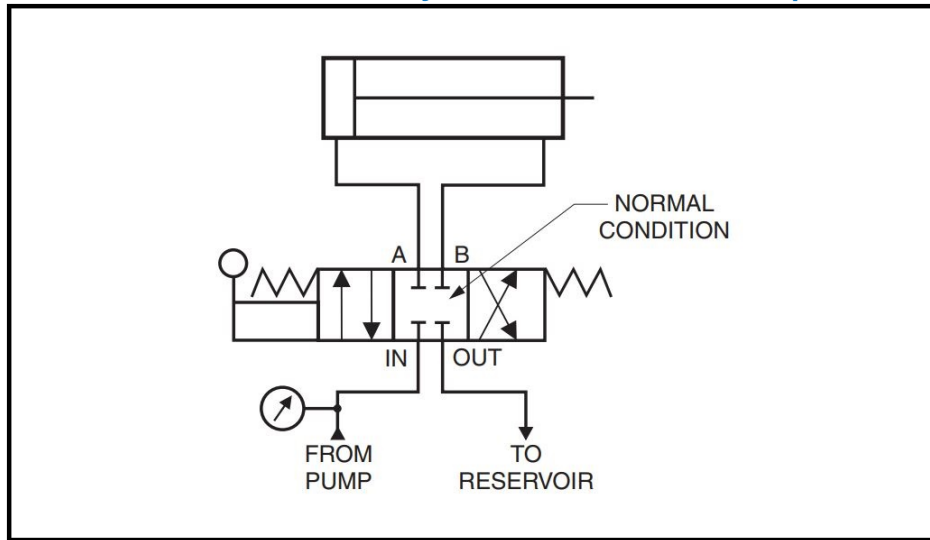


Figure 4.3.1: Schematic diagram of a 3-position, 4-way directional control valve.

To control the movement of a **double-acting cylinder** without manually switching hoses, a **directional control valve (DCV)** is used. In hydraulic systems, **DCVs function as flow switches**, directing hydraulic fluid to different ports to control actuator movement.

A **3-position, 4-way DCV** provides three essential functions:

1. Extend the cylinder rod

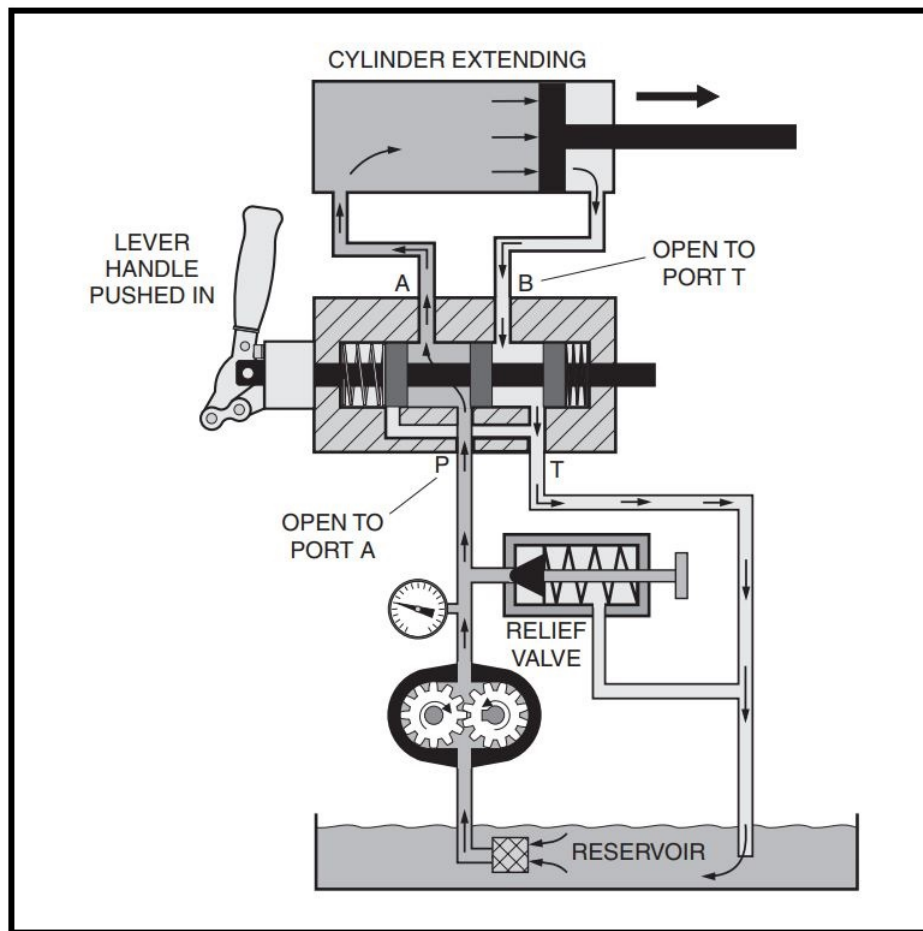


Figure 4.3.2: Diagram of a 3-position, 4-way DCV with the cylinder rod extended.

2. Retract the cylinder rod

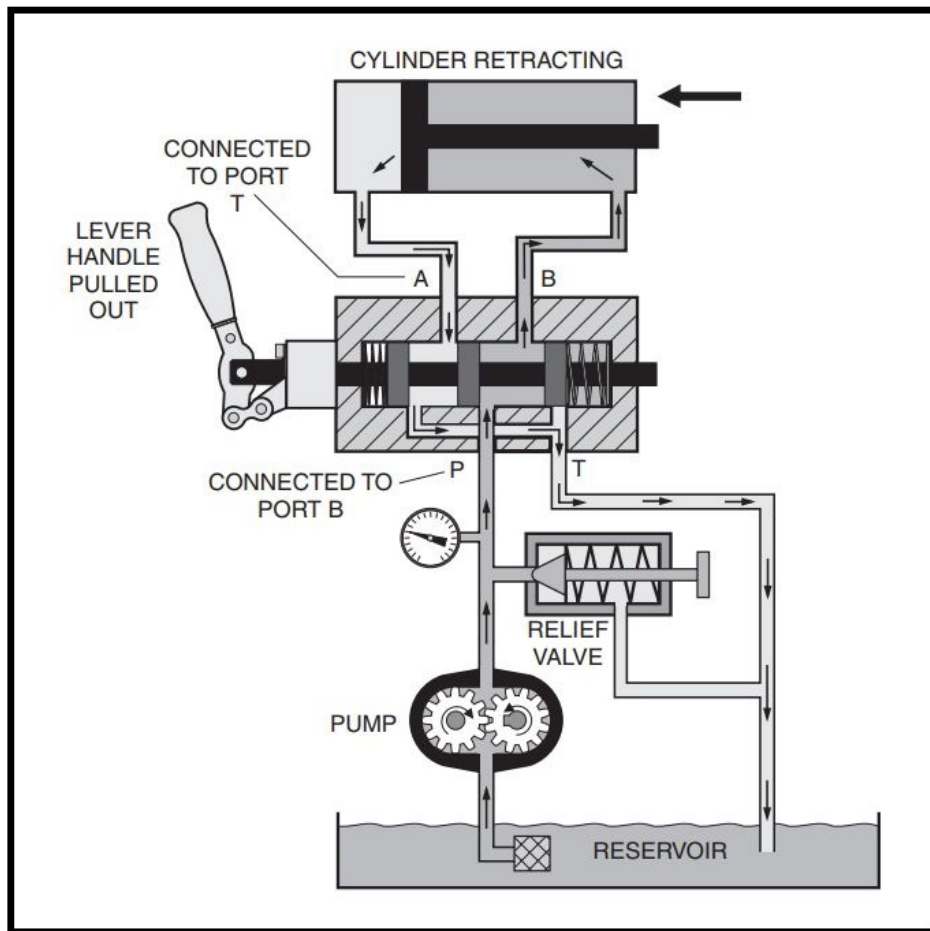


Figure 4.3.3: Diagram of a 3-position, 4-way DCV with the cylinder rod retracted.

3. Hold the cylinder rod in position (neutral state)

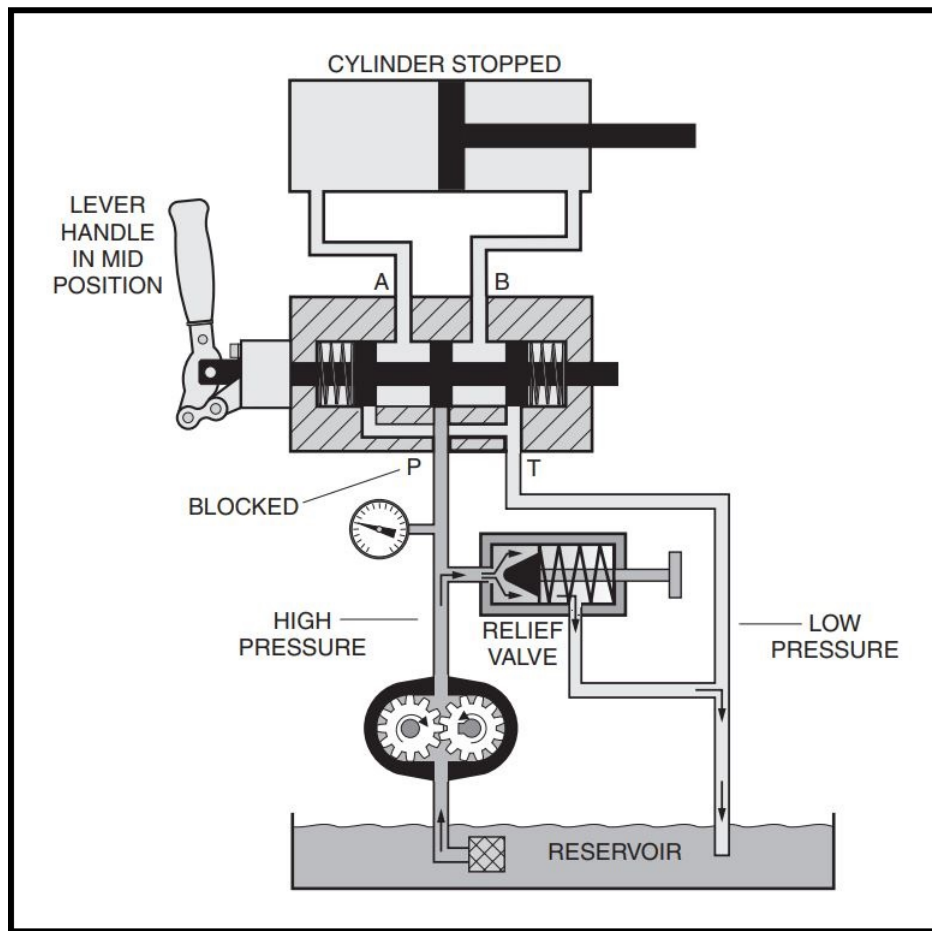


Figure 4.3.4: Diagram of a 3-position, 4-way DCV in a neutral state.

This type of valve is commonly found in hydraulic circuits that require **precise directional control**, such as **industrial automation, presses, and heavy machinery**.

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4.4: Operation and Schematic Symbol of a 4/3 DCV

3-Position, 4-Way Directional Control Valve (DCV): Main Components

A **3-position, 4-way directional control valve (DCV)** is a crucial component in hydraulic systems, responsible for directing the flow of hydraulic fluid. This type of valve provides three distinct operating positions and four flow paths, allowing precise control of actuators like hydraulic cylinders and motors.

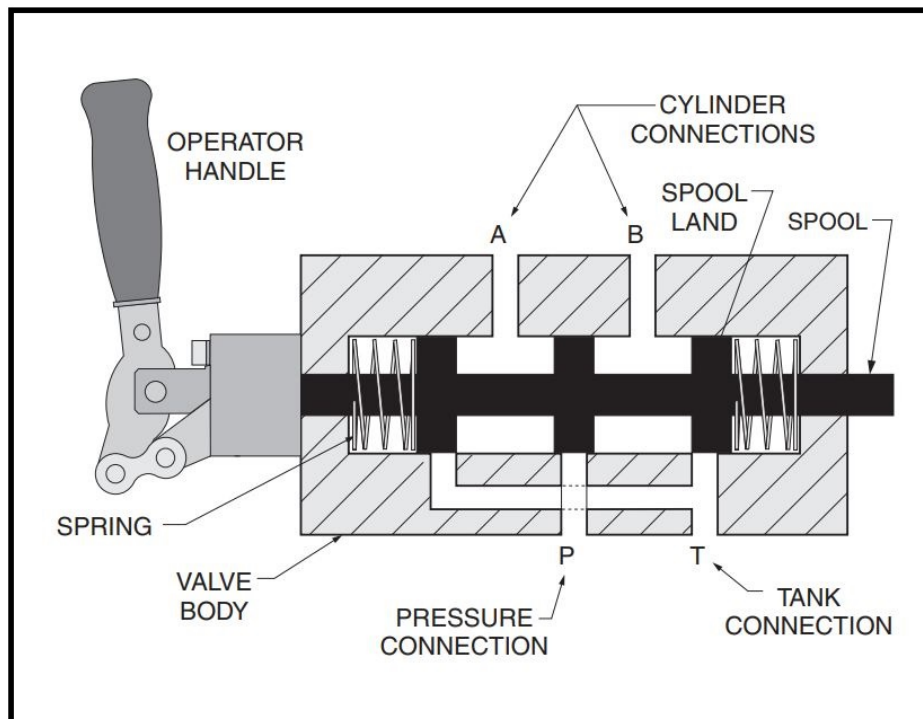


Figure 4.4.1: Diagram of the parts of a 3-position, 4-way DCV.

A **3-position, 4-way DCV** consists of four key components:

- **Valve Body** – The **main housing** of the valve, machined with internal passages to guide fluid flow. Hydraulic valve bodies are typically constructed from **cast iron, steel, or aluminum** to withstand high-pressure conditions.
- **Spool** – A **sliding internal component** with machined "lands" that direct hydraulic fluid to different ports as it moves within the valve body. Changing the spool's position alters the flow paths.
- **Operator** – The **mechanism that shifts the spool** between positions. Operators can be **manual (lever, push-button), electrical (solenoid), hydraulic, or pneumatic**.
- **Springs** – A **3-position valve** is typically spring-centered, meaning **springs return the spool to its neutral position** when no operator force is applied.

Understanding DCV Ports

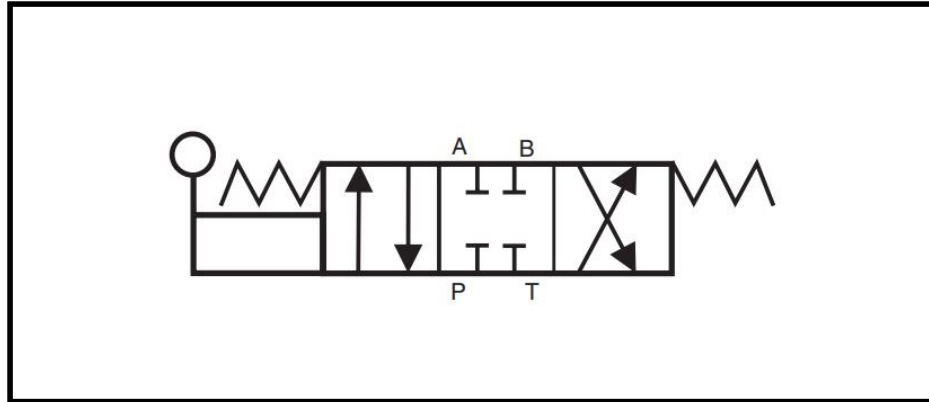


Figure 4.4.2: Schematic diagram depicting DCV ports.

DCV ports are labeled according to their function:

- **P (Pressure Port)** – The inlet port where **pressurized hydraulic fluid enters** the valve.
- **T (Tank Port)** – The return port that **directs oil back to the reservoir**.
- **A & B (Actuator Ports)** – Ports that connect to the actuator (e.g., a **cylinder or motor**) and **control movement by directing flow to and from the actuator**.

Classifications of Directional Control Valves

Directional control valves are categorized based on:

1. **The number of flow paths ("ways")** – DCVs are available in **one-way, two-way, three-way, and four-way configurations**.
2. **The number of positions** – Most industrial DCVs are either **2-position or 3-position**. A **3-position valve** allows for additional control by providing a **neutral or center position**.

Schematic Symbols for DCVs

The **schematic representation of a DCV** uses a **flow envelope** to illustrate flow paths for each spool position. The **flow envelope** visually indicates whether a particular passage is **open or blocked**.

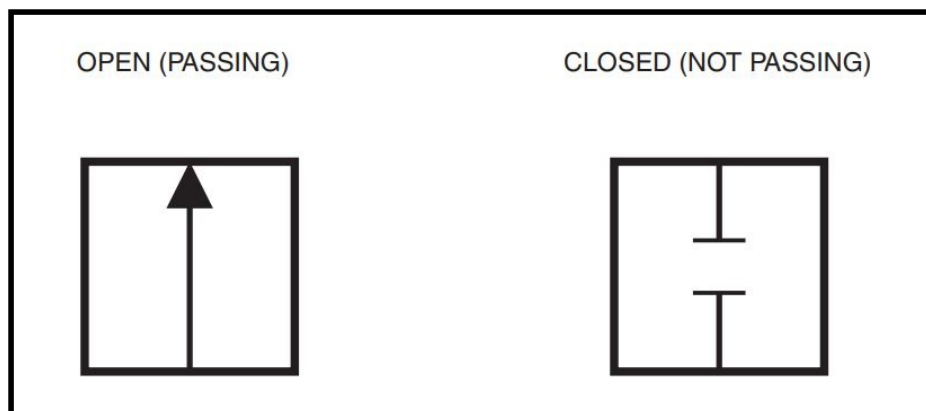


Figure 4.4.3: Schematic symbols for open and closed flow envelopes.

For example, in a **2-position, 2-way DCV symbol**:

- One spool position **connects two ports**, allowing flow.
- The other position **blocks the ports**, stopping flow.

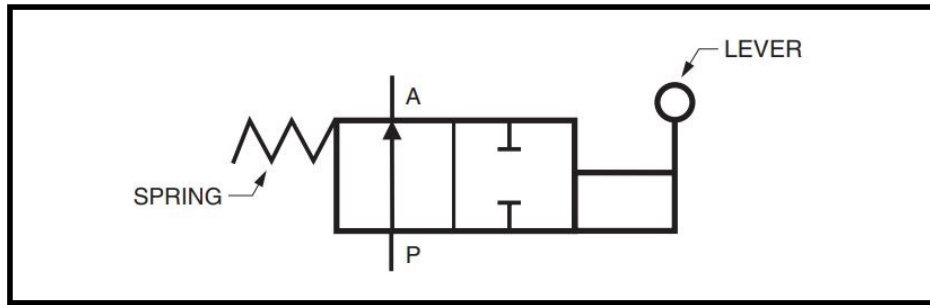


Figure 4.4.4: Schematic diagram depicting a spring symbol and an operator symbol.

To determine the **default (de-energized) position** of the spool, symbols for **operators and springs** are placed beside the flow envelopes:

- A **spring symbol** indicates the **default position when no force is applied**.
- An **operator symbol** (e.g., lever, solenoid) shows the **actuated position** when the valve is energized.

By understanding these elements, technicians can interpret hydraulic schematics effectively, allowing them to **troubleshoot, assemble, and operate hydraulic systems with confidence**.

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CHAPTER OVERVIEW

5: Pumps

[5.1: Flow Rate and Its Measurement](#)

[5.2: Types of Flowmeters and Their Operation](#)

[5.3: Fixed-Displacement Pumps - Operation and Schematic Symbol](#)

[5.4: Types of Fixed-Displacement Pumps and Their Applications](#)

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5.1: Flow Rate and Its Measurement

Understanding Flow Rate

Flow rate refers to the **amount of fluid moving past a specific point within a given time**. It can be measured in terms of either **weight or volume**, but in hydraulics, volume is the most common unit of measurement.

- In the **U.S. customary system**, flow rate is typically measured in **gallons per minute (gpm)**.
- In the **metric system**, the standard unit is **liters per minute (lpm)**.

Methods for Measuring Flow Rate

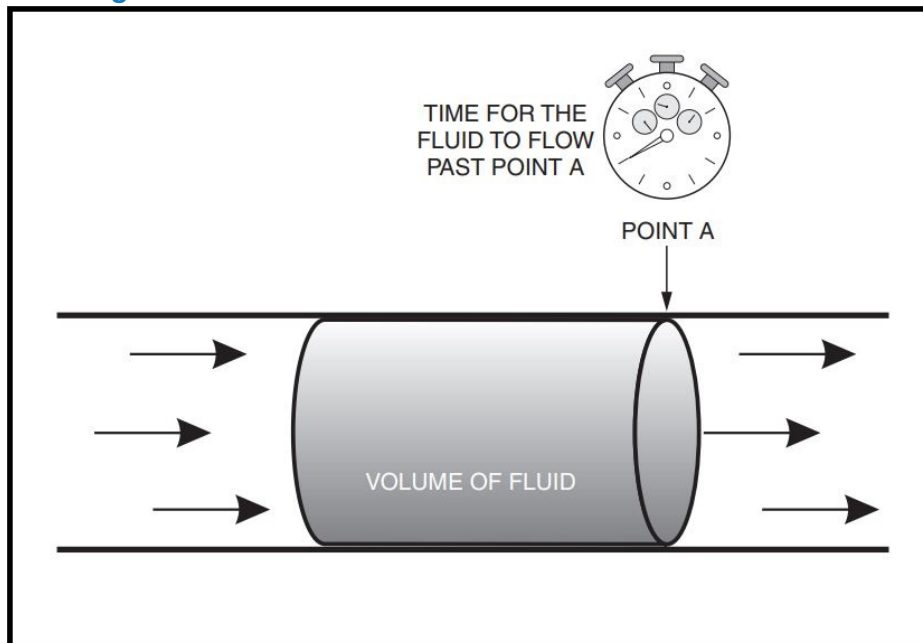


Figure 5.1.1: Flow rate may be determined by timing how long it takes for a volume of fluid to flow past a specified point.

One simple way to determine flow rate is by **timing how long it takes to fill a container of known volume**. For instance, if a pump fills a **5-gallon bucket in one minute**, its flow rate is **5 gpm**. While this method can be **highly accurate**, it is also **messy and time-consuming**.

A more practical approach is to use a **flowmeter**, which provides a direct reading of flow rate. While flowmeters may not always be as precise as the **container-and-stopwatch method**, they offer **convenience and efficiency** for regular system monitoring.

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5.2: Types of Flowmeters and Their Operation

A **flowmeter** is a device designed to measure the **rate at which fluid flows through a hydraulic system**. These instruments are invaluable for **troubleshooting** hydraulic circuits as they can help identify **pump wear, blockages, or flow restrictions**. Flowmeters are also commonly used in **testing and laboratory environments**.

The two most common types of hydraulic flowmeters are:

1. **Rotameter**
2. **Turbine-Type Flowmeter**

Rotameter

A **rotameter** consists of a **transparent tube with a movable piston inside**. Hydraulic oil flows through the tube, lifting the piston to a height that corresponds to the flow rate.

There are two main variations of rotameters:

- A **standard rotameter**, which must be **installed vertically** and is typically **rated for low pressure**, making it suitable only for **return lines**.
- A **spring-loaded rotameter**, where the piston is pushed against a calibrated spring. This design allows the meter to be installed in **any orientation**.

Turbine-Type Flowmeter

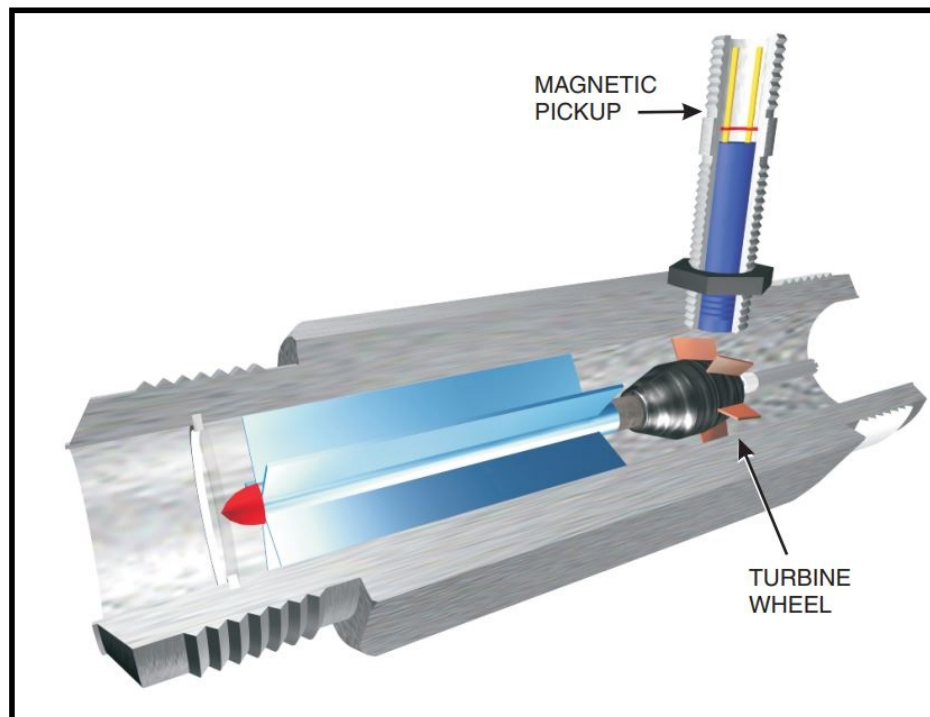


Figure 5.2.1: The inner workings of a turbine-type flowmeter.

A **turbine-type flowmeter** consists of a **bladed wheel that spins as hydraulic fluid flows through it**. The **rotation speed of the wheel is measured electronically**, with a sensor sending pulses as each blade passes. The **pulse frequency is then converted into a flow rate reading**.

This type of flowmeter offers **greater flexibility** than a rotameter:

- It can be **installed in any position**.
- It can operate at both **high and low pressures**.

Schematic Representation of Flowmeters

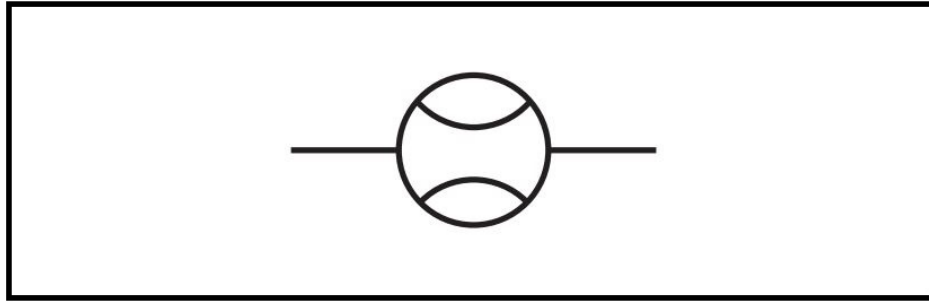


Figure 5.2.2: Schematic symbol of a flowmeter.

All types of flowmeters share a common **schematic symbol**. While the **symbol itself does not indicate flow direction**, most flowmeters are designed to be read in **only one direction**.

By understanding the **different types of flowmeters and their applications**, technicians can accurately **monitor and diagnose** hydraulic systems, ensuring **optimal performance and reliability**.

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5.3: Fixed-Displacement Pumps - Operation and Schematic Symbol

Understanding Hydraulic Pumps

In a hydraulic system, the **pump is responsible for generating fluid flow**. Most industrial hydraulic pumps use a **positive displacement design**, meaning they deliver a consistent volume of fluid with each revolution of the pump shaft. If the pump's shaft is driven at a constant speed by an **electric motor**, the pump provides a nearly **constant flow rate**, regardless of pressure fluctuations in the system.

Fixed vs. Variable Displacement Pumps

Positive displacement pumps fall into two main categories:

1. **Variable displacement pumps** – These pumps can adjust their flow output based on system demand.
2. **Fixed-displacement pumps** – These pumps deliver a **constant flow rate**, meaning the output remains fixed as long as the pump speed does not change.

It is important to understand that a **fixed-displacement pump does not generate pressure—only flow**. System pressure develops **only when there is resistance to flow**. Resistance may come from:

- A **load on an actuator** (such as a hydraulic cylinder or motor).
- **Fluid friction** within the system, caused by narrow passages, bends, or control valves.

How a Fixed-Displacement Pump Works

A typical hydraulic pump consists of a **housing with an inlet and an outlet port**, along with **internal rotating components** connected to a **shaft**. This shaft extends outside the housing and is generally driven by an **electric motor**.

Fluid Flow Process

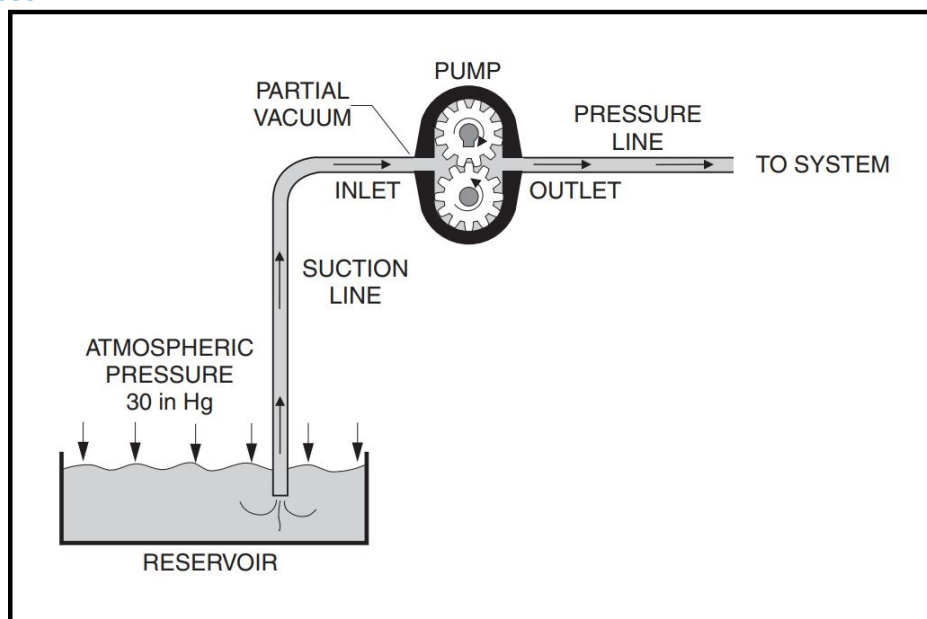


Figure 5.3.1: Diagram of the fluid flow process of a fixed-displacement pump.

1. **Oil is drawn from the reservoir.** As the pump operates, it creates a **partial vacuum** at its inlet by increasing the volume inside the pump. This vacuum allows **atmospheric pressure to push hydraulic oil from the reservoir through the suction line into the pump's inlet port**.
2. **Oil is forced into the pressure line.** The pump then moves the oil through the system by **reducing the volume inside the pump and forcing fluid out through the outlet port**.
3. **System pressure builds only when flow meets resistance** – The pump itself does not create pressure; it simply moves fluid. Pressure forms **only if there is an obstruction or a load preventing free flow**.

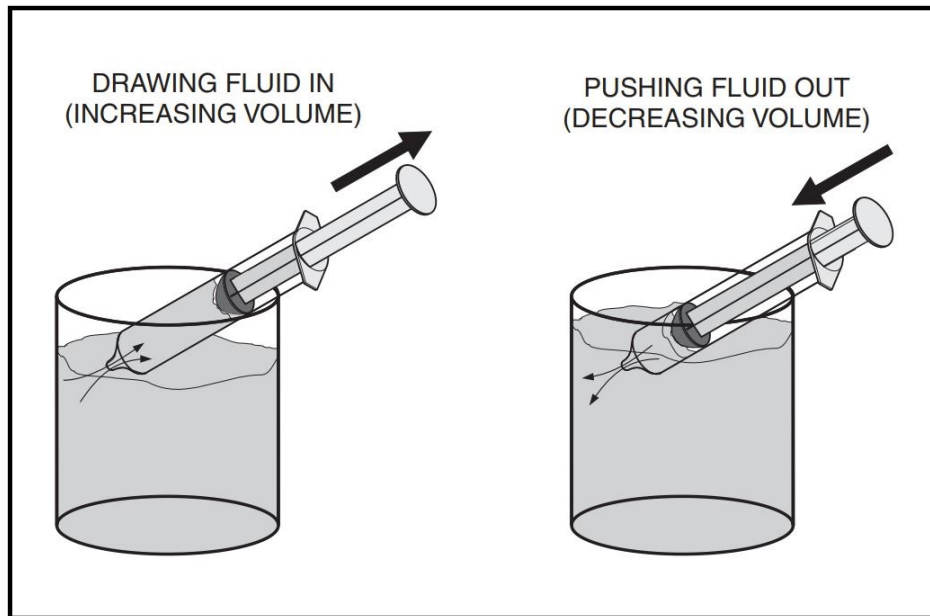


Figure 5.3.2: Fixed-displacement pumps work like a syringe. As the syringe draws fluid in, it increases the volume of fluid in the syringe. As the syringe pushes fluid out, it decreases the volume of fluid in the syringe.

A simple way to visualize this process is by using a **syringe**:

- **Pulling the plunger back** increases the volume inside the syringe, drawing liquid in (like the pump's suction process).
- **Pushing the plunger forward** decreases the volume, forcing the liquid out (similar to the pump's discharge process).

Observing Flow in a Fixed-Displacement Pump

When the pump is running, a **flow meter placed either before or after the pump** will typically show a **steady flow rate** as long as the pump speed remains constant. However, as **system pressure increases due to flow restrictions**, a slight decrease in flow may be observed.

This flow reduction occurs because:

- **Higher pressure reduces pump efficiency.** Some hydraulic fluid may leak internally from the **outlet back to the inlet** due to **clearances inside the pump**.
- **All pumps have inherent inefficiencies.** While fixed-displacement pumps are generally reliable, their performance can decline slightly at higher pressures.

Understanding these principles helps technicians **troubleshoot performance issues** and **optimize hydraulic system efficiency**.

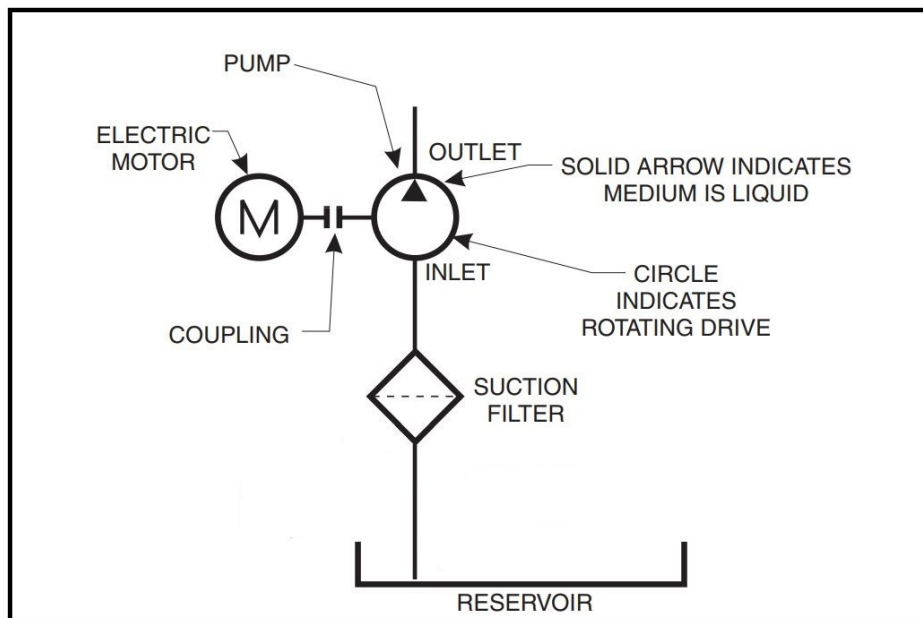


Figure 5.3.3: The schematic symbol for a fixed-displacement hydraulic pump is shown with symbols for a coupling, electric motor, reservoir, and filter.

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5.4: Types of Fixed-Displacement Pumps and Their Applications

Hydraulic systems commonly use **fixed-displacement pumps** to deliver a steady flow of fluid. The three most frequently used types are:

- **Gear pumps**
- **Vane pumps**
- **Piston pumps**

All of these pumps operate on the **positive displacement principle**, meaning they move a set volume of fluid with each rotation of the pump shaft. However, their **internal mechanisms differ**, affecting their performance, efficiency, and application.

Gear Pumps

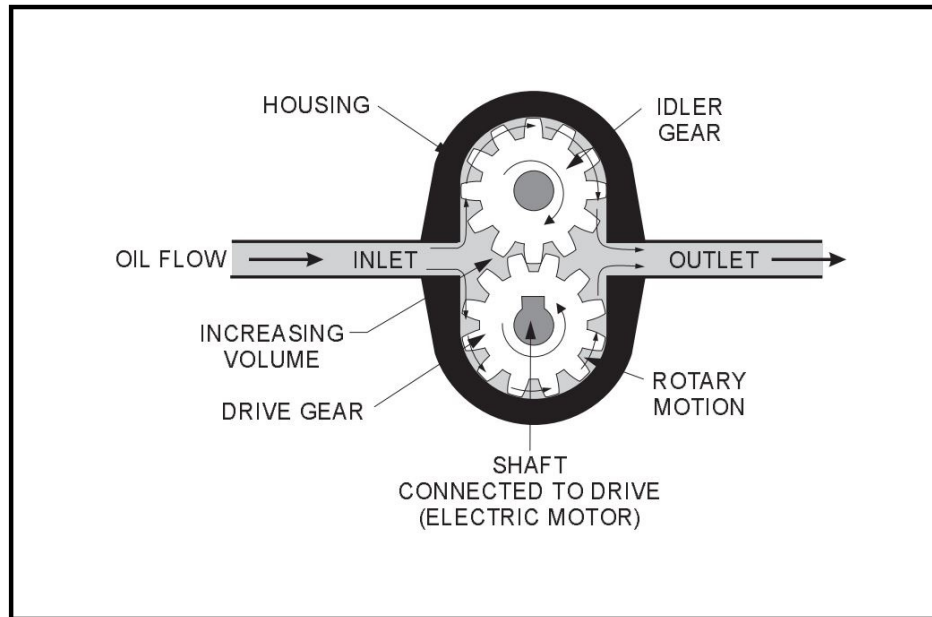


Figure 5.4.1: Diagram of a gear pump.

A **gear pump** consists of two **meshing gears** enclosed within a housing:

- The **drive gear** is connected to the pump shaft and receives power from a motor.
- The **idler gear** rotates in sync with the drive gear.

Operation

1. As the gears rotate **away from each other** at the inlet side, they create an **expanding volume**, generating a **partial vacuum**. This allows atmospheric pressure to push oil from the **reservoir into the pump**.
2. The oil becomes **trapped between the gear teeth and the housing**, then carried to the outlet side.
3. As the gears mesh together again, they **force the oil out** into the system.

Application

Gear pumps are **affordable** and commonly used in **low- to medium-pressure applications**, such as **trash compactors** and **industrial lubrication systems**.

Vane Pumps

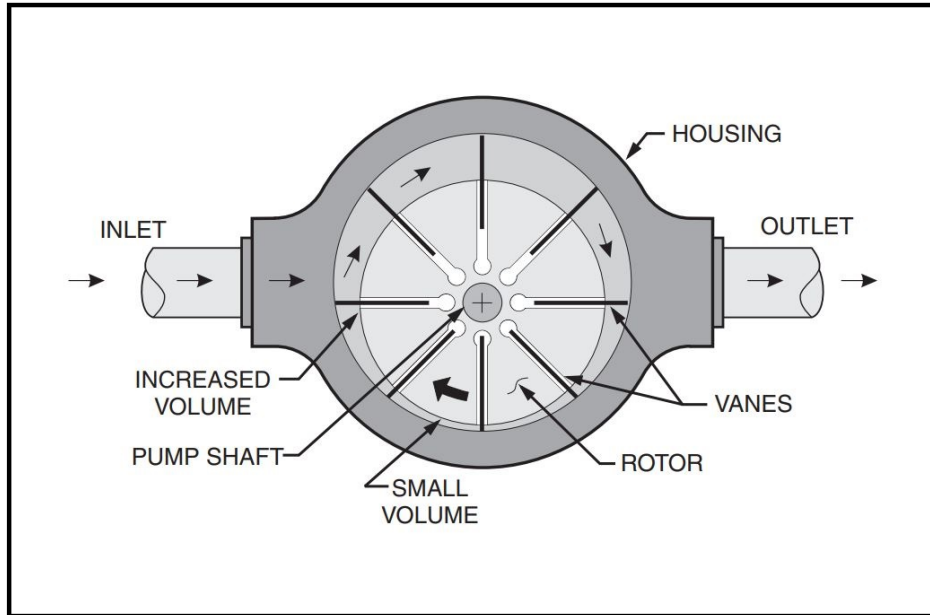


Figure 5.4.2: Diagram of a vane pump.

A **vane pump** consists of a **rotor** with several **sliding vanes** housed inside a **cam ring**.

Operation

1. As the rotor spins, **centrifugal force** pushes the vanes outward against the cam ring.
2. The **off-center rotor position** creates an **expanding volume** at the inlet, generating a **partial vacuum** that draws oil in.
3. The oil is trapped between the vanes and housing and is **carried around** to the outlet.
4. At the outlet, the **decreasing volume** forces the oil out into the system.

Application

Vane pumps are often used where **moderate efficiency** is needed, such as in **plastic injection molding machines** and **hydraulic presses**.

Piston Pumps

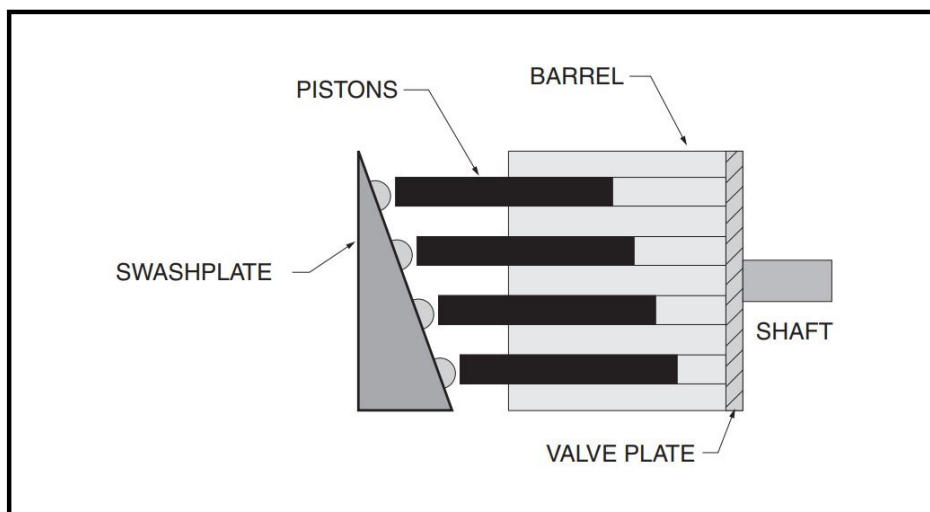


Figure 5.4.3: Diagram of a piston pump.

A **piston pump** uses multiple **reciprocating pistons** arranged inside a rotating **barrel**. The movement of these pistons is controlled by an **angled swashplate**.

Operation

1. As the barrel rotates, the **swashplate angle** causes the pistons to move in and out.
2. On the **inlet stroke**, pistons retract, creating a vacuum that **draws in fluid**.
3. On the **outlet stroke**, the pistons extend, forcing **oil out under pressure**.

Application

Piston pumps are the **most efficient** but also the **most expensive**. They are used in **high-pressure applications**, such as **hydraulic presses, injection molding machines, and heavy machinery**.

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CHAPTER OVERVIEW

6: Needle Valves

[6.1: Needle Valve Function and Application](#)

[6.2: Needle Valve Operation](#)

[6.3: Controlling Actuator Speed Using a Manually-Operated DCV](#)

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6.1: Needle Valve Function and Application

A **needle valve** is a precise **flow control valve** that regulates the speed of an actuator by **controlling the oil flow rate**.

How Needle Valves Work

- The valve contains a **tapered needle-like plunger** that moves into or out of the flow path.
- **Turning the valve handle** adjusts the orifice size, allowing for **fine control of flow restriction**.

Application

Needle valves are typically used to **control cylinder or motor speed** in hydraulic systems, ensuring **smooth and precise motion**.

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6.2: Needle Valve Operation

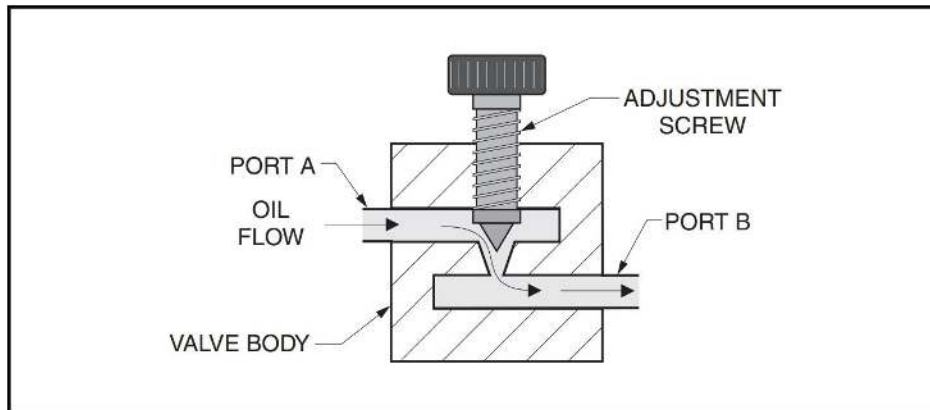


Figure 6.2.1: Diagram showing how a needle valve works.

A **needle valve** is a type of flow control valve designed to **regulate fluid flow** by creating a restriction in the hydraulic line. It consists of two primary components: the **valve body** and an **adjustment screw**.

The **valve body** features two ports connected by a passage through which hydraulic fluid flows. The **adjustment screw**, which has a **tapered end**, moves in and out of this passage to precisely control the size of the opening. By turning the adjustment screw **counterclockwise**, the passage opens wider, allowing more fluid to pass with minimal restriction. Turning it **clockwise** reduces the opening, increasing resistance and slowing the flow rate.

The ability to finely adjust the flow rate makes the needle valve **useful in applications where precise control is necessary**. Unlike on/off valves that simply start or stop flow, the needle valve allows for **gradual changes**, making it ideal for adjusting actuator speeds or controlling flow to delicate components.

To better understand how the needle valve functions, imagine a hydraulic system operating at **maximum pump flow** with the needle valve fully open. In this state, fluid moves freely through the passage with minimal resistance. As the adjustment screw is gradually turned in, the opening begins to narrow, forcing the fluid through a **smaller orifice**. This restriction increases resistance to flow, leading to a **drop in flow rate downstream** while upstream pressure may rise depending on the system's design.

Because of its precise control capabilities, the needle valve is commonly used in **metering applications**, fine speed adjustments for **cylinders and motors**, and other scenarios where steady, controlled flow is essential.

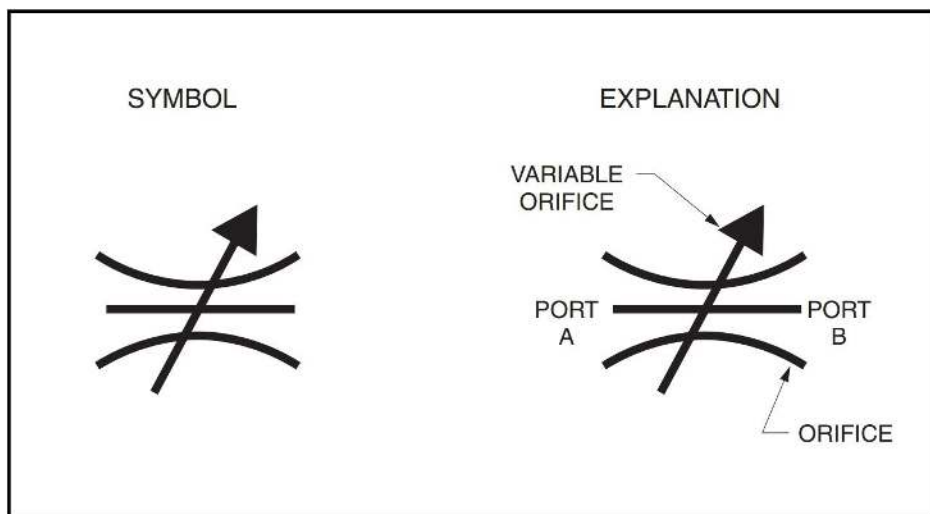


Figure 6.2.2: The schematic symbol for a needle valve is shown. It shows two ports and an orifice. The angled arrow across the flow path indicates that the orifice is variable.

Needle Valve Function and Flow Restriction

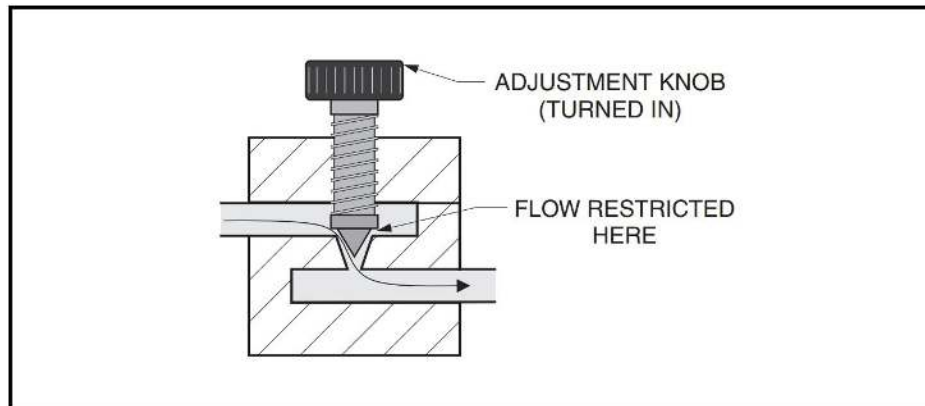


Figure 6.2.3: When the adjustment knob of a needle valve is turned in, the fluid flow is restricted.

Imagine a hydraulic circuit where a fixed displacement pump is providing flow to a needle valve where the needle valve's output is connected to the reservoir. As the needle valve adjustment is gradually turned **clockwise**, the passage through which hydraulic fluid flows becomes increasingly restricted. This narrowing of the opening creates **greater resistance to flow**, forcing the pressure upstream of the valve to rise. A pressure gauge positioned before the valve could reflect this pressure increase, which climbs steadily as the restriction increases.

Despite the rising pressure, the **flow rate would remain nearly constant**. This occurs due to flow from a **positive displacement pump**, which can deliver fluid at a steady rate, even as system resistance increases. However, once the valve is closed enough to cause a significant restriction, the effects on flow rate become more noticeable.

As the needle valve's adjustment knob is turned further, **pressure continues to build ahead of the needle valve**. Eventually, it approaches the pressure setting of the system's **relief valve**. At this point, an important shift occurs where the relief valve begins to open slightly, **allowing some of the fluid flow to bypass the needle valve and return directly to the reservoir through the relief valve**. The moment this happens, the flow rate starts to decline through the needle valve, as the pump's output is now being split between two paths. To allow the needle valve to do its job and restrict flow, the relief valve must have enough pressure to open first when using a fixed displacement pump.

Interestingly, the needle valve **restricts flow in both directions**. If the hydraulic lines are reversed so that the supply line now enters the opposite port, the same principle applies. The flow of oil is still regulated, ensuring that the valve can control actuator speed regardless of flow direction.

The impact of flow restriction on actuator motion becomes even clearer when used with a hydraulic cylinder. For the cylinder to extend, oil must fill the increasing volume inside it. The speed at which this happens is directly determined by the **flow rate of oil entering the actuator**. For instance, if a fully extended cylinder requires **two gallons of oil** and the flow rate is set to **one gallon per minute**, the extension will take **two minutes** to complete. If the flow rate is increased, the actuator moves faster; if restricted, it moves slower. This would be independent of the load of the cylinder as long as the force created by the cylinder is marginally larger than the load itself.

By adjusting the needle valve, it is possible to precisely control actuator speed. Turning the valve **clockwise** reduces flow and slows the cylinder's movement, while turning it **counterclockwise** increases flow and allows the actuator to extend more quickly.

This fundamental principle of **flow control** is essential in hydraulic systems, ensuring smooth, predictable operation in applications where precise movement is required.

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6.3: Controlling Actuator Speed Using a Manually-Operated DCV

In many hydraulic applications, controlling the speed of an actuator is essential for smooth and precise operation. One way to achieve this is by **partially shifting the spool of a manually-operated directional control valve (DCV)**. By carefully adjusting the DCV's lever, the operator can restrict fluid flow in a manner similar to a needle valve. This technique, commonly referred to as **feathering the valve**, is frequently used in mobile hydraulic equipment such as tractors, backhoes, and excavators.

When the DCV lever is gently pushed slightly off-center, the spool does not fully open the flow path. Instead, it **creates a partial restriction**, reducing the rate at which hydraulic fluid reaches the actuator. As a result, the cylinder extends more slowly than it would with the valve fully open. However, precise control can be challenging if the DCV spool lacks tapered edges, as this design influences how smoothly the restriction is applied.

Similarly, when the lever is moved in the opposite direction, the same principle applies to the retraction speed of the actuator. By carefully adjusting the position of the DCV spool, the operator can regulate the rate at which the cylinder retracts, allowing for gradual and controlled motion. This method is particularly useful in applications where fine speed adjustments are needed without the use of a separate flow control valve.

Generally, in hydraulic systems, **purpose-built DCVs** will feature long, tapered spools that are specifically designed for smooth flow regulation. This design allows operators to vary flow rates effortlessly, enabling precise control of equipment movements. The ability to manually adjust actuator speed in real-time enhances both efficiency and safety in hydraulic systems.

When the system is no longer in use, it is standard practice to ensure that **hydraulic pressure is relieved** by returning the DCV to its neutral position and moving the handle back and forth. This action helps discharge any residual pressure in the circuit, preventing unintended movement when the system is powered down or in a critical step of lockout/tagout before maintenance.

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CHAPTER OVERVIEW

7: Basic Motor Circuits

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[7.2: Operation of a Hydraulic Motor](#)

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7.1: Hydraulic Motors - Function and Applications

A **hydraulic motor** is an actuator that **converts hydraulic energy into rotary mechanical power**. These motors are used in applications where continuous rotary motion and high torque output are required.

Interestingly, hydraulic motors share a similar construction with hydraulic pumps. In fact, many motor designs are simply modified pump designs. However, unlike pumps, which move fluid to generate pressure, motors use incoming pressurized fluid to create **mechanical rotation**.

Common Applications of Hydraulic Motors

Hydraulic motors are widely used in industrial and mobile applications where **high torque, durability, and fluid compatibility** are essential. Some examples include:

- **Winches and Hoists** – Hydraulic motors power **winches on ships and heavy-lifting equipment** due to their ability to generate high torque at slow speeds.
- **Construction Equipment** – Motors are used in **excavators, drilling rigs, and concrete mixers**, where electric motors might not be feasible.
- **Food Processing Conveyors** – In **food processing plants**, equipment must be regularly washed down, and electric motors would pose a **shock hazard** in wet environments. Hydraulic motors provide a **safe and efficient alternative**.

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7.2: Operation of a Hydraulic Motor

A **hydraulic motor** functions as the inverse of a hydraulic pump. While a pump creates fluid flow by rotating its shaft, a motor **uses hydraulic flow to drive its shaft** and produce mechanical motion. These motors operate on the principle of **positive displacement**, meaning that as the flow rate increases, the motor's rotational speed also increases proportionally.

A mechanical device (or **load**) can be **powered by the mechanical energy that the motor provides**. The **more power that is needed to turn the motor's mechanical output** due to high load, **the greater the resistance that occurs** to the fluid flow through the motor. This **can cause pressure build-up** that can occur **before the motor** until the relief valve within the system opens due to this pressure increase. The **higher the pressure** that can be built up before the motor, **the more power or torque can be created** from the output shaft of the motor, allowing the motor to push more load if needed.

One of the key characteristics of hydraulic motors is their ability to rotate in **either direction**, depending on the design. **Bi-directional motors** are the most common in industrial applications, allowing flexible operation by simply reversing fluid flow. However, in some cost-sensitive applications, **uni-directional motors**, which rotate in only one direction, are used.

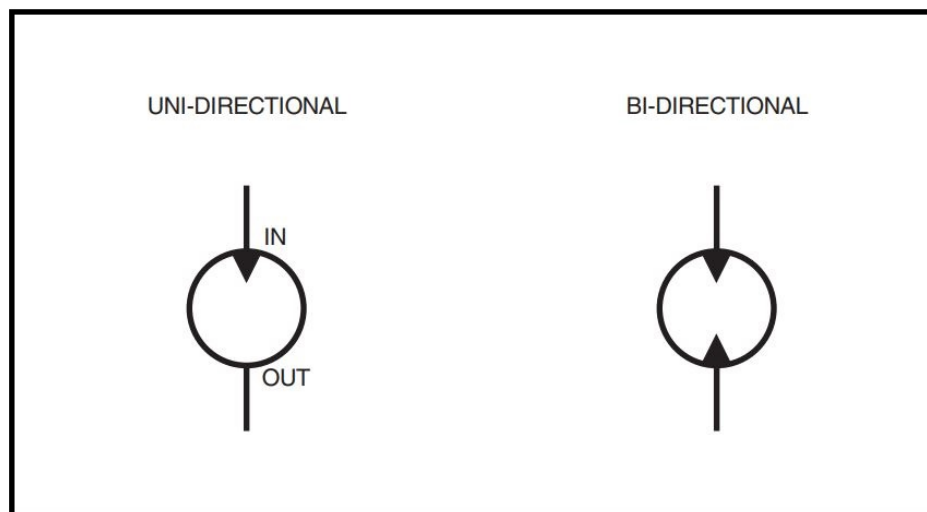


Figure 7.2.1: Uni-directional and bi-directional symbols

The schematic symbols for uni-directional and bi-directional motors are shown. They use solid arrows pointing inward which represents flow into the motor. This is the basic difference to how pump and motor symbols are drawn.

Motor Behavior During Reversals

When a hydraulic motor is running, the **direction of rotation can be reversed almost instantly** by shifting a directional control valve (DCV). If the flow rate is relatively low, say about **0.75 gallons per minute (gpm)**, transition from one direction to another occurs smoothly, causing only a moderate spike in system pressure from the inertia of the load. However, as flow rates increase, the system experiences a **higher pressure surge** when reversing direction.

At **higher speeds**, the sudden reversal places greater strain on the system, resulting in a **notable peak pressure increase**. This happens because the inertia of the rotating components resists the immediate change in direction, momentarily causing pressure to spike before stabilizing. Despite this, well-designed hydraulic motors handle rapid reversals efficiently, maintaining **smooth and controlled operation**.

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7.3: Hydraulic Motors - Types and Applications

Just as hydraulic pumps generate fluid flow, **hydraulic motors** convert that flow into **mechanical motion**, producing rotary force or torque. These motors operate using the principles of fluid power, where pressurized hydraulic fluid applies force to internal components, generating rotation.

There are three primary types of hydraulic motors, categorized by their internal design:

- **Gear Motors**
- **Vane Motors**
- **Piston Motors**

Each type has distinct characteristics that make it suitable for specific applications.

Gear Motors

Gear motors come in two variations: **standard gear motors** and **gerotor motors**.

- A **standard gear motor** consists of two meshing spur gears housed within a casing. As pressurized fluid enters the housing, it forces the gears to rotate, creating mechanical motion. Because of their similarity in design to gear pumps, some gear motors can be used interchangeably as pumps in certain systems.
- A **gerotor motor** functions using an internal gear that rotates inside a surrounding ring gear, somewhat resembling a planetary gear system. While these motors are generally **less efficient than other types**, they offer **high durability and cost-effectiveness**, making them well-suited for **light-duty mobile applications** such as **agricultural equipment, mining machinery, and construction vehicles**.

Vane Motors

Vane motors operate similarly to vane pumps, with one key difference: their vanes must be **spring-loaded** to ensure full extension even when the motor is stopped. In contrast, vane pumps rely on **centrifugal force** to extend their vanes as the shaft rotates.

Vane motors offer a **balanced performance** in terms of **efficiency, cost, and durability**. They **outperform gear motors** in efficiency due to reduced internal leakage but do not reach the high precision of piston motors. Their **moderate pricing and reliable performance** make them ideal for **industrial applications**, including **conveyors, winches, and machine tools**, where efficiency is important but extreme precision is not required.

Piston Motors

Piston motors are the **highest-performing** type of hydraulic motor and are available in three designs:

- **In-line piston motors** – The most commonly used type, featuring pistons arranged parallel to the drive shaft.
- **Bent-axis piston motors** – Similar in function to in-line models but with pistons set at an angle to improve efficiency and torque output.
- **Radial piston motors** – Featuring pistons arranged radially around the drive shaft, these motors are used in **high-torque, low-speed applications** such as heavy-duty industrial and marine equipment.

Piston motors are known for their **high efficiency, precise speed control, and ability to handle both low-speed, high-torque, and high-speed, low-torque conditions**. Their **low internal friction and tight tolerances** result in superior energy efficiency, making them the preferred choice for **high-performance applications** like **hydraulic presses, injection molding machines, and large-scale construction equipment**.

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CHAPTER OVERVIEW

8: Hydraulic Schematics

[8.1: Rules for Drawing Hydraulic Schematics](#)

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8.1: Rules for Drawing Hydraulic Schematics

Understanding hydraulic schematics is essential for designing, troubleshooting, and maintaining hydraulic systems. To ensure clarity and consistency, **eight fundamental rules** should be followed when creating schematic diagrams:

1. **Symbol Orientation** – Most hydraulic symbols can be **rotated or reversed** without changing their meaning. However, **vented reservoirs and accumulators** must always be depicted in the **upright position**.

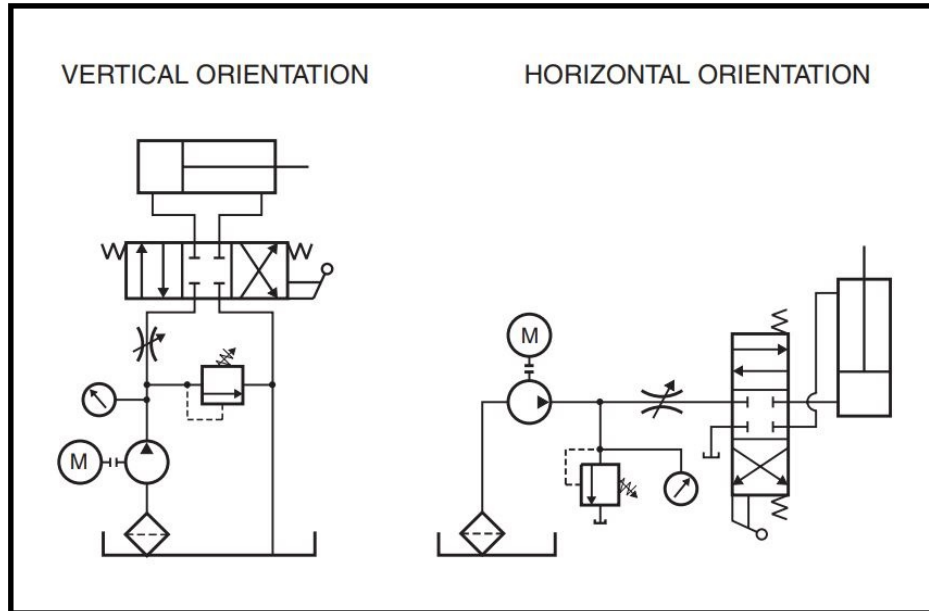


Figure 8.1.1: Hydraulic symbol schematics may be viewed in a vertical or horizontal orientation.

2. **Reservoir Representation** – The **vented reservoir symbol** can be **repeated multiple times** within a schematic without indicating multiple reservoirs. This improves **readability**, showing where lines return to the tank without unnecessary connections.

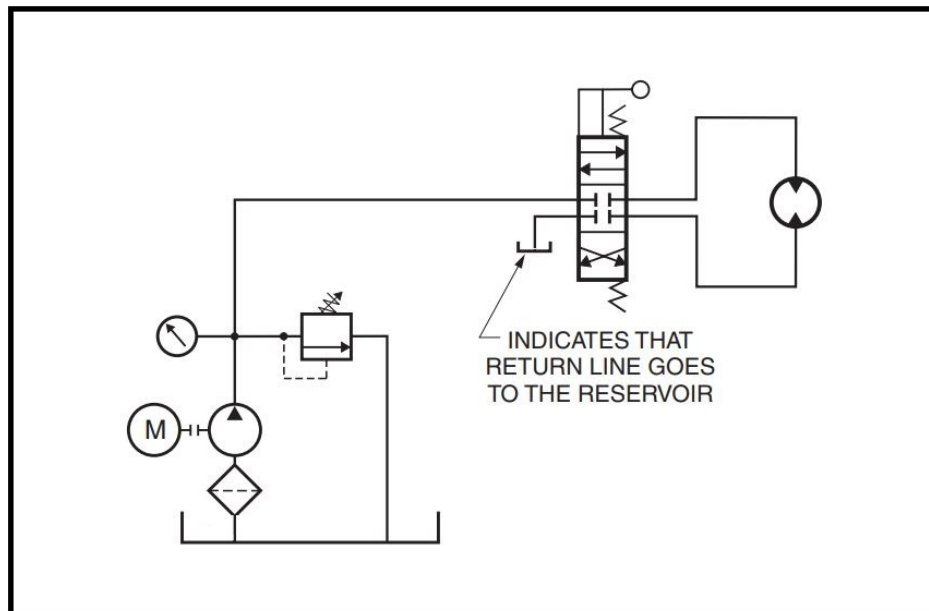


Figure 8.1.2: Hydraulic schematic diagram showing the vented reservoir symbol.

3. **Line Alignment** – Lines (conductors) should be drawn **horizontally or vertically**. Diagonal lines should be avoided for **clarity and standardization**.

4. **Line Representation** – Schematics must distinguish between **connected lines**, **crossing lines**, and **blocked lines** to ensure clear circuit interpretation.

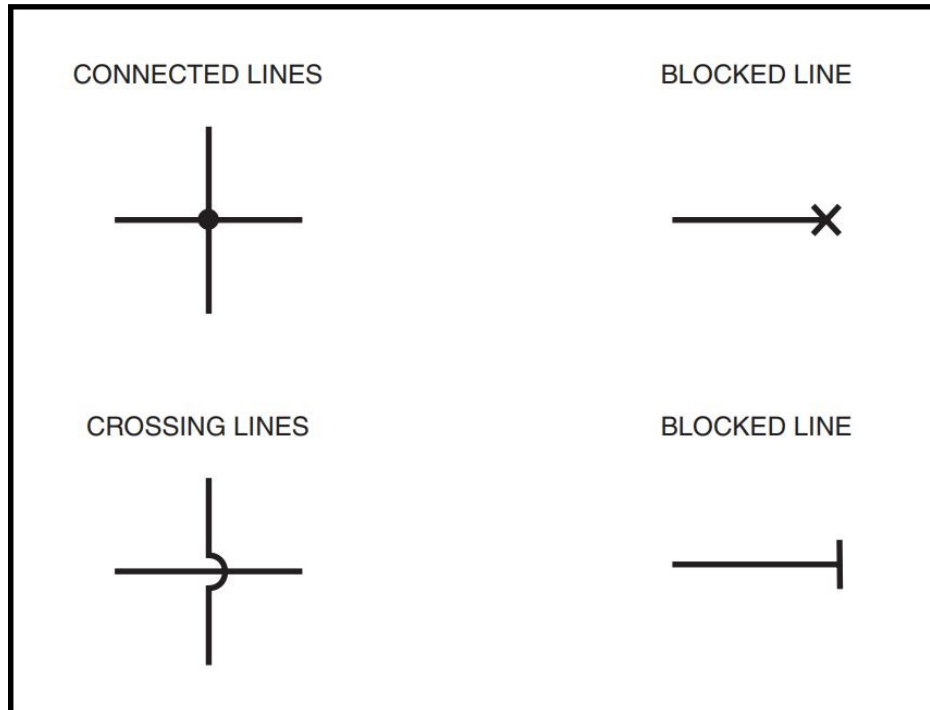


Figure 8.1.3: Schematic symbols for connected lines, crossing lines, and blocked lines.

5. **Symbol Functionality** – Schematic symbols represent function, flow paths, and connections only. They do not indicate:

- Physical construction
- Size or dimensions
- Port locations
- Flow rates or pressure values

6. **Default Component Position** – Symbols should be drawn to represent the **normal (at rest), de-energized, or neutral** position of each component unless showing different operational phases.

7. **Use of Letters in Symbols** – While letters are generally unnecessary in schematics, two exceptions apply:

- "M" inside a circle indicates an **electric drive motor**.
- "I" inside a flowmeter symbol designates a **totalizing flowmeter**.

8. **Flow Direction Arrows** – A **solid arrow or triangle** is used to indicate the **direction of fluid flow from the pump through the circuit**. This arrow can also be used **alone to represent a power unit**.

By following these standardized rules, hydraulic schematics remain **clear, interpretable, and universally understood** in design and maintenance settings.

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CHAPTER OVERVIEW

9: Pressure and Cylinder Force

[9.1: How to Calculate the Force Output of an Hydraulic Cylinder in Extention \(Pushing\)](#)

[9.2: How to Calculate the Force Output of an Hydraulic Cylinder in Retraction \(Pulling\)](#)

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9.1: How to Calculate the Force Output of an Hydraulic Cylinder in Extention (Pushing)

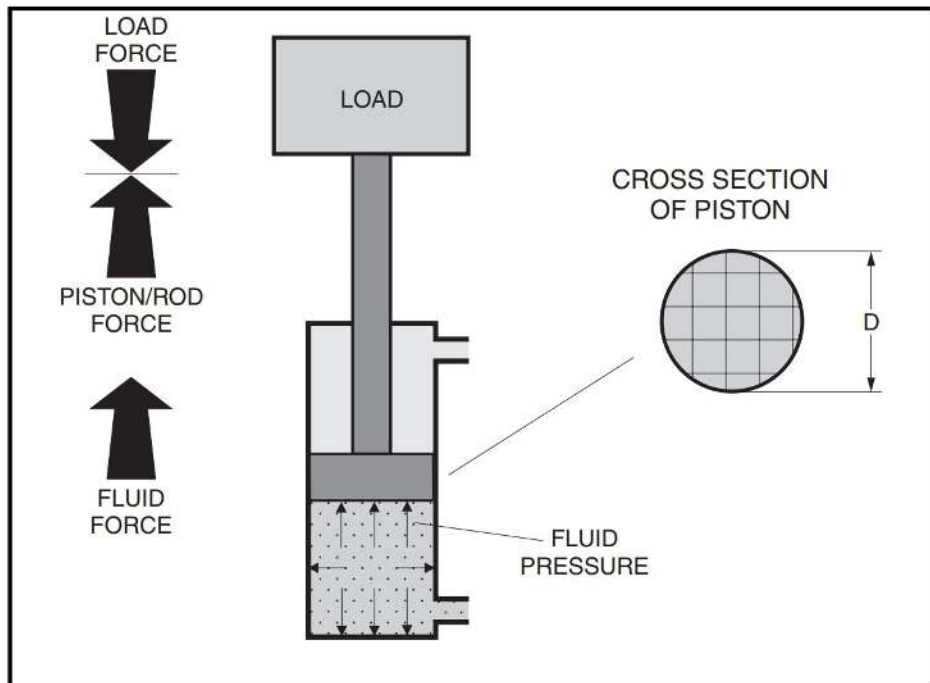


Figure 9.1.1: Diagram of a hydraulic cylinder in extension.

The output force of a hydraulic cylinder depends on two factors:

1. The **pressure** supplied by the hydraulic system
2. The **area** over which that pressure is applied

When a cylinder is extending, fluid pressure acts across the full **piston area** on the cap end of the cylinder. The force produced is the product of pressure and this piston area.

To calculate theoretical force output:

$$\text{Force (lbs)} = \text{Pressure (psi)} \times \text{Piston Area (in}^2\text{)}$$

Where the piston area is calculated by:

$$A = 0.7854 \times D^2$$

This formula assumes no losses due to friction or leakage. In practice, the actual force may be slightly lower due to these factors, but this gives a reliable baseline for sizing components and understanding system capabilities.

✓ Example: Calculating the Extension Force of a Cylinder Given its Size and Pressure

To determine the force output of a hydraulic cylinder when it's extending, use the following formula:

$$P \times A = F$$

Where:

- F = Force in pounds (lbs)
- P = Pressure in pounds per square inch (psi)
- A = Area of the piston in square inches (in²)

Since hydraulic cylinders use round pistons, we calculate piston area using the formula for the area of a circle:

$$A = 0.7854 \times D^2$$

Where D is the bore diameter of the cylinder.

Example Calculation

Let's say the cylinder has a **bore diameter of 2.0 inches** and is subjected to **1000 psi** of hydraulic pressure.

$$A = 0.7854 \times D^2$$

$$A = 0.7854 \times (2.0)^2$$

$$A = 0.7854 \times 4 = 3.1416 \text{ in.}^2$$

$$F = P \times A$$

$$F = 1000 \times 3.1416 = 3,142 \text{ lbs}$$

Result:

The cylinder can theoretically exert **3,142 pounds of force** while extending at 1000 psi.

? Additional Practice Problem

Determine the minimum pressure required to lift a known load given:

- Load to lift = 5,000 lbs
- Cylinder Bore = 3.0 in
- Rod Diameter = 1.0 in

We're lifting, so this is an extension force problem. First, calculate piston area:

$$A = 0.7854 \times (3.0)^2 = 0.7854 \times 9 = 7.069 \text{ in}^2$$

Now solve for pressure:

$$P = F / A = 5000 / 7.069 \approx 707 \text{ psi}$$

Answer

A pressure of approximately **707 psi** is required to lift a 5,000 lb load using a 3-inch bore cylinder.

A **big lesson** to learn here is that **larger bore cylinders** reduce the pressure **required** to move a load.

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9.2: How to Calculate the Force Output of an Hydraulic Cylinder in Retraction (Pulling)

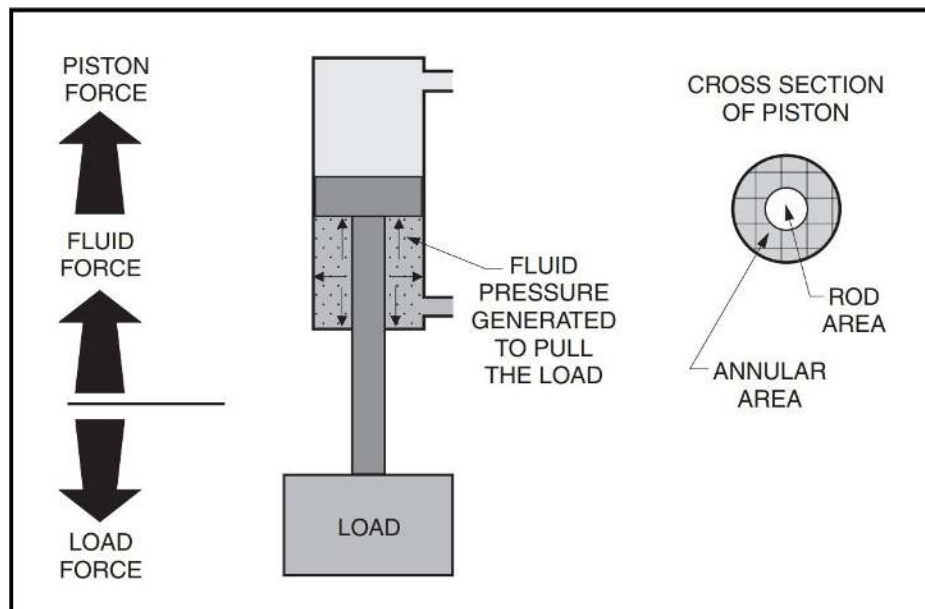


Figure 9.2.1: Diagram of a hydraulic cylinder in retraction.

When a cylinder is retracting, the piston rod takes up some of the area inside the bore. This means that the effective surface area the fluid can push against is reduced. This **annular area** (sometimes called the "ring area") is what we use to calculate retraction force.

To find the retraction force, we use:

$$F = P \times A_{\text{annular}} = P \times (A_{\text{piston}} - A_{\text{rod}})$$

Or, combining both into a single formula:

$$F = P \times 0.7854 \times (D^2 - d^2)$$

Where:

- D = piston (bore) diameter
- d = rod diameter

✓ Example: Calculating the Retraction Force of a Cylinder Given its Size and Pressure

Let's use the same cylinder from the previous example, but now account for a **1.0-inch diameter rod** and the same **1000 psi** system pressure.

$$\begin{aligned} A_{\text{annular}} &= 0.7854 \times (2.0^2 - 1.0^2) \\ &= 0.7854 \times (4 - 1) = 0.7854 \times 3 \\ &= 2.356 \text{ in}^2 \end{aligned}$$

$$F = 1000 \times 2.356 = 2,356 \text{ lbs}$$

Result

The retracting force of this cylinder is **2,356 lbs**, which is less than the extending force (3,142 lbs) because of the reduced surface area.

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CHAPTER OVERVIEW

10: Pascal's Law and Force Multiplication

[10.1: Pascal's Law and Its Significance in Hydraulics](#)

[10.2: How Force Is Multiplied Using Pascal's Law](#)

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10.1: Pascal's Law and Its Significance in Hydraulics

In earlier sections, we discussed how hydraulic actuators convert fluid pressure into mechanical force to perform useful work. The fundamental principle behind this capability is **Pascal's Law**, discovered in the 17th century by French mathematician and physicist **Blaise Pascal**.

Pascal's Law (Stated)

Pressure applied to a confined fluid is transmitted undiminished in all directions and acts with equal force on equal areas and at perpendicularly to the surface.

Let's break this down:

- **Confined fluid** means the fluid is trapped—it cannot escape or move freely because it's completely enclosed.
- **Undiminished** means the pressure doesn't weaken or reduce as it moves through the fluid.
- The pressure acts **equally** in all directions and **perpendicularly** (at right angles) to the walls of the container.

Visualizing Pascal's Law

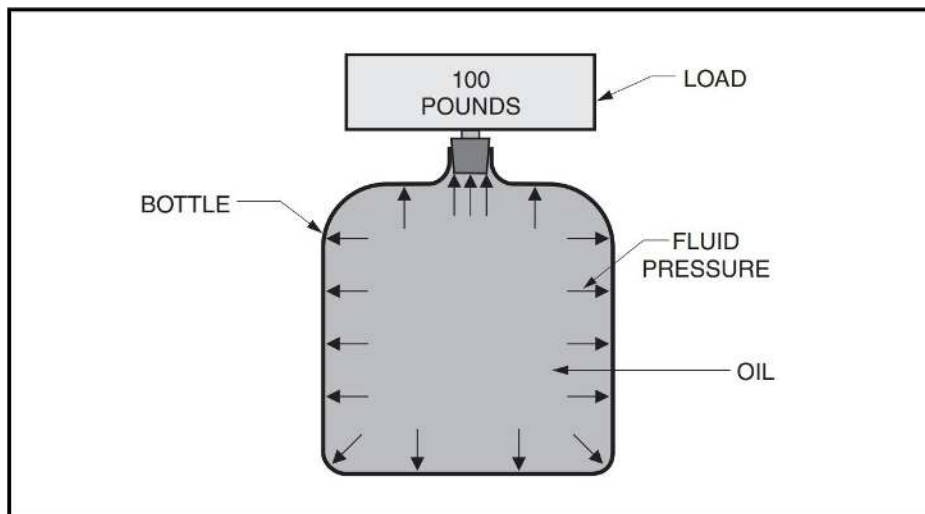


Figure 10.1.1: Diagram of Pascal's Law in action. As the load (the stopper) presses into a sealed bottle of fluid, the fluid pressure spreads evenly outward against the walls of the bottle and the stopper.

Imagine pressing down on a stopper inside a sealed bottle full of fluid. The force you apply compresses the fluid inside. Since the fluid cannot escape, the pressure spreads evenly throughout the entire fluid volume, pushing outward against the walls of the bottle and back up on the stopper. That same pressure exists everywhere inside the bottle and acts in all directions.

Why This Is Important in Hydraulics

Pascal's Law is the foundation for **hydraulic leverage**—a principle that allows us to use a small input force to create a much larger output force. This makes it possible to move heavy loads using relatively compact equipment. You'll learn more about force multiplication in the next section.

Another important result of Pascal's Law is that **hydraulic actuators produce full force immediately upon movement**. Since pressure is constant throughout the confined system, the moment a valve opens that feeds an actuator, full pressure is available at the cylinder or motor. This gives hydraulics a major advantage over other systems like electric motors, which may struggle under high starting loads or may stall if overloaded.

Hydraulics also has the unique ability to be **stalled at full pressure indefinitely** without damaging system components. This is particularly useful in applications where loads must be held stationary under heavy force, like lifting arms, presses, or jacks.

Pascal's Law influences pressure gauge placement in a circuit. Since pressure is the same throughout the confined fluid, a gauge placed anywhere in the pressure line will read the same value, assuming the line is not obstructed and the fluid is not flowing

through a pressure-reducing device.

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10.2: How Force Is Multiplied Using Pascal's Law

One of the most powerful and useful aspects of hydraulics is its ability to **multiply force**, allowing a small input force to generate a much larger output force. This is known as **hydraulic leverage** or **force multiplication**, and it works thanks to Pascal's Law.

How It Works

Let's look at a simple example:

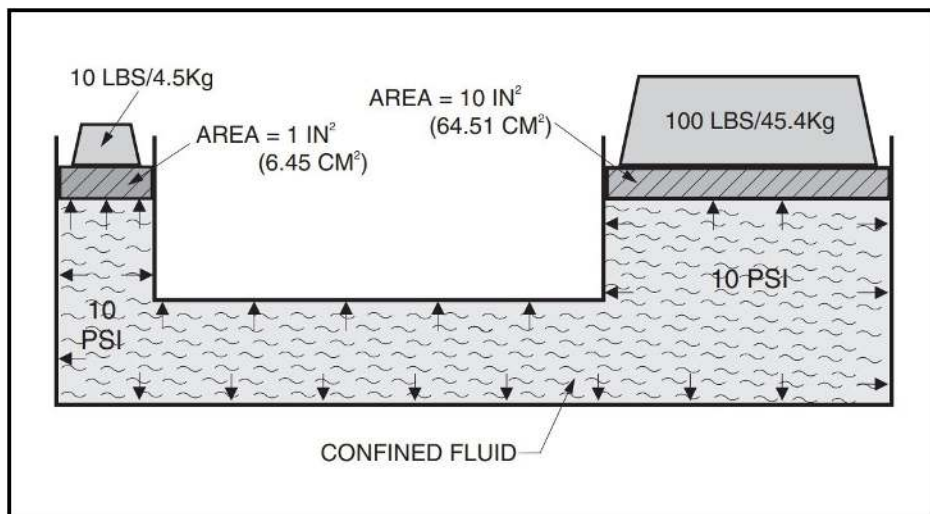


Figure 10.2.1: Diagram showing how Pascal's Law affects hydraulic leverage.

✓ Pascal's Law Example

Suppose you apply **10 pounds of force** on a small piston with a surface area of **1 in²**. This creates **10 psi** of pressure in the fluid.

$$P = F \times A = 10 \text{ lbs} \times 1 \text{ in}^2 = 10 \text{ psi}$$

Now, imagine this pressure is transmitted through the fluid to a larger piston with a surface area of **10 in²**. According to Pascal's Law, the pressure is the same, 10 psi, everywhere in the system.

So on the large piston:

$$F = P \times A$$

$$= 10 \text{ psi} \times 10 \text{ in}^2 = 100 \text{ lbsF}$$

Result

Your small 10-pound input force on the small piston has resulted in a 100-pound output force at the large piston.

Real-World Example: The Brake System

Automotive brake systems provide a practical application of hydraulic leverage. When you press the brake pedal, a small master cylinder sends pressurized fluid through the brake lines to larger slave cylinders at the wheels. This small input force from your foot can be multiplied to generate enough force to stop a moving vehicle.

Industrial Applications

In industrial hydraulic systems, we usually don't use pistons to push fluid. Instead, a **hydraulic pump** (driven by an electric motor) generates flow. The pressure produced by this flow acts on a cylinder's large piston area to create a powerful output force.

This means that **even a small motor can produce a large mechanical output** when paired with the right hydraulic components — another example of force multiplication in action.

The Tradeoff: Speed vs. Force

Force multiplication comes at a cost: **distance (or speed)**.

In the earlier example, while we increased the force from 10 to 100 pounds, the **displacement of fluid** must also be considered. To move the large piston **1 inch**, the small piston must be pushed **10 inches**, assuming incompressible fluid and perfect efficiency.

This is an important concept:

As the output force increases, the distance moved by the piston on the output side decreases. The same occurs with speed as the volume is larger to fill.

In practical terms, a **larger cylinder area** will provide more force, but it will also require more fluid volume to move, making the cylinder slower if the pump flow rate remains the same.

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CHAPTER OVERVIEW

11: Fluid Friction

[11.1: Two Types of Resistance in a Hydraulic System](#)

[11.2: How Delta P Describes Hydraulic Resistance](#)

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11.1: Two Types of Resistance in a Hydraulic System

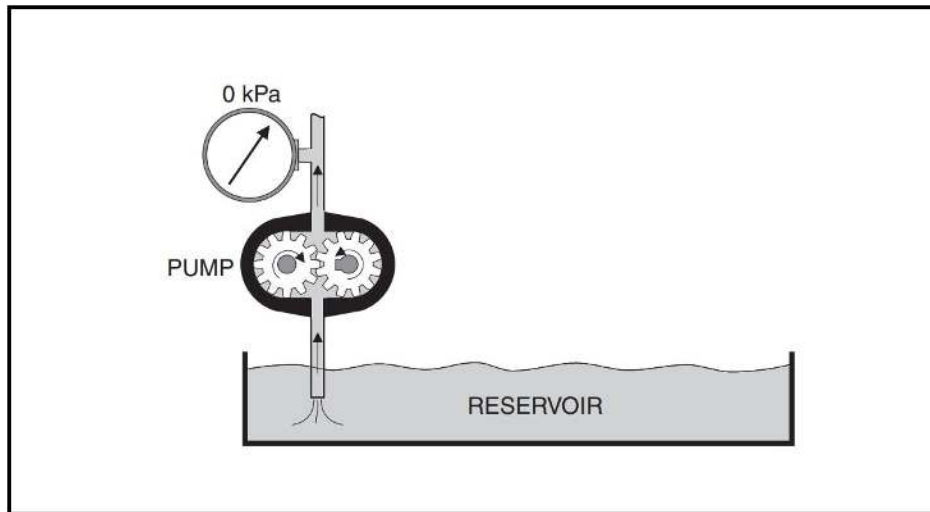


Figure 11.1.1: When there is no resistance in a hydraulic system, there is no fluid pressure, just flow.

In hydraulic systems, there's often a misconception that pumps create pressure. That's not quite true. **Pumps create flow**, and **pressure is the result of resistance to that flow**. If a hydraulic system had no resistance—say, if it were pumping fluid into an open tank—then there would be no pressure at all, just flow.

In the real world, however, resistance is always present. This resistance is what creates the system pressure, and it comes from two main sources:

- **Frictional resistance from the fluid and system components**
- **Resistance from the load being moved**

Let's take a closer look at each one.

Fluid Friction (Frictional Resistance)

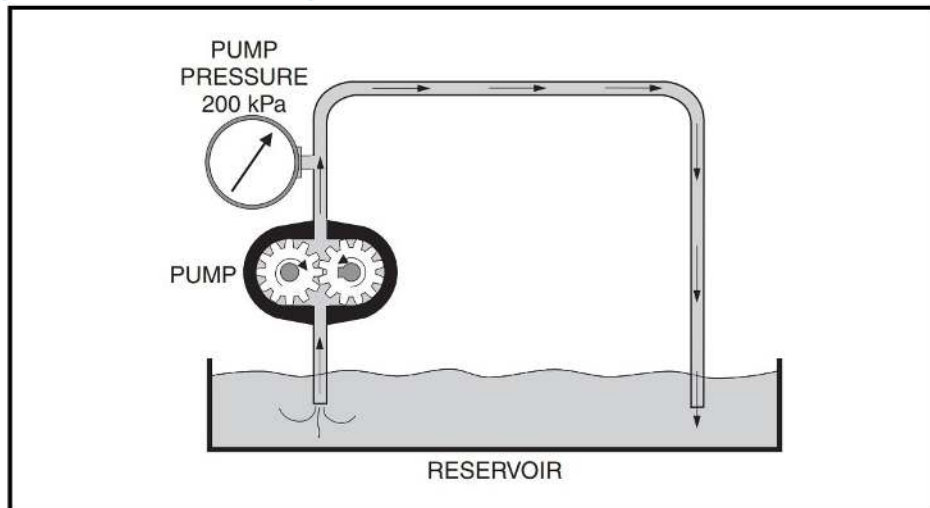


Figure 11.1.2: Frictional resistance causes a pressure increase upstream. The system must generate more pressure to keep fluid moving past that resistance.

As hydraulic fluid travels through pipes, valves, fittings, and other components, it encounters internal surfaces that slow it down. Even the smoothest components still create **some** friction. This is referred to as **fluid friction**, and it shows up as a pressure drop across each part of the circuit.

Key Factors Affecting Frictional Resistance

- **Component size and design** – Narrow passages, sharp turns, or rough internal surfaces increase resistance.
- **Fluid viscosity** – Thicker fluids (higher viscosity) have a harder time flowing and generate more resistance.
- **Flow rate** – Higher flow means more friction due to increased turbulence in the fluid.

Each of these factors causes a **pressure increase upstream** of the component. The system must generate more pressure to overcome this resistance and keep the fluid moving.

While some friction is unavoidable, **excessive friction wastes energy**, turning it into heat. That heat buildup can reduce system efficiency and shorten component life. That's why designers aim to **minimize friction by properly sizing system components**. For example, using larger-diameter hoses and fittings reduces resistance, just like using a wider straw makes it easier to drink a thick milkshake.

Load Resistance

The second major source of resistance is the **load** being acted upon by the actuator, usually a hydraulic cylinder or motor. When a cylinder pushes or lifts a load, the pressure needed to do that work depends on the force required and the piston area.

Pressure (P) = Area (A) x Force (F)

For example, to lift a load that requires 7000 psi with a known piston area, the system must generate at least that amount of pressure. However, this load pressure doesn't exist in isolation. You still have to add the **pressure drop from fluid friction**.

Let's look at a quick breakdown of total system pressure:

- Load pressure: 7000 psi
- Frictional pressure: 60 psi
- **Total pressure at the pump = 7060 psi**

The 60 psi of friction might come from several points in the system. For example:

- $(7060 - 7020) = 40$ psi drop due to one part (maybe a DCV)
- $(7020 - 7000) = 20$ psi drop across another (possibly a pressure regulating device and the hoses of the system)
- Combined: $40 + 20 = 60$ psi total frictional resistance

This shows how **system pressure is the sum of both the load and all frictional losses** throughout the system.

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11.2: How Delta P Describes Hydraulic Resistance

In fluid power, we use the term **ΔP (Delta P)** to describe the pressure drop across a hydraulic component or section of the system. It simply means "**change in pressure**", and it's a very useful tool for analyzing system performance.

ΔP (Delta P) = Pressure inlet – Pressure outlet

For example, suppose we place pressure gauges ahead and behind a needle valve:

- Pressure at Gauge A (upstream): 540 psi
- Pressure at Gauge B (just before the valve): 520 psi

$$\Delta P = 540 - 520 = 20 \text{ psi}$$

This **20 psi** is the resistance caused by drag within the fluid lines.

Now let's measure again across the needle valve:

- Gauge B (inlet to the valve): 520 psi
- Gauge C (outlet of the valve): 20 psi

$$\Delta P = 520 - 20 = 500 \text{ psi}$$

This **500 kPa** is the resistance caused by the needle valve.

What Causes Delta P?

- **Frictional Resistance** – Any component (valve, fitting, hose) has internal surfaces that restrict flow.
- **Load Resistance** – Actuators like cylinders and motors also create ΔP based on the force needed to move the load.

Why Delta P Matters

Delta P gives you a **localized view** of pressure loss across each component. This is critical when:

1. **Designing a system** – You need to ensure components can handle the expected flow and pressure drops without overheating or stalling.
2. **Sizing components** – Manufacturers provide performance curves showing how ΔP varies with flow rate. You use these to select the right valves, hoses, and filters.
3. **Troubleshooting** – A higher-than-normal ΔP can signal a clogged or failing component. If a filter's inlet pressure stays steady but its outlet pressure drops, ΔP increases, indicating it might be clogged.

Imagine you have a hose connected downstream of the needle valve, and it adds 20 psi of resistance. That 20 psi shows up **after** the valve and has **nothing to do with the valve's resistance**. The needle valve's ΔP is still 500 psi—it just happens that the pressure **after** the valve is not zero because of further downstream components.

This separation is what makes ΔP such a useful metric. It allows you to measure **each component's impact on pressure**, regardless of what's happening further down the line.

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CHAPTER OVERVIEW

12: Pressure

[12.1: Pressure in a Hydraulic System](#)

[12.2: Pulling Suction of a Fluid](#)

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Component	Gauges Used	Pressure Drop (ΔP)
Hose No. 1	Gage S - Gage A	1000 psi - 980 psi = 20 psi
Directional Control Valve (P → A)	Gage A - Gage B	980 psi - 940 psi = 40 psi
Hose No. 2	Gage B - Gage C	940 psi - 920 psi = 20 psi
Cylinder (Load + Friction)	Gage C - Gage D	920 psi - 80 psi = 840 psi
Hose No. 3	Gage D - Gage E	80 psi - 60 psi = 20 psi
Directional Control Valve (B → T)	Gage E - Gage F	60 psi - 20 psi = 40 psi
Hose No. 4 (Return Line)	Gage F - Gage R	20 psi - 0 psi = 20 psi

Now, when you add up all those individual pressure drops, you get the full system pressure at the pump:

$$20 + 40 + 20 + 840 + 20 + 40 + 20 = 1000 \text{ psi}$$

This confirms that the pump is working against the **total resistance** created by all downstream components in the flow path.

Deadheading and Pressure Equalization

Using the image above, when the cylinder reaches full extension and can no longer move, the flow of oil stops —this is called **deadheading**. Since the pump continues to produce flow but the oil has nowhere to go, pressure quickly rises. Since the relief valve is set to open at 1100 psi, the pressure will build to **1100 psi**, at which point the **relief valve** will open. The relief valve is designed to protect the system from overpressure by diverting excess fluid back to the reservoir. At this point, fluid is **not flowing** through the working circuit but rather through the relief valve, which changes how pressure is distributed.

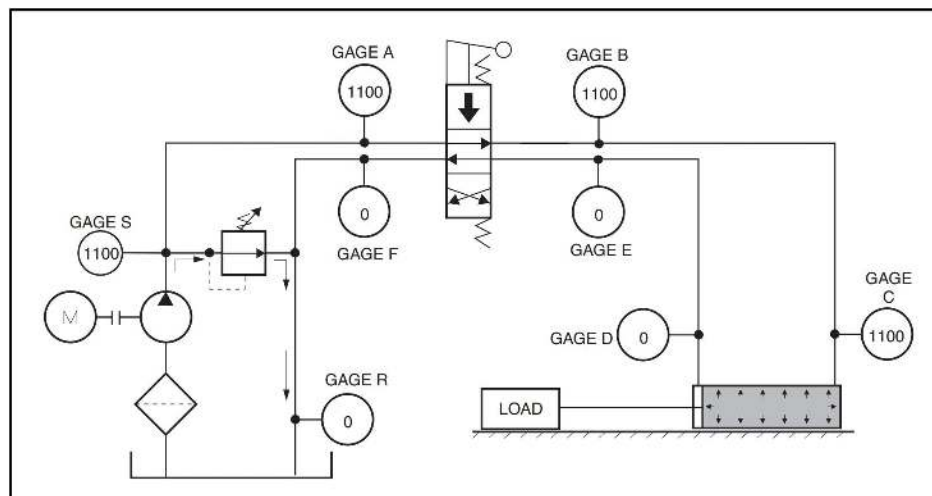


Figure 12.1.2: Deadheading example

Due to **Pascal's Law**, in a confined fluid where no flow is occurring, **the pressure is equal at all points in that volume of fluid**. In our circuit, that means the pressure is the same from the pump outlet through to the cap end of the cylinder. Specifically:

- Gauges **S, A, B, and C** all read the **same pressure**—1100 psi.
- These gauges are measuring the same body of stationary fluid, so their readings are identical.

On the return side of the cylinder (rod end), the story is different. That volume of fluid is **isolated** from the high-pressure side by the **cylinder piston**. Since this side of the system is connected to the reservoir (and there's no active flow), the pressure reads **zero**:

- Gauges **D, E, F, and R** all read **0 psi**.

What this means is that when flow stops (e.g., deadheading), **pressure equalizes** in each isolated fluid volume, as described by Pascal's Law. Understanding how pressure is distributed is essential and can help with system design, troubleshooting, and safe

operation.

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12.2: Pulling Suction of a Fluid

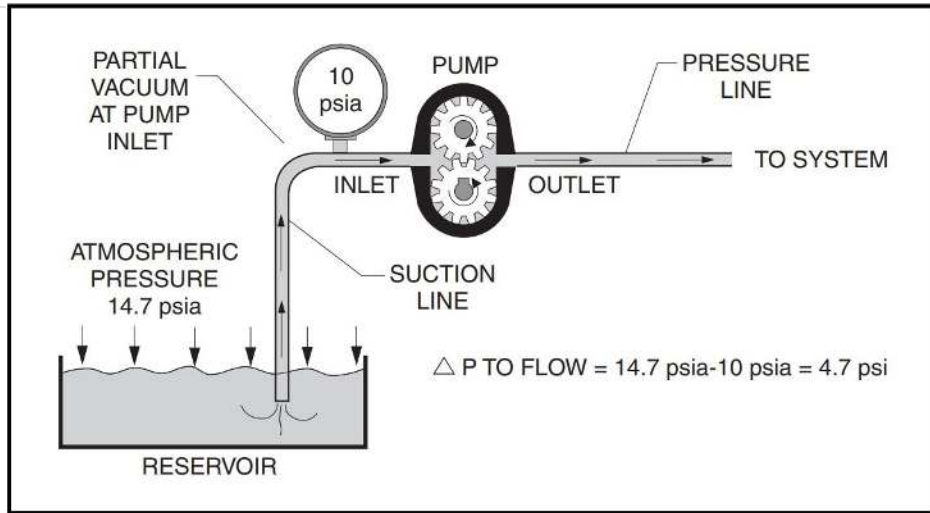


Figure 12.2.1: Schematic representation of suction flow.

One common misconception in hydraulics is that a pump "sucks" oil out of the reservoir. In reality, **a pump doesn't pull fluid in—it relies on atmospheric pressure to push the oil into its inlet.**

Let's break that down.

The Role of Pressure Differential

Fluid always moves from areas of higher pressure to lower pressure. A hydraulic pump takes advantage of this by creating a **low-pressure area** at its inlet during rotation. When the pump begins to turn, the internal components (such as gears or pistons) **create space at the inlet**, increasing its internal cavity space and reducing the pressure below atmospheric pressure.

At the same time, the surface of the reservoir is exposed to the atmosphere. Since atmospheric pressure is now **higher than the pressure at the pump inlet**, it pushes the oil through the suction line into the pump.

This flow process only works **if there's a clear, unrestricted path** for the oil to follow.

Issues That Affect Suction Flow

If anything restricts the inlet flow, the pressure differential may not be enough to move the oil fast enough. This can result in **cavitation** or **pump starvation**, which are damaging to the pump.

Here are a few things that can cause this:

- **Clogged inlet filters**
- **Too small or too long of a suction line**
- **Poor reservoir design or low oil levels**

Even a simple restriction can prevent oil from reaching the pump in time, which may lead to internal scoring, noise, loss of flow, or even total pump failure.

Effect of Altitude

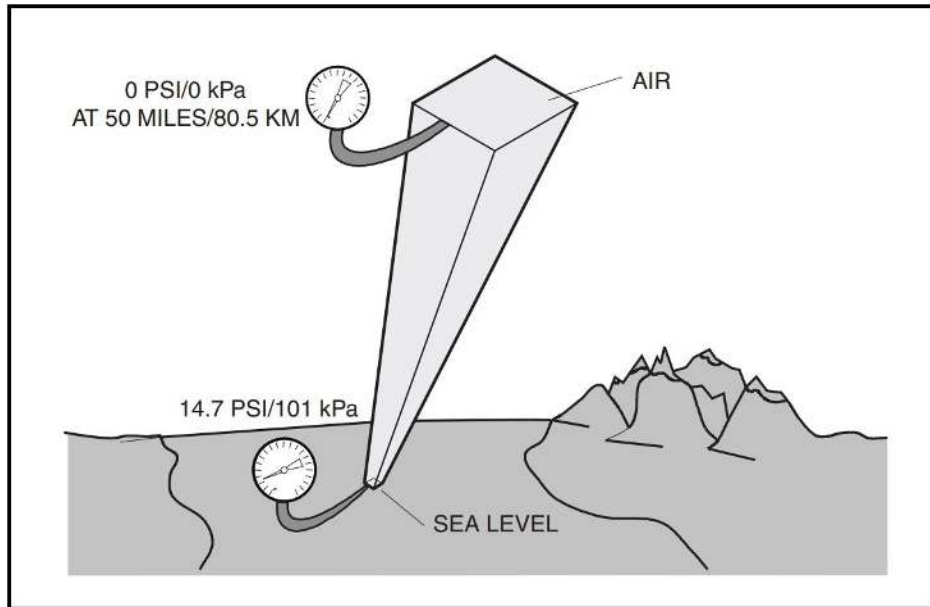


Figure 12.2.2: Schematic representation of altitude's effect on suction pressure.

Another factor to consider is **elevation**. At higher altitudes, **atmospheric pressure decreases**, which means there's **less force available** to push the oil into the pump inlet.

For example, a system designed to run at **sea level** in Seattle, Washington, might not operate correctly at high elevation in **Denver, Colorado**. The atmospheric pressure in Denver is lower, so the effective suction pressure drops. This could cause performance issues—or worse, pump damage—if the system isn't adjusted for the new conditions.

Designers must account for this when sizing suction lines and selecting pumps, especially for systems expected to operate in a wide range of altitudes.

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CHAPTER OVERVIEW

13: Relief Valves

[13.1: Function and Application of a Relief Valve](#)

[13.2: Operation of a Direct-Acting Relief Valve and Its Schematic Symbol](#)

[13.3: The Role of a Relief Valve in System Protection](#)

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13.1: Function and Application of a Relief Valve

A relief valve is a critical component in hydraulic systems, designed to regulate pressure and protect system components from potential damage. It does this by providing a pathway for excess fluid to bypass the system and flow directly to the reservoir when pressure exceeds a predetermined limit.

Relief valves serve two primary functions:

- **Protecting system components from excessive pressure**, preventing damage to pumps, actuators, and other hydraulic elements.
- **Assisting flow control valves in regulating actuator speed**, ensuring smooth and controlled operation.

Without a relief valve, a hydraulic system would be at risk of pressure buildup, which could lead to component failure, leaks, or even catastrophic system damage.

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13.2: Operation of a Direct-Acting Relief Valve and Its Schematic Symbol

There are two common designs of relief valves used in hydraulic applications: **direct-acting relief valves** and **pilot-operated relief valves** (which will be covered in later sections). While their fundamental function is the same —opening at a preset pressure to divert excess fluid back to the reservoir— their internal construction and operation differ.

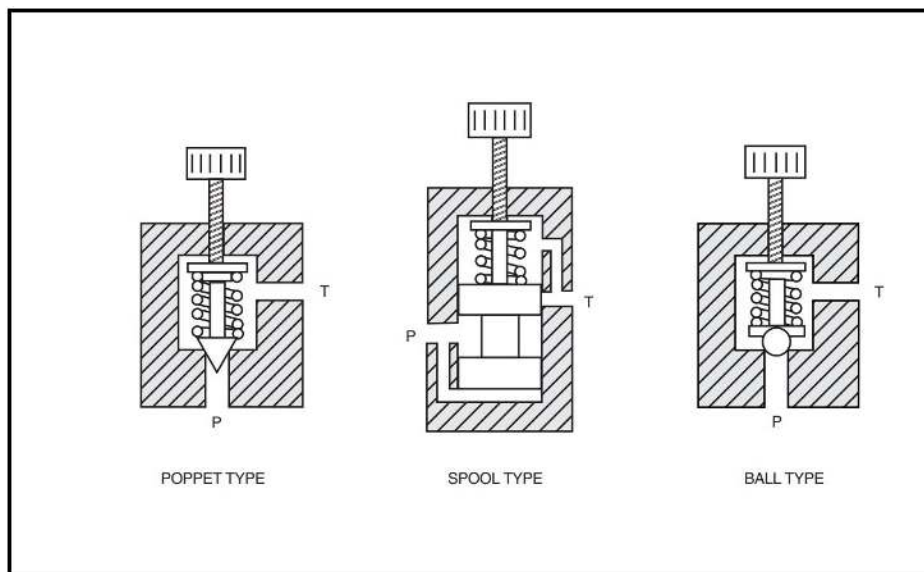


Figure 13.2.1: Diagrams of a poppet type, spool type, and ball type direct-acting relief valve.

A **direct-acting relief valve** consists of a valve body with two ports: an **inlet** and an **outlet**. Inside the body can be a **movable poppet** (or dart), **spool** or **ball** that is held in a closed position by a spring. When pressure at the inlet rises to a critical level, the force overcomes the spring tension, pushing the poppet off its seat and allowing fluid to flow through the outlet, thereby reducing system pressure.

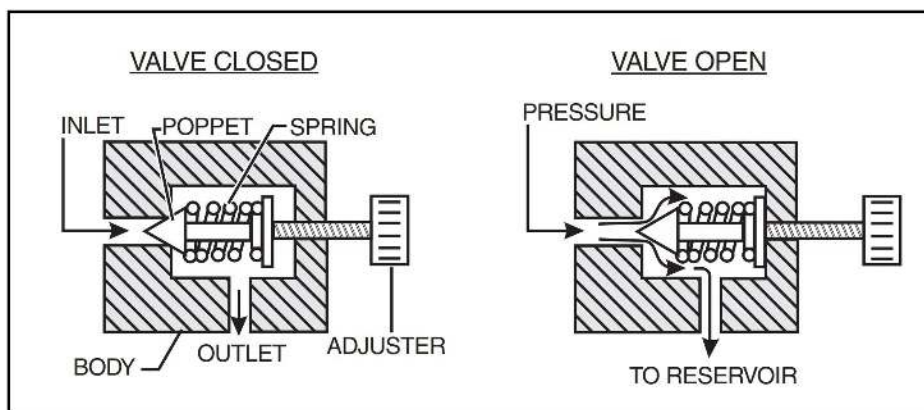


Figure 13.2.2: Diagrams of a direct-acting relief valve when the valve is closed and open.

The opening pressure of the valve can be adjusted by modifying the compression of the spring. This adjustability is crucial for setting the appropriate system pressure limits based on the hydraulic circuit's requirements.

Schematic Symbol Interpretation

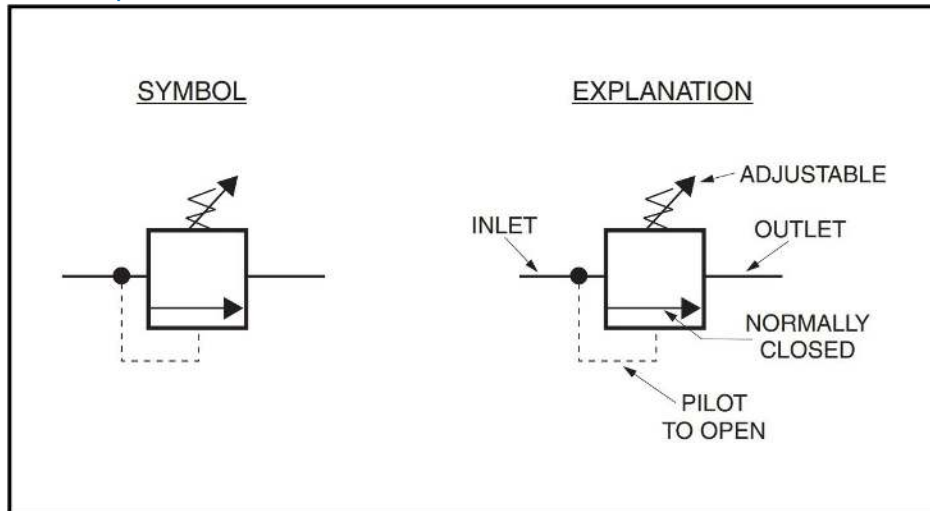


Figure 13.2.3: Schematic representation of a direct-acting relief valve.

The schematic representation of a direct-acting relief valve is identical to that of a **pilot-operated relief valve**. Key elements of the symbol include:

- A **normally closed** valve (shown as a disconnected arrow between the inlet and outlet).
- A **pilot line** (dashed line) that senses pressure and initiates valve opening.
- A **spring symbol**, indicating that the valve remains closed until pressure reaches a set threshold.
- An **angled arrow through the spring**, signifying that the pressure setting is adjustable.
- The pilot line connected to the inlet, meaning the valve reacts solely to the **inlet (upstream) pressure**.

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13.3: The Role of a Relief Valve in System Protection

In nearly all hydraulic systems, a relief valve is included as a **safety mechanism** to prevent dangerous pressure buildup. Excessive pressure can occur if fluid flow is restricted or blocked within the system.

How High Pressure Can Develop

Pressure spikes commonly occur when:

- A **directional control valve** is in a blocked-center position, preventing fluid from moving freely.
- A **cylinder reaches full extension or retraction**, also known as deadheading, when it stops fluid movement.
- An **actuator is stalled by an excessive load**, restricting the pump's output flow.

In these situations, a relief valve ensures system protection by opening when pressure reaches its preset limit, diverting excess flow to the reservoir. Without this safeguard, components such as pumps, hoses, seals, and actuators could be damaged due to over-pressuring.

By functioning as both a **pressure regulator** and a **safety feature**, the relief valve ensures that hydraulic systems operate efficiently and reliably, even under fluctuating load conditions.

The Role of a Relief Valve in a Hydraulic Circuit

In a hydraulic system, pressure must be carefully managed to prevent damage to system components. One of the key safety devices responsible for this function is the **relief valve**, which ensures that pressure never exceeds a predetermined limit.

Imagine a hydraulic circuit where a **fixed displacement pump** continuously supplies oil to the system. This type of pump delivers a constant volume of fluid, regardless of demand. If the flow is suddenly blocked, such as when a **directional control valve (DCV)** is in a center position, or a cylinder reaches the end of its stroke, the pressurized oil has nowhere to go. Without a relief valve, the pressure in the system would rise uncontrollably, potentially leading to burst lines, damaged components, or even motor failure.

The relief valve prevents this dangerous situation by acting as a **pressure-sensitive gateway**. Under normal conditions, it remains **closed**, allowing oil to flow through the system as intended. However, when pressure at the valve's inlet reaches its **preset limit**, the valve **opens**, providing an escape path for excess oil. This diverted flow is sent directly back to the **reservoir**, preventing further pressure buildup.

The relief valve's behavior can be observed by monitoring **flow and pressure changes** in the system. When the relief valve remains **closed**, a flowmeter downstream of the relief valve would read **zero**, indicating that all oil is moving through the working circuit. The moment the valve **opens**, the flow through the relief port jumps to full pump capacity, confirming that excess pressure is being safely redirected.

Relief valves can be either **internally or externally drained**. Most are internally drained, meaning no external drain line is required. However, some designs feature an **external drain**, which must be connected to the return manifold to function properly.

In essence, the relief valve serves as the hydraulic system's **pressure safeguard**, automatically regulating flow when necessary to protect components from excessive force. By opening precisely when needed, it ensures both **operational efficiency** and **system longevity**.

Connecting and Testing a Relief Valve to Limit System Pressure

In hydraulic systems using a **fixed displacement pump**, oil is constantly being pushed into the system whenever the pump is running. If that flow has nowhere to go—if it's "deadheaded"—pressure will climb rapidly. Without a safeguard, this pressure can become dangerously high, potentially bursting hoses or causing the electric motor to stall.

That's where a **relief valve** comes in. A relief valve is a safety device designed to **limit maximum system pressure**. It does this by opening at a preset pressure level and diverting excess fluid back to the reservoir.

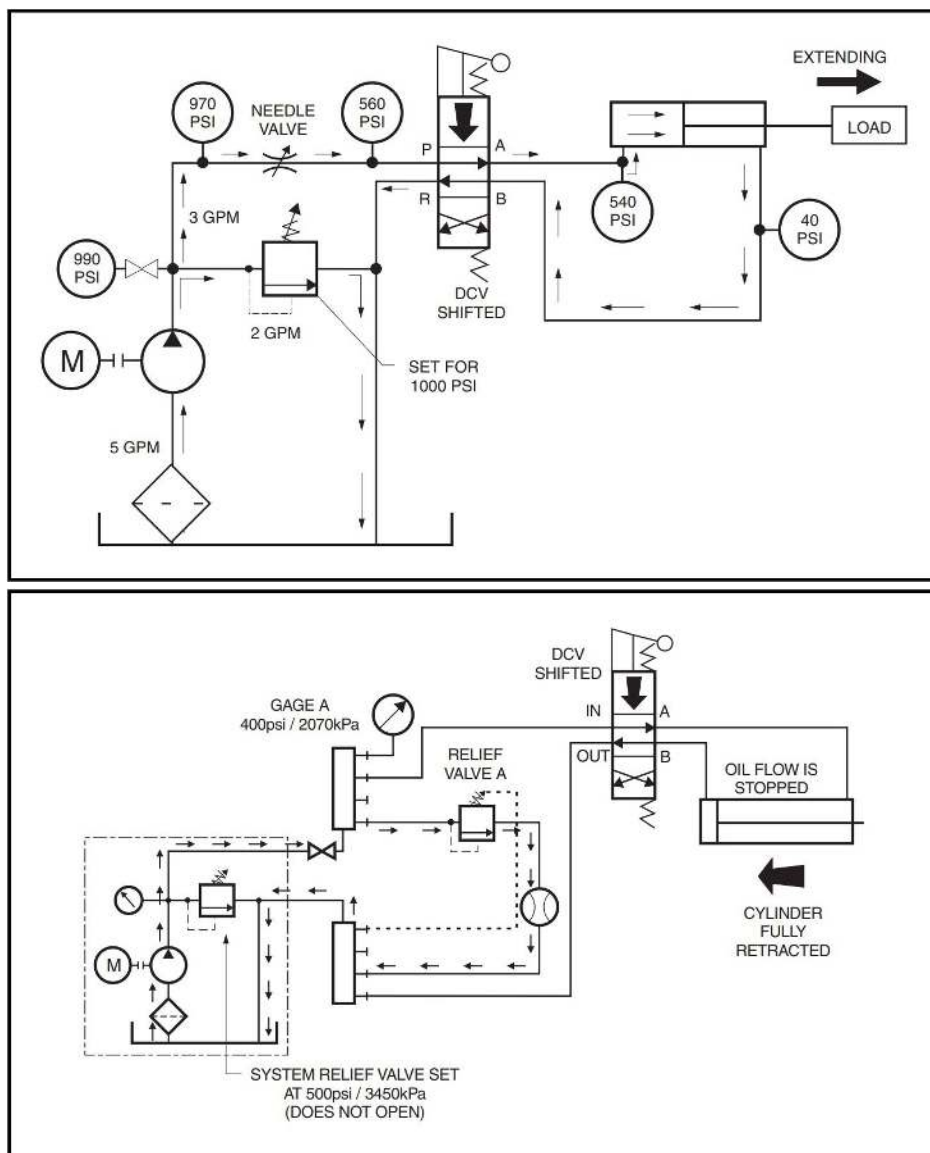


Figure 13.3.1: Schematic diagrams of a double-acting cylinder in extension and retraction.

Imagine a situation where a **directional control valve (DCV)** operates a **double-acting cylinder**. Cycling the cylinder (extending and retracting), the **relief valve** behaves at various stages. Those stages would include **closed** at pressures lower than the previous set and **open** completely when pressures exceed the set point. These stages of the relief valve protect the system during blocked or high-pressure conditions.

Observing the Relief Valve in Action

Relief valves come in two drainage types:

- **Internally drained**, where excess oil is routed back through the valve body into the tank line.
- **Externally drained**, which requires a separate line to carry excess fluid back to the reservoir or return manifold.

If no external drain line is shown in a schematic, the valve is assumed to be internally drained. The hydraulic stand that we work with uses an **externally drained** relief valve, which **must** have a drain line connected to the return manifold —this prevents pressure from building up behind the valve spool and interfering with operation.

What is Happening Physically

Let's walk through what's occurring when the actuator is blocked:

- The **pump continues to deliver flow**, but the flow path is restricted.
- This causes pressure to **climb quickly**, which is the set pressure on the relief valve.
- Once the pressure at the inlet of the relief valve reaches the set pressure, the valve **pops open**, relieving excess pressure and allowing oil to flow safely back to the reservoir.

This process protects both the pump and the hydraulic components from damage. In a live system, the momentary opening of a relief valve may not even be noticeable—unless you're watching the flowmeter or pressure gauge. But it's a crucial part of keeping the system safe and functional.

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CHAPTER OVERVIEW

14: Check Valves

[14.1: Check Valves in Hydraulic Systems](#)

[14.2: Types of Check Valves and Their Operation](#)

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14.1: Check Valves in Hydraulic Systems

A **check valve** is a simple yet essential component in hydraulic systems, designed to allow fluid flow in **one direction** while **completely blocking** flow in the opposite direction. Because of this function, it is often referred to as a **one-way directional control valve**.

Despite their simplicity, check valves play a crucial role in many hydraulic applications. They ensure the proper operation of pumps, prevent system damage, and contribute to the overall efficiency of fluid power circuits. Some of the most common applications of check valves include:

- **Holding Prime** – In many hydraulic systems, especially those using **larger pumps**, oil can drain from the **inlet line** when the system is idle for extended periods. This condition, known as **losing prime**, occurs when the pump struggles to draw oil back into the system because atmospheric pressure alone is insufficient to push the fluid up the supply tube. A **check valve** installed in the inlet line prevents oil from draining out, ensuring the pump maintains its prime and is ready for operation when restarted.
- **Avoiding Pump Reversal** – In some hydraulic circuits, when the electric motor driving the pump is turned off, **fluid pressure in the system can force oil backward through the pump**. Many pumps are not designed to rotate in reverse and can suffer severe damage if this occurs. To prevent reverse flow, a check valve is placed at the **pump outlet**, allowing flow to move forward while blocking any reverse movement.
- **Bypass Flow** – Check valves are often used to create **bypass pathways** around specific components in a circuit. For example, a check valve may be placed in parallel with a **flow control valve** to regulate flow in one direction while allowing free flow in the other. This setup ensures controlled operation in one direction while **minimizing restriction** in the reverse direction.
- **Creating Back Pressure** – In some **directional control valves (DCVs)**, oil pressure is required to shift the spool. Certain valve designs require a **minimum system pressure** to ensure proper shifting. A check valve can be installed in the **tank line** to create **back pressure**, preventing pressure from dropping too low and ensuring reliable valve operation.

Beyond these applications, check valves are also used to **lock actuators in place** and provide **free-flow pathways for hydraulic motors during deceleration**. These functions will be explored in greater detail in later chapters.

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14.2: Types of Check Valves and Their Operation

While all check valves serve the same basic purpose of allowing flow in one direction and blocking it in the other, their **internal design** can vary. The three most common types of check valves used in hydraulic systems are:

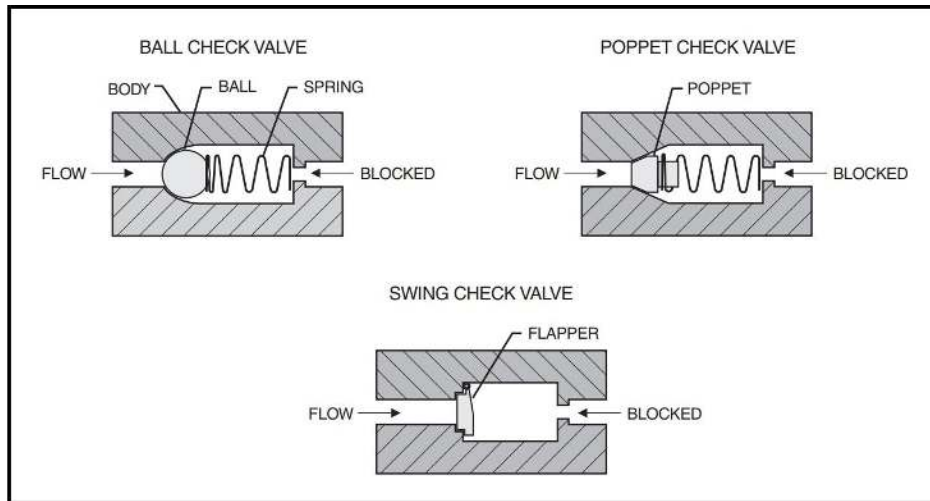


Figure 14.2.1: Three types of check valves: ball, poppet, and swing.

1. Ball Check Valves
2. Poppet Check Valves
3. Swing Check Valves

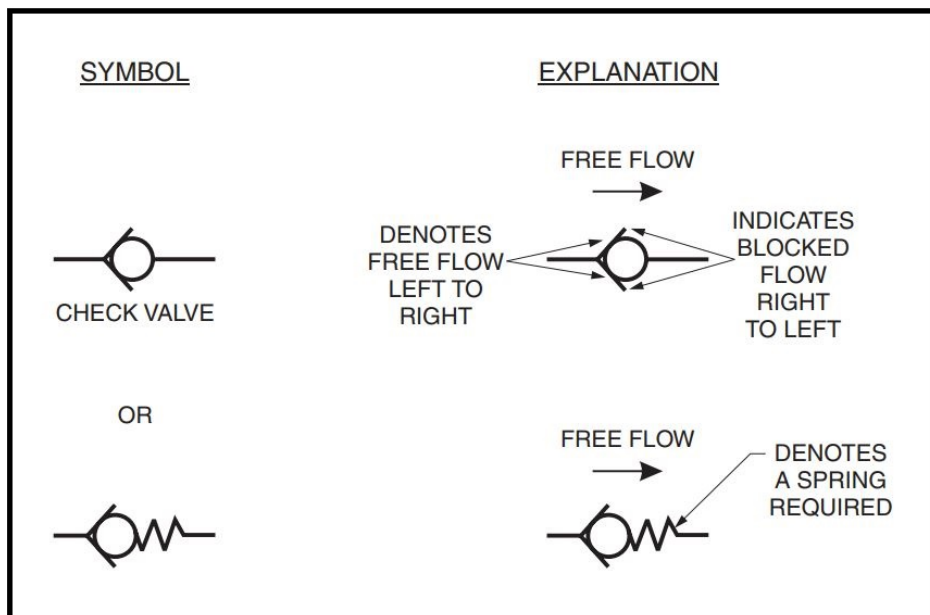


Figure 14.2.2: Schematic symbols with corresponding explanations.

Despite their differences in design, these valves share the same **schematic symbol**, indicating their function remains consistent across various applications.

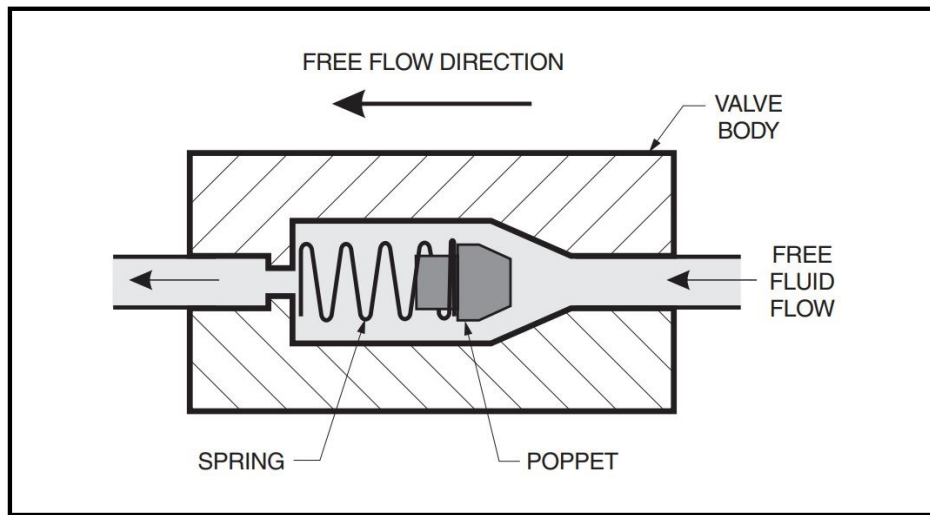


Figure 14.2.3: Schematic representation of a poppet check valve.

A **poppet-style check valve** provides a clear example of how these valves operate. Inside the valve body, a **spring-loaded poppet** rests against a **seat**, preventing flow in the checked direction. The spring is typically very light, meaning that only a **small amount of pressure** is needed to push the poppet off the seat and allow flow in the open direction.

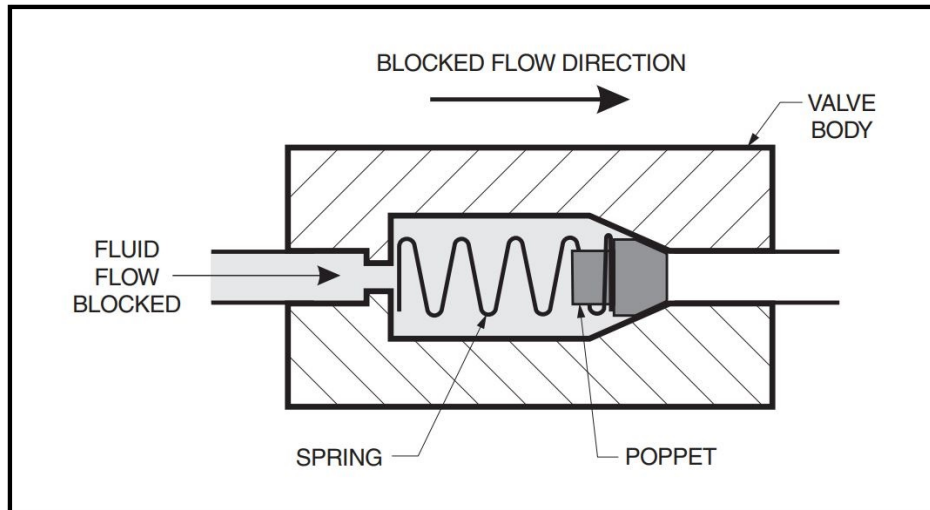


Figure 14.2.4: Schematic representation of a poppet check valve with blocked flow direction.

However, when fluid attempts to move in the reverse direction, it pushes the **poppet more firmly against the seat**, completely blocking flow. This design ensures **minimal leakage**, with many check valves providing a near **zero-leakage seal** in the checked direction.

Check valves, despite their small size, are indispensable in hydraulic circuits, contributing to both **operational efficiency and system protection**. By preventing unwanted flow conditions, they help maintain stable and controlled hydraulic performance.

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CHAPTER OVERVIEW

15: Flow Control Valves

[15.1: The Function of a Flow Control Valve](#)

[15.2: Operation of a Flow Control Valve and its Schematic Symbol](#)

[15.3: The Effect of Actuator Load Changes on Flow Control Valve Operation](#)

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15.1: The Function of a Flow Control Valve

A **flow control valve** is a specialized hydraulic valve designed to **regulate the speed of actuators** by controlling fluid flow. It combines two key components in a single body:

- A **needle valve**, which will be used to **restrict flow in one direction**, controlling the actuator speed
- A **check valve**, which **allows free flow in the opposite direction**, preventing unnecessary restriction when the flow direction changes

This design is especially useful in **bi-directional actuator circuits**, where different speeds are required for the forward and return strokes. For instance, a hydraulic cylinder may need to extend **slowly** while retracting **quickly**. By installing a flow control valve in the return line, fluid flow can be unrestricted in one direction, ensuring a **rapid retraction**, while controlled restriction in the opposite direction ensures a **steady and controlled extension speed**.

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15.2: Operation of a Flow Control Valve and its Schematic Symbol

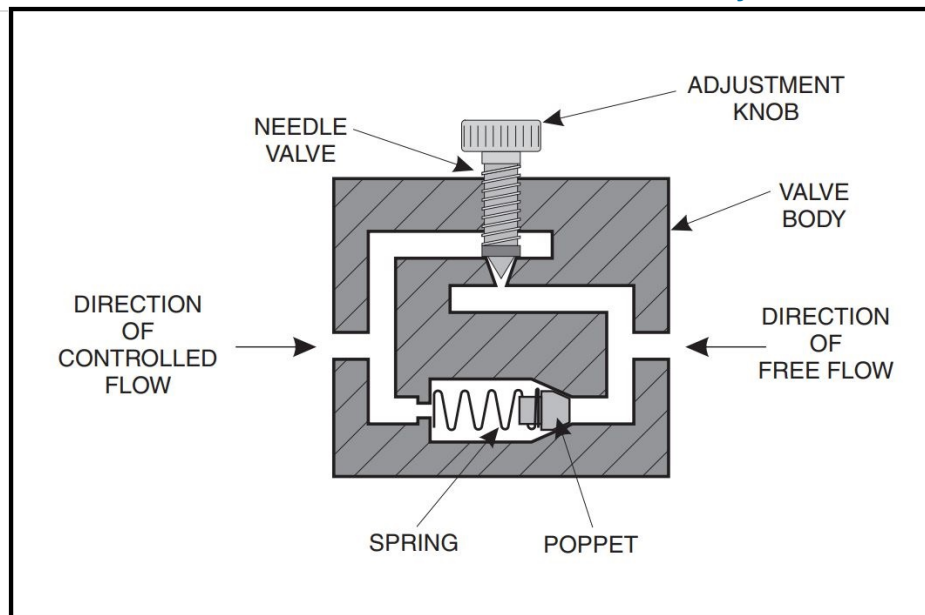


Figure 15.2.2: Schematic representation of a flow control valve.

A flow control valve regulates the speed of an actuator by controlling the flow rate of hydraulic fluid. The basic components of a flow control valve include:

- A valve body with inlet and outlet ports
- A tapered adjustment screw
- An adjustment knob
- An internal check valve poppet
- A small spring to assist the poppet function

This valve can be configured to restrict flow in one direction while allowing near-unrestricted flow in the other. This is accomplished using the check valve in parallel with the variable orifice. The schematic symbol for this type of valve typically shows a variable restriction with a check valve in parallel, often drawn as a parallel line bypassing the orifice.

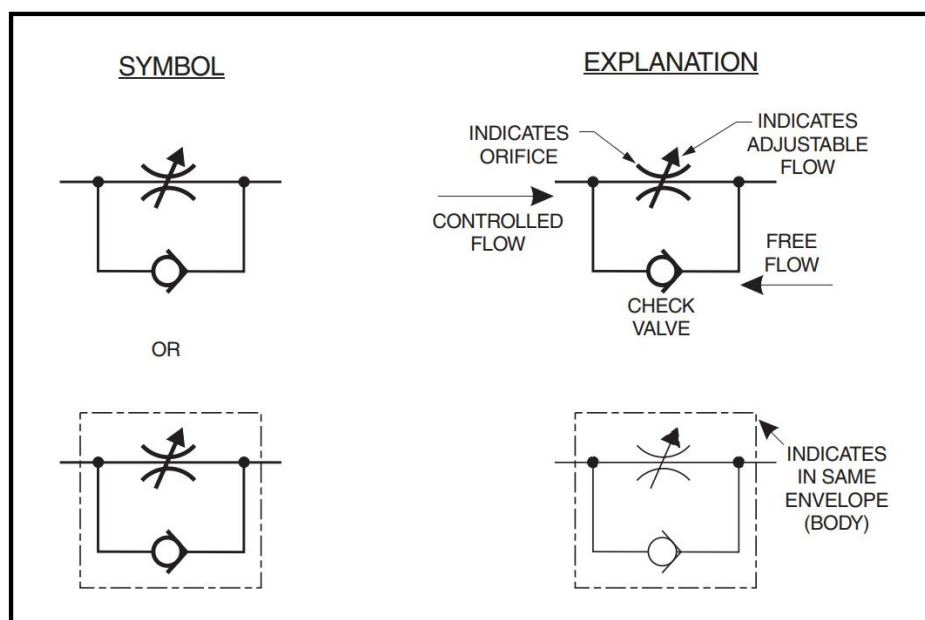


Figure 15.2.1: Control valve schematic symbol and explanation.

The control valve schematic symbol is drawn with a needle valve inline with the transmission lines and parallel will be a check valve. A second version provides a ghost line around the device to represent that both components are in the same valve body.

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15.3: The Effect of Actuator Load Changes on Flow Control Valve Operation

When working with flow control valves, it's important to recognize that setting a desired flow rate doesn't necessarily guarantee a consistent actuator speed. One key factor that can disrupt the flow rate is a **change in the load on the actuator**.

Here's why: The pressure at the inlet of the relief valve in a hydraulic system is made up of several components—primarily the **pressure drop across the flow control valve, fluid friction**, and the **resistance caused by the load**. If the actuator's load increases, the system must work harder to move it, which raises the pressure at the pump outlet. As this pressure rises, more flow can be diverted through the relief valve rather than continuing to the actuator. The result? **Less flow reaches the actuator**, and the actuator **slows down**.

On the flip side, when the load decreases, there's less resistance to movement. More of the pump's flow reaches the actuator, and the actuator **speeds up**. This can lead to uneven or unpredictable motion when the load varies throughout the cycle.

In many systems, this isn't a problem. If the load is relatively constant or if a small variation in speed is acceptable, a basic flow control valve provides a simple and cost-effective solution. But in systems where **load conditions change**, such as when lifting varying weights or during different phases of a machining operation, this inconsistency in speed can become a major issue.

To maintain steady actuator speed regardless of load changes, a **pressure-compensated flow control valve** is a better option. These valves automatically adjust to fluctuations in pressure, keeping the flow rate —and therefore the actuator speed —much more consistent.

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CHAPTER OVERVIEW

16: Metered Flow Circuits

[16.1: The Operation of a Meter-In Flow Control Circuit and an Application](#)

[16.2: The Operation of a Meter-Out Flow Control Circuit and an Application](#)

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16.1: The Operation of a Meter-In Flow Control Circuit and an Application

So far, the function of needle valves and flow control valves have been introduced without placing much emphasis on where they appear in the circuit. However, in real-world applications, **valve placement becomes crucial**, especially when it comes to controlling actuator speed under various load conditions.

When a **flow control valve is installed at the inlet side of the actuator**, the setup is referred to as a **meter-in circuit**. In this arrangement, the fluid entering the actuator is **metered** or **restricted**, while the fluid exiting the other end of the actuator is allowed to flow freely back to the reservoir with **minimal restriction**.

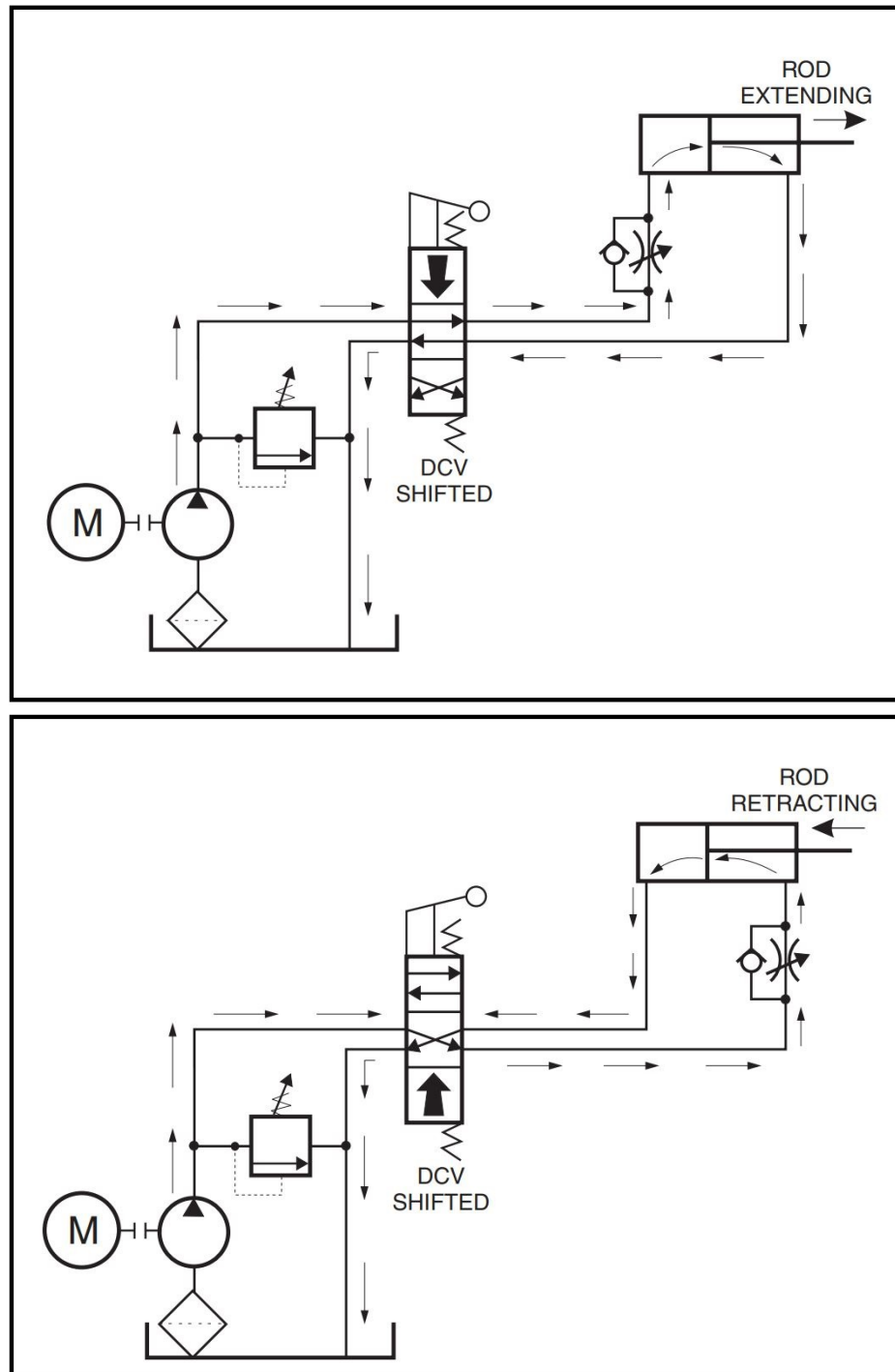


Figure 16.1.1: Schematic representations of meter-in flow control.

Imagine a cylinder extending in a system configured this way: as fluid enters the cap end of the cylinder, the flow control valve regulates the rate of flow, which in turn determines how fast the cylinder extends. The return fluid from the rod end flows out unimpeded. The same logic applies if the goal is to control retraction speed by placing the flow control valve on the inlet to the rod side instead.

Meter-in flow control offers **precise and stable speed control**, but its effectiveness depends heavily on the type of load the actuator is working against. A side-load application or situations that have limited space that require metered-in control are best suited.

Problems arise when the load **assists** actuator movement. Think of a crane lowering a heavy load—gravity now works **with** the cylinder's retraction. In such scenarios, the meter-in circuit cannot effectively regulate speed. The assisting force can overpower the restricted inlet flow, causing the actuator to move faster than desired or even "run away." Because of this, meter-in is generally **not suitable** for loads that **aid motion**, particularly in hydraulic motor circuits where aiding loads are common due to inertia and system dynamics.

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16.2: The Operation of a Meter-Out Flow Control Circuit and an Application

Controlling **actuator speed** in a hydraulic system is typically done by regulating the flow rate of hydraulic fluid. One effective and commonly used method is the **meter-out flow control circuit**.

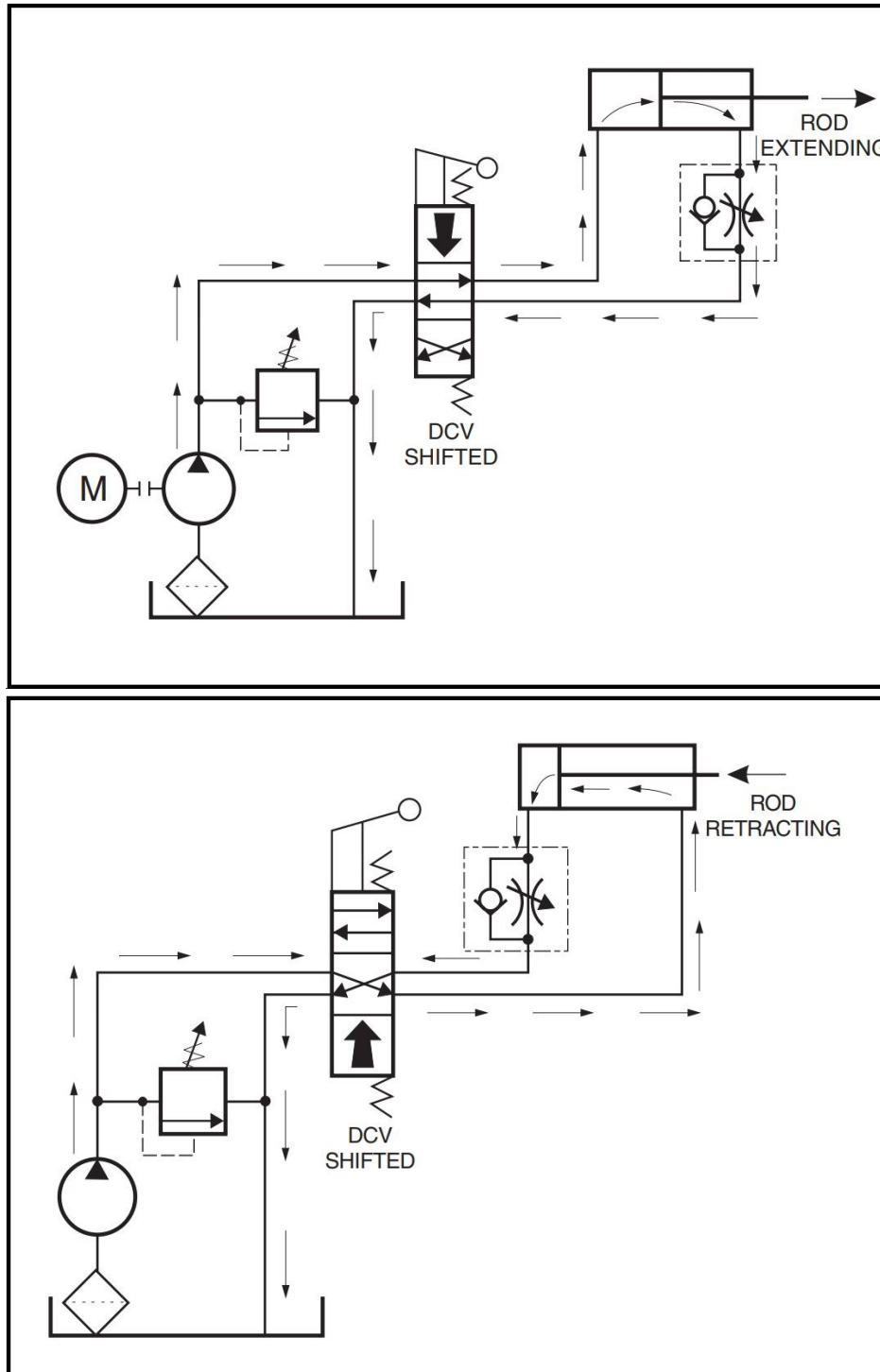


Figure 16.2.1: Schematic representations of meter-out flow control circuits.

In a **meter-out setup**, flow is restricted **after** it has passed through the actuator. That means oil enters the cylinder (or motor) with little to no restriction, but the flow leaving the actuator is throttled to **control how fast the actuator can retract or extend**.

Why Meter-Out Works So Well

One of the biggest advantages of a meter-out configuration is that it handles **aiding loads**—loads that tend to move on their own, such as a descending weight or an overrunning motor. Without some form of back pressure, these loads could cause the actuator to accelerate uncontrollably.

By placing the restriction **on the return side**, the meter-out circuit creates a **controlled back pressure** in the actuator. This back pressure forms a **hydraulic cushion** that prevents the actuator from moving too fast, surging, or bouncing. As a result, the actuator stays under smooth, steady control—even when the load is trying to run away.

Typical Applications

Meter-out circuits are ideal for:

- **Vertically mounted cylinders** that lower heavy loads
- **Hydraulic motors** under decreasing load conditions
- **Press operations**, where slow, controlled movement is important during return strokes

In fact, most industrial circuits using flow control valves will default to a **meter-out arrangement** unless there's a specific reason to meter-in. It's simply the most versatile, stable, and effective way to regulate actuator speed under a wide range of operating conditions.

Troubleshooting Tip:

When troubleshooting speed issues in a hydraulic circuit, always check **where the flow control valve is placed**. If you're seeing erratic motion or surging in a vertically loaded cylinder, chances are the system needs a meter-out configuration—or a better one than it currently has.

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CHAPTER OVERVIEW

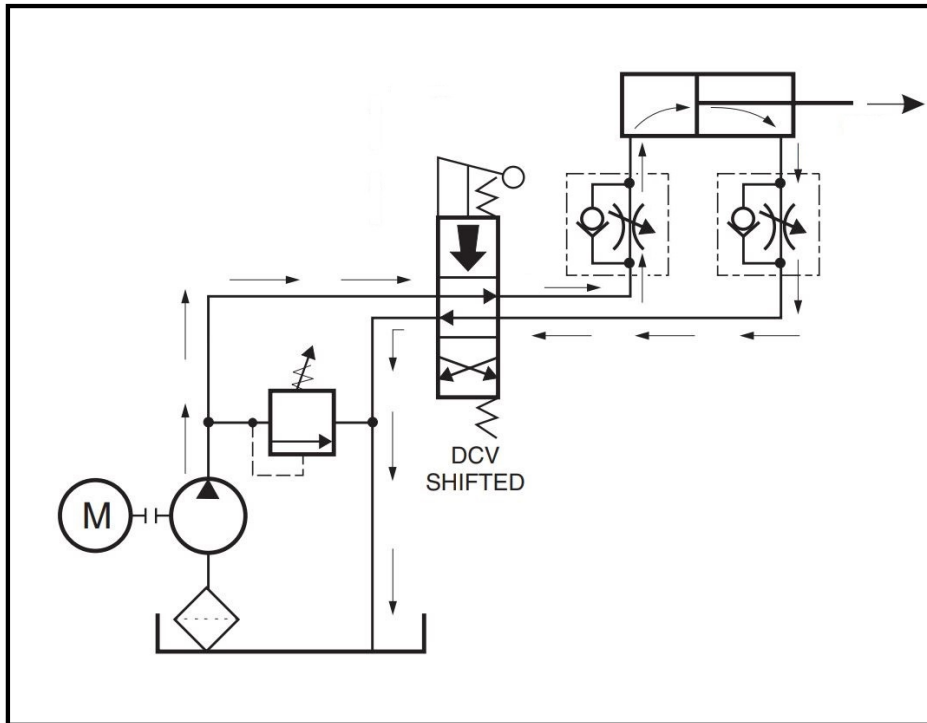
17: Independent Speed Control

[17.1: Definition of Independent Speed Control and Application](#)

[17.2: How Speed Control Valves Can Be Used to Provide Multiple Speeds](#)

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17.1: Definition of Independent Speed Control and Application



In many industrial applications, the speed at which an actuator extends is not the same speed desired for its retraction. In fact, it's quite common to require **different speeds in each direction**, a setup known as **independent speed control**.

There are a few common reasons this is needed:

- **Slow Approach / Fast Reset:** In some machines, a slow, controlled movement is required while the actuator performs work, such as pushing, expanding, or clamping. Once that task is complete, the return stroke isn't doing any work, it's just resetting the actuator. In this case, faster movement during retraction improves efficiency and shortens the machine's cycle time.

A good example is a **metal tube expander**. During operation, the cylinder extends slowly to expand the tube precisely. Once the operation is complete, the cylinder can **quickly retract** to prepare for the next part.

- **Identical Speeds in Both Directions:** Since the rod end and cap end of a double-acting cylinder have different surface areas, the cylinder will naturally extend and retract at **different speeds** when the same flow rate is applied. If a process requires consistent speeds in both directions, independent flow control is the only way to achieve it.

To implement independent speed control, the system needs **two separate flow control valves** —one for each direction of motion. Each valve can be configured in a **meter-in** or **meter-out** (preferred) arrangement, depending on whether you're metering the flow entering or exiting the actuator. This setup gives the operator precise control over actuator behavior in both directions, which is essential in applications demanding repeatability, precision, or efficiency.

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17.2: How Speed Control Valves Can Be Used to Provide Multiple Speeds

In many industrial processes, it's beneficial for actuators to operate at **different speeds during different phases** of a cycle. One widely used method is known as **rapid traverse-slow feed**. This approach is common in machine tools where the actuator must first move quickly to position the tool and then slow down for precision work, such as cutting or forming.

To achieve this, multiple speed control valves can be integrated into the circuit, **each preset to allow a different flow rate**. By controlling which valve is active, the operator can shift between high-speed and low-speed operation as needed.

This is typically accomplished using a **directional control valve (DCV)** to route the fluid through the selected flow control valve. For instance, when rapid motion is needed, the DCV directs flow through a valve with a larger orifice, allowing higher flow and faster actuator movement. When precise or delicate work is required, the DCV switches to a valve with a smaller orifice, reducing flow and slowing the actuator.

This setup offers a **simple yet effective** way to boost both productivity and control in operations that require varying actuator speeds throughout a cycle.

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CHAPTER OVERVIEW

18: Flow Rate and Cylinder Speed

[18.1: How to Calculate the Extend Speed of a Hydraulic Cylinder](#)

[18.2: Calculate the Extend Speed of a Hydraulic Cylinder Given its Size and a Flow Rate](#)

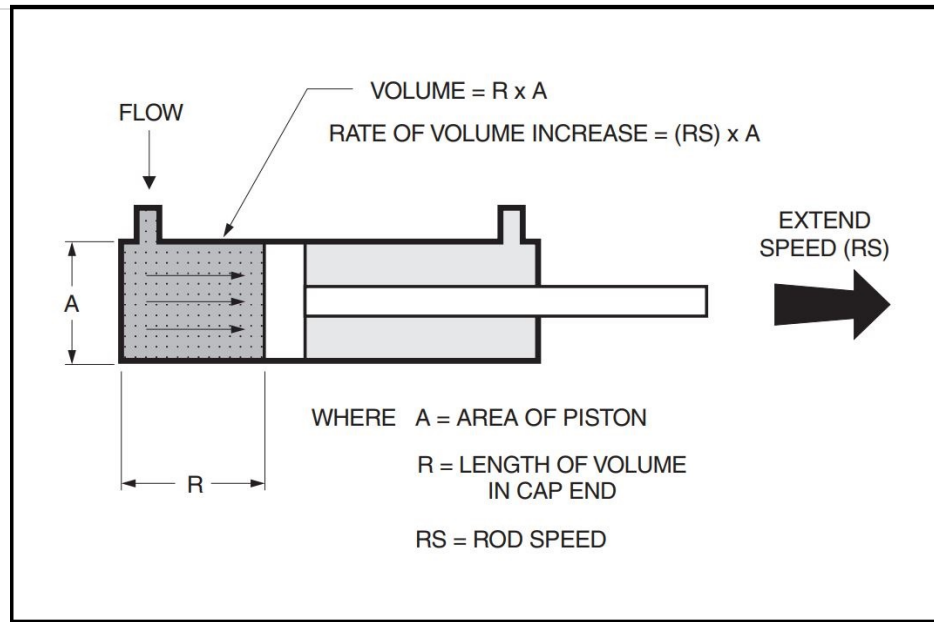
[18.3: How to Calculate the Retraction Speed of a Cylinder](#)

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18.1: How to Calculate the Extend Speed of a Hydraulic Cylinder



The extend speed of a hydraulic cylinder is determined by how fast oil fills the cap end of the cylinder. This speed is dependent on two factors:

- The **flow rate (Q)** delivered to the cap end
- The **volume** that must be filled per inch of stroke

Since the rod is moving as the fluid fills the cap end, the effective volume being created per unit of time determines the piston's travel speed.

The formula used to calculate **rod speed during extension** is:

$$\text{Rod Speed (in/min)} = \text{Flow Rate (in}^3/\text{min)} / \text{Cap End Area (in}^2\text{)}$$

To use this formula effectively:

1. Convert the pump flow rate into cubic inches per minute (1 GPM = 231 in³/min).
2. Calculate the cap end area of the cylinder using the piston diameter:

$$\text{Cap Area} = 0.7854 \times D^2$$

where D is the piston diameter.

3. Divide the flow rate by the cap area to get speed in inches per minute.

✓ Example

A 2-inch diameter piston with a 1 GPM flow rate:

$$\text{Cap Area} = 0.7854 \times (2^2) = 3.14 \text{ in}^2$$

$$\text{Flow Rate} = 231 \text{ in}^3/\text{min}$$

$$\text{Rod Speed} = 231 \div 3.14 \approx 74 \text{ in/min}$$

Understanding this calculation helps you size actuators correctly and verify that system performance matches design requirements. It also sets the foundation for troubleshooting flow-related speed issues.

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18.2: Calculate the Extend Speed of a Hydraulic Cylinder Given its Size and a Flow Rate

Hydraulic cylinder speed depends on two primary factors: the area being filled with fluid and the flow rate of oil entering that area. To calculate the **extend speed**, we use the area of the **cap end** of the cylinder, which is determined by the bore diameter.

1. Calculate the piston areas of a large bore and small bore cylinder.

Use the following formula for the area of a circle:

$$A = 0.7854 \times D^2$$

Where:

- A is the area in square inches (in^2)
- D is the bore diameter in inches

Given:

- Large Bore Cylinder Diameter = 1.5 in
- Small Bore Cylinder Diameter = 1.125 in

Large Bore Cylinder Piston Area =

$$A = 0.7854 \times (1.5)^2$$

$$= 0.7854 \times 2.25$$

$$= 1.767 \text{ in}^2$$

Small Bore Cylinder Piston Area =

$$A = 0.7854 \times (1.125)^2$$

$$= 0.7854 \times 1.266$$

$$= 0.994 \text{ in}^2$$

2. Using the areas from Step 1, calculate the extend speeds for the flow rates shown below.

Use this formula to calculate cylinder extend speed:

$$\text{Rod Speed (in/min)} = \text{Flow Rate (in}^3\text{/min)} / \text{Piston Area (in}^2\text{)}$$

Remember:

- 1 GPM = 231 $\text{in}^3\text{/gal}$

Where:

- Flow Rate = 4 GPM = 924 $\text{in}^3\text{/min}$

$$\text{Rod Speed for large bore (in/min)} = 924 \text{ in}^3\text{/min} / 1.767 \text{ in}^2$$

$$\approx 523 \text{ in/min}$$

$$\text{Rod Speed for small bore (in/min)} = 924 \text{ in}^3\text{/min} / 0.994 \text{ in}^2$$

$$\approx 930 \text{ in/min}$$

3. Determine the cylinder size for a required speed and flow rate.

Given:

Required Extend Speed = 74 in/min

Available Flow Rate = 4 GPM = 924 in³/min

Area = Flow Rate / Rod Speed

= 924 in³/min / 74 in/min

= 12.5 in²

Solve for bore diameter:

$D = A / 0.7854$

= 12.5 in² / 0.7854

= 15.9 ≈ 4 in

Answer:

Cylinder Bore Diameter = **4 inches**

4. Determine the flow rate needed to extend a cylinder at 12 in/min.

Given:

Speed = 12 in/min

Bore Diameter = 6 in

Cap Area = $A = 0.7854 \times 6^2$ in²

= $0.7854 \times 36 = 28.27$ in²

Required Flow Rate (in³/min)

= 12 in/min × 28.27 in²

= 339.24 in³/min

Convert to GPM:

Flow Rate = 339.24 in³/min / 231 in³/gal ≈ 1.47 GPM

Answer:

Flow Rate Needed = **1.47 GPM**

5. Determine cylinder bore size and max force output for a specified application.

Given:

Flow Rate = 26 GPM = 6006 in³/min

Required Speed = 300 in/min

Pressure Available = 1500 PSI

$A = (6006 \text{ in}^3/\text{min}) / (300 \text{ in}/\text{min}) = 20.02$ in²

Solve for bore:

$D = 20.02 \text{ in}^2 / 0.7854 = 25.5 \approx 26$ in

Cylinder Bore Diameter = **5 in**

Force Output:

$$F = P \times A$$

$$= 1500 \times 20.02 \text{ in}^2$$

$$= 30,030 \text{ lbsF}$$

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18.3: How to Calculate the Retraction Speed of a Cylinder

Unlike extend speed, which fills the full piston area, the retract speed uses the **annular area** of the piston, since the rod occupies part of the cap-end volume. The formula for **annular area** is:

$$\text{Annular Area} = 0.7854 \times (D^2 - d^2)$$

Where:

- D = Bore diameter
- d = Rod diameter

To calculate retract speed:

$$\text{Rod Speed (in/min)} = \text{Flow Rate (in}^3\text{/min)} / \text{Annular Area (in}^2\text{)}$$

A double-acting single-rod cylinder will typically retract faster than it extends, as there is less volume to fill, due to the rod taking up the volume space.

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18.4: Calculate the Retract Speed of a Cylinder Given its Size and a Flow Rate

When a double-acting hydraulic cylinder retracts, fluid enters the rod end rather than the full bore area. Because the rod takes up space inside the cylinder, only the volume resulting from the **annular area** of the piston is filled. This is why retract speeds are typically faster than extend speeds for the same flow rate.

1. Calculate the annular area of each cylinder.

The **annular area** is calculated using the formula:

$$A = 0.7854 \times (D^2 - d^2)$$

Where:

- D is the piston (bore) diameter
- d is the rod diameter

Given:

- **Large Bore Cylinder:** $D = 1.5$ in, $d = 0.44$ in
- **Small Bore Cylinder:** $D = 1.125$ in, $d = 0.31$ in

Large Bore Cylinder Annular Area:

$$\begin{aligned} A &= 0.7854 \times (1.5^2 - 0.44^2) \\ &= 0.7854 \times (2.25 - 0.1936) \\ &= 0.7854 \times 2.0564 \\ &= 1.615 \text{ in}^2 \end{aligned}$$

Small Bore Cylinder Annular Area:

$$\begin{aligned} A &= 0.7854 \times (1.125^2 - 0.31^2) \\ &= 0.7854 \times (1.266 - 0.0961) \\ &= 0.7854 \times 1.1699 \\ &= 0.918 \text{ in}^2 \end{aligned}$$

2. Using the areas above, calculate the retract speeds for the given flow rates.

Use the same speed formula:

$$\text{Rod Speed (in/min)} = \text{Flow Rate (in}^3\text{/min)} / \text{Annular Area (in}^2\text{)}$$

Remember:

- 1 GPM = 231 in³/min

Where:

- Flow Rate = 3 GPM = 924 in³/min

$$\begin{aligned} \text{Rod Speed for large bore (in/min)} &= 924 \text{ in}^3\text{/min} / 1.615 \text{ in}^2 \\ &\approx 429 \text{ in/min} \end{aligned}$$

$$\text{Rod Speed for small bore (in/min)} = 924 \text{ in}^3\text{/min} / 0.918 \text{ in}^2$$

≈755 in/min

3. Compare these speeds with the extend speeds.

In both cylinders, the retract speeds are significantly higher than the extend speeds at the same flow rates. This is because the rod reduces the volume that needs to be filled during retraction, leaving a smaller area for oil to act on, resulting in higher speeds. This difference is more pronounced in cylinders with larger rod diameters.

4. Determine the cylinder size needed for a specific retract speed.

Given:

Target Retract Speed = 110 in/min

Rod Diameter = 1 in

Flow Rate = 3 GPM = 693 in³/min

First, find the annular area:

$A = \text{Flow Rate} / \text{Rod Speed}$

$= 693 \text{ in}^3/\text{min} / 110 \text{ in/min} = 6.3 \text{ in}^2$

Now solve for bore diameter:

$6.3 \text{ in}^2 = 0.7854 \times (D^2 - 1^2)$

$\Rightarrow D^2 - 1 = 6.3 / 0.7854 = 8.02 \text{ in}^2$

$\Rightarrow D^2 = 8.02 \text{ in}^2$

$\Rightarrow D \approx 2.83 \text{ in}$

Answer:

Cylinder Bore Diameter = **2.83 inches**

5. Determine the flow rate needed to retract a cylinder at a speed of 30 in/min.

Given:

Speed = 30 in/min

Bore Diameter (D) = 6 in

Rod Diameter (d) = 1.15 in

Annular Area = $0.7854 \times (D^2 - d^2)$

$A = 0.7854 \times (6^2 - 1.15^2)$

$= 0.7854 \times (36 - 1.3225)$

$= 0.7854 \times 34.6775$

$= 27.24 \text{ in}^2$

Volume = Rod Speed $\times$ Area = 30 in/min $\times$ 27.24 in² = 817.2 in³/min

Convert to GPM:

Flow Rate = 817.2 (in³/min) / 231 (in³/gal) $\approx$ 3.54 GPM

Answer:

Flow Rate Needed = **3.54 GPM**

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18.5: How to Calculate the Stroke Time of a Cylinder

Stroke time is the time it takes for a cylinder to **extend or retract** over its **full stroke length** at a known speed.

It is calculated using:

$$\text{Stroke Time (min)} = \text{Stroke Length (in)} / \text{Rod Speed (in/min)}$$

Where rod speed is determined as explained in sections 18.4 and 18.5, depending on the direction of movement (extend or retract).

Alternatively, if only flow and area are known:

$$\text{Stroke Time} = \text{Stroke Length (in)} \times \text{Area} / \text{Flow Rate (in}^3\text{/min)}$$

These calculations are essential when cycle times are critical in automated systems, such as packaging, pressing, or loading equipment.

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CHAPTER OVERVIEW

19: Sequence Valves

19.1: The Function and Application of a Pressure Sequence Valve

19.2: Understanding the Operation of a Direct-Acting Sequence Valve and Its Schematic Symbol

19.3: Describe the Function of a Bypass Check Valve in a Sequence Valve Circuit

19.4: Why a Sequence Valve Is Externally Drained

19.5: The Operation and Schematic Symbol of an Integral Check Valve

19.6: Describe the Function of a Two-Sequence Valve Control Circuit

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19.1: The Function and Application of a Pressure Sequence Valve

Many hydraulic systems are designed to perform tasks in a specific order. This is called a *sequence of operations*, and it is common in industrial automation, machining, and production environments. A simple example is when one actuator—like a clamping cylinder—must finish its movement before a second actuator—such as a drill or press—can begin.

One common way to achieve this sequence mechanically is by using a **hydraulic sequence valve**. This normally closed valve responds to system pressure and opens only when the pressure reaches a set value known as the crack pressure. That pressure typically builds after the first actuator completes its movement and can no longer absorb flow. Once that happens, the sequence valve opens and sends flow to the second actuator, creating a reliable two-step process.

The way the sequence valve works is based on a simple principle: as an actuator reaches the end of its stroke, resistance increases and causes pressure to rise. The sequence valve senses this rise in upstream pressure and responds by opening. That lets oil flow to the next part of the circuit. It's important to note that the valve doesn't "know" whether the actuator has finished—it only knows when pressure has reached the preset threshold.

Physically, a sequence valve looks very similar to a relief valve, and in fact, its internal operation is nearly the same. The major difference is that a sequence valve includes an **external drain line**, which allows internal leakage or spring chamber oil to exit freely to the tank. This is essential because pressure buildup in the spring chamber would interfere with the valve's ability to open at the correct setting. With that being said, a relief valve **cannot** be used as a sequence valve.

These valves are often used in basic sequencing applications where you want to avoid the complexity and cost of an electrical control system. For example, a simple machine tool may use a sequence valve to extend a clamp cylinder before engaging a drill motor, ensuring safe and consistent operation without any electronics involved.

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19.2: Understanding the Operation of a Direct-Acting Sequence Valve and Its Schematic Symbol

In many hydraulic applications —especially in automated machine tools —tasks must occur in a specific order. One typical example is a clamping operation that must be completed before any secondary action, such as drilling, grinding, or pressing, begins. This is where the sequence valve plays a critical role.

A sequence valve ensures that one actuator completes its motion, and pressure builds before another actuator is allowed to operate. In a clamping application, for instance, the valve prevents flow to the second actuator (like a hydraulic motor or a drill) until the clamp cylinder fully extends and holds its position. Only then does the valve open, allowing the next stage to begin. This sequential control is automatic and entirely pressure-driven.

How the Valve Works

There are **two main types** of sequence valves: **direct-acting** and **pilot-operated**. Both serve the same purpose, but the direct-acting type is simpler in construction and is often the first one students learn about. It provides a great foundation for understanding how sequencing is achieved in hydraulic circuits.

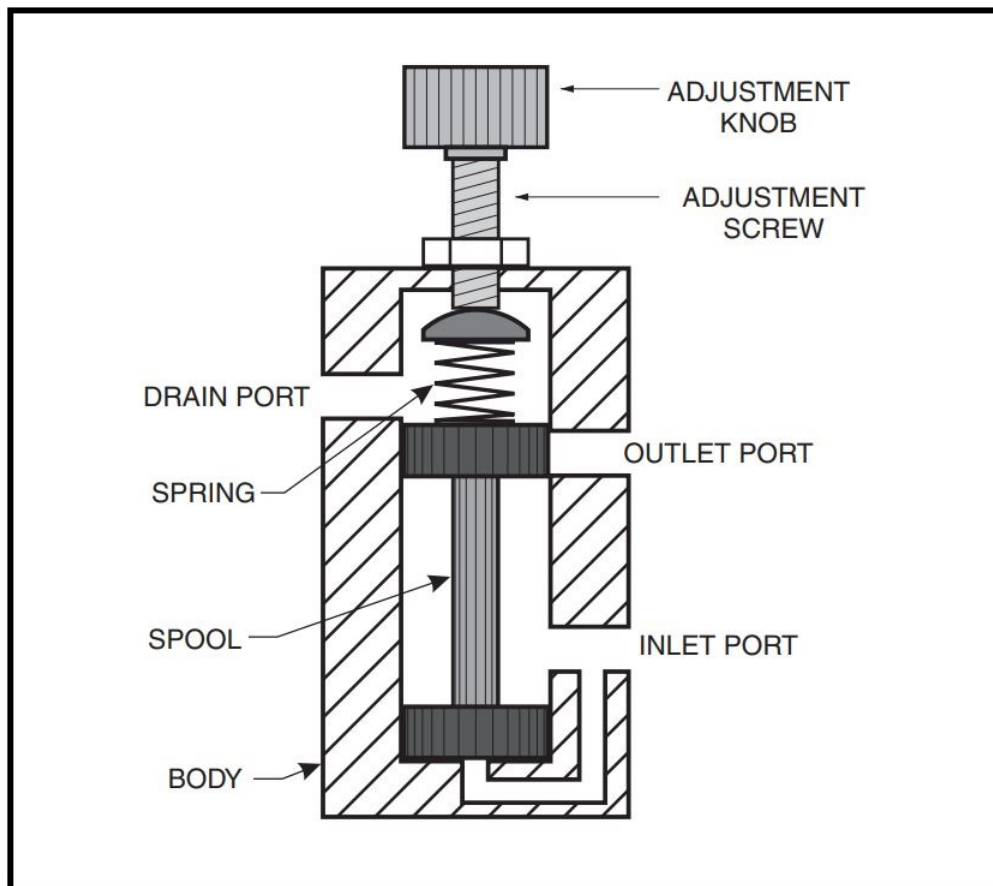


Figure 19.2.1: Schematic representation of a sequence valve.

A direct-acting sequence valve is made up of a valve body, an internal spool, a compression spring, and an adjustable screw or knob to fine-tune the spring tension. The valve has two main flow ports: an inlet (also called the primary port) and an outlet (secondary port), along with a third, smaller drain port connected at the top side of the valve. The inlet port is supplied with oil from the hydraulic system, and the outlet port connects to the next actuator in the sequence.

The spring chamber —where the spool is seated —is isolated from pressure by the smaller drain port, which routes any internal leakage to the tank. This helps ensure that the spring force remains consistent and is not affected by trapped pressure. There's also an internal passage that routes the inlet pressure to the end of the spool opposite the spring.

In its normal state, the valve is closed. The spring holds the spool in a position that blocks the path from the inlet to the outlet. No oil can pass through to the second actuator. However, once system pressure builds to a level high enough to overcome the spring tension, the spool shifts. This opens the path from inlet to outlet, allowing oil to flow through to the next stage of the circuit.

The pressure at which the valve opens is determined by the spring's preload, which is adjustable and is called the set crack pressure. This means you can precisely control at what pressure the next actuator is activated.

Reading the Schematic Symbol

The schematic symbol for a sequence valve resembles that of a relief valve, but with a few key differences. In both symbols, you'll see a normally closed valve with a spring pushing against a movable component (typically an arrow). However, the sequence valve symbol also includes a pilot line that senses pressure from the inlet side and an external drain line coming from the spring chamber.

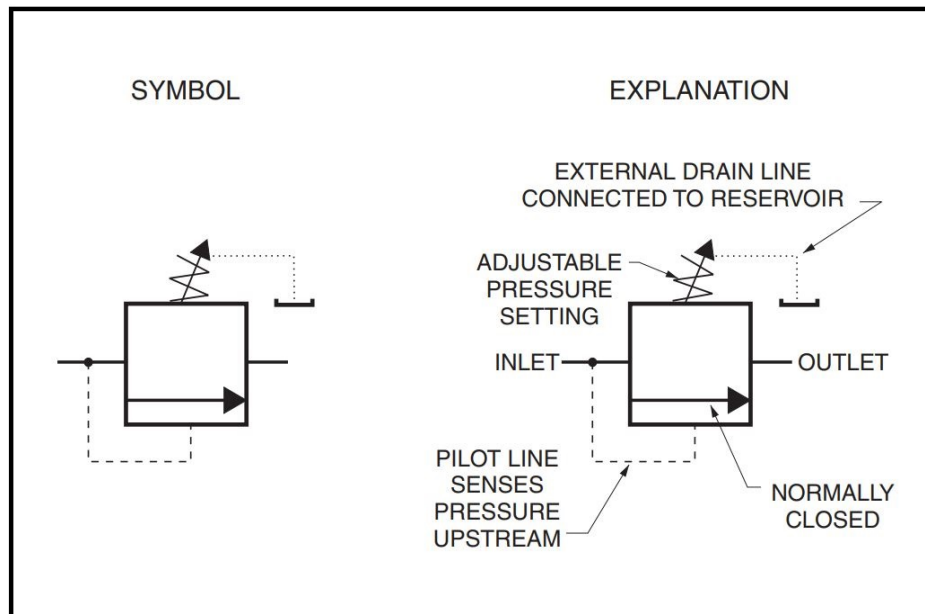


Figure 19.2.2: The schematic symbol for a sequence valve.

This symbol tells us a few important things: the valve stays closed under normal conditions, opens in response to upstream pressure, and relieves internal leakage through the drain. Understanding the symbol is essential for interpreting and designing hydraulic circuits that involve sequencing.

Visualizing the Sequence in Action

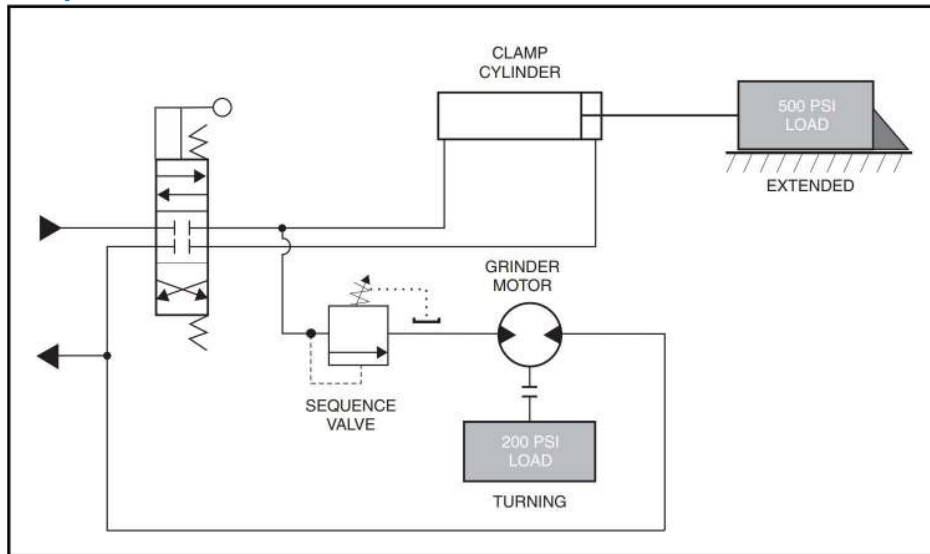


Figure 19.2.3: Schematic representation of valve sequence action.

Consider a circuit where a clamp cylinder and a hydraulic motor are both connected to a directional control valve (DCV), with a sequence valve placed in the line to the motor. When the DCV is shifted to begin operation, oil flows first to the clamp cylinder. Because the sequence valve is normally closed, no oil reaches the motor initially.

The clamp cylinder extends easily, requiring less pressure than the sequence valve's setting. As the cylinder reaches full extension and begins to resist further motion—by clamping onto a workpiece, for example—pressure in the system rises. Once it surpasses the valve's setting (say, 500 psi), the spool inside the sequence valve moves, opening a flow path to the motor. Now the motor begins to operate.

This setup ensures that the clamp cylinder always completes its function before the motor starts. It's worth noting that the pressure at the motor (downstream of the sequence valve) depends only on the load the motor sees. It is not influenced by the upstream pressure that caused the valve to open. That means the valve regulates the *timing* of when flow begins, but it does not control the downstream *pressure* once flow has started.

In the example circuit, the grinder motor requires less pressure than the valve's opening setting. The sequence valve delays flow until the clamping step is complete, and after that, the motor operates based on its own load conditions.

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19.3: Describe the Function of a Bypass Check Valve in a Sequence Valve Circuit

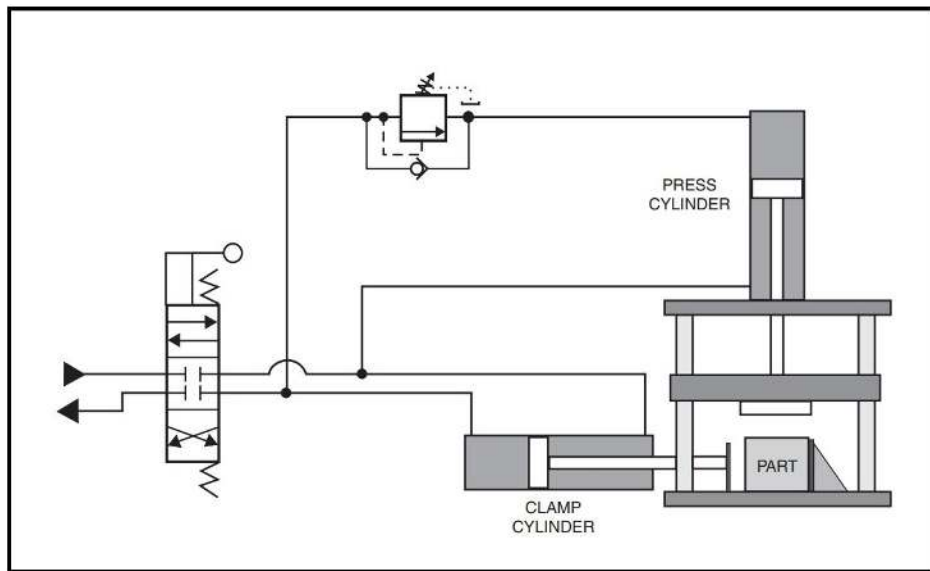


Figure 19.3.1: Schematic diagram of a bypass check valve in a sequence valve circuit.

In the earlier example, we saw how a sequence valve can control the *extension* of actuators. But what happens when the actuators also need to retract—or when oil must flow in the *opposite* direction? This becomes a challenge because a typical sequence valve is a **normally closed valve**. It only allows flow in one direction—*after* pressure builds—so it blocks flow in reverse.

To solve this, we add a **bypass check valve**. This simple but effective addition allows reverse flow around the sequence valve without disrupting the sequencing function in the forward direction.

A common application that uses a bypass check valve is a clamp-and-press machine. In this type of circuit, a sequence valve ensures that the clamp cylinder extends first and holds the workpiece before the press cylinder activates. However, once the press operation is complete, both cylinders need to retract. Without a bypass path, the sequence valve would block flow from the retracting press cylinder, causing a bottleneck or pressure buildup.

Here's how the circuit works:

1. When the directional control valve (DCV) is shifted to extend the actuators, the clamp cylinder moves first at low pressure.
2. Once the clamp is fully extended and pressure rises, the sequence valve opens and the press cylinder extends.
3. At this stage, the **bypass check valve is closed**, allowing the sequence valve to maintain proper control over the timing.

When the DCV is shifted in the opposite direction to retract both cylinders:

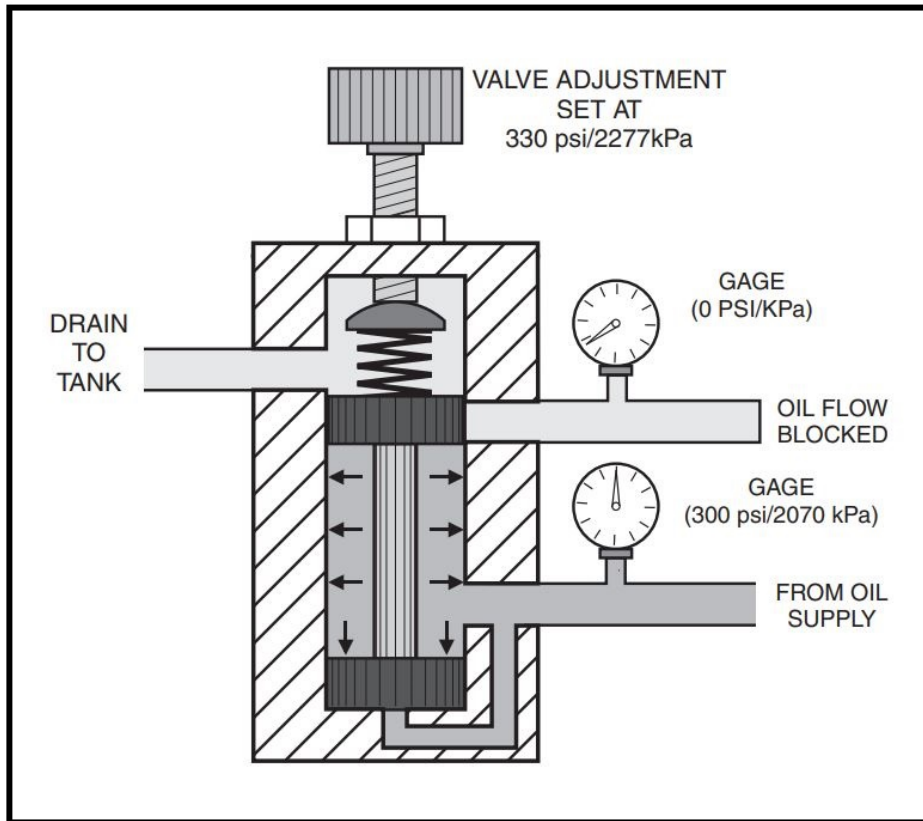
- The oil being forced out of the press cylinder's cap end flows through the **check valve**, bypassing the sequence valve entirely.
- This allows unrestricted return flow to the reservoir and ensures that the press cylinder can retract freely, without delay or back-pressure from the sequence valve.

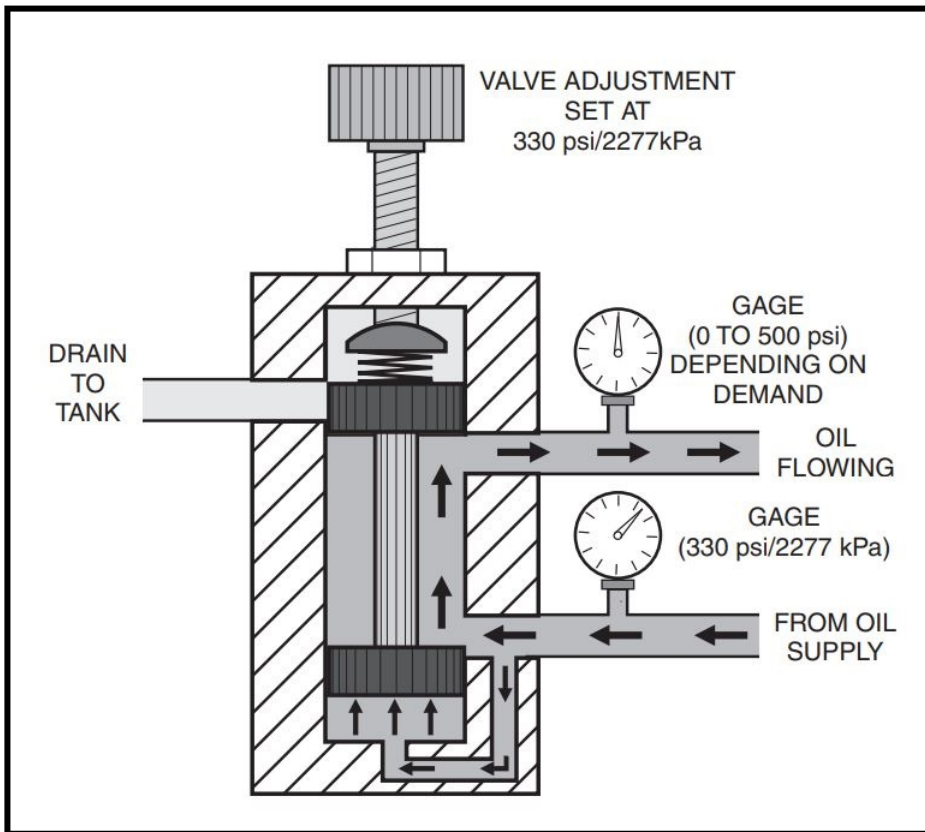
This setup preserves proper sequencing during extension and prevents problems during retraction, making it a reliable and efficient solution for many two-actuator hydraulic circuits.

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19.4: Why a Sequence Valve Is Externally Drained

A key difference between sequence valves and relief valves lies in **how they manage internal leakage**, especially around the spring chamber.





In a **sequence valve**, the **outlet port is typically under pressure** during operation. This can cause oil to seep past internal clearances and into the **spring chamber**. If that oil builds up and becomes trapped, it puts pressure on the back side of the spool. That backpressure can prevent the spool from shifting properly, effectively **locking the valve closed** even when upstream pressure is high enough to open it.

To prevent this issue, sequence valves are **externally drained**. This means that any oil that seeps into the spring chamber is sent directly to the reservoir through a separate, unpressurized drain line. This keeps the spring chamber at or near atmospheric pressure and allows the spool to move freely.

In contrast, a **relief valve** is usually **internally drained**. Since its outlet is connected directly to the tank and is not pressurized, any internal leakage can naturally drain away without interfering with valve operation. This design difference is subtle but critical to ensure the proper function of each valve type in its intended application.

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19.5: The Operation and Schematic Symbol of an Integral Check Valve

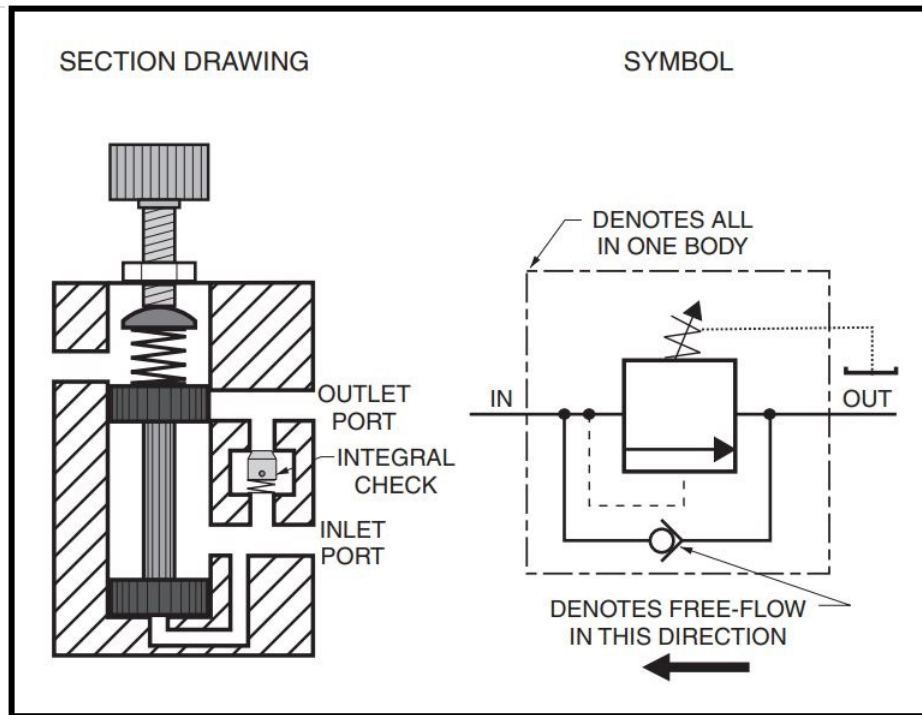


Figure 19.5.1: Schematic representation of integral check valve and its schematic symbol.

In hydraulic systems, we often need to allow flow in one direction while blocking it in the other. When working with sequence valves, one way to manage reverse flow is by adding a separate **bypass check valve**, which is plumbed around the sequence valve externally. This solution works, but it takes up space and adds plumbing complexity.

To simplify things, many manufacturers now offer **sequence valves with built-in check valves**, known as **integral check valves**. These perform the same function as the external check valve but are packaged neatly within the body of the sequence valve itself. This reduces the number of connections, saves space in the circuit, and simplifies assembly and troubleshooting.

The schematic symbol for a sequence valve with an integral check valve includes a small check valve drawn in parallel with the main valve path. This clearly shows that flow is permitted in one direction (usually reverse), bypassing the main valve's control spool.

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19.6: Describe the Function of a Two-Sequence Valve Control Circuit

Some hydraulic applications require very specific timing, not only during **extension** of actuators but also during **retraction**. One such example is a **clamp and drill circuit**, where safety and part control are critical. In this type of circuit, it's important that the clamp cylinder remains extended to hold the part securely until the drill cylinder has fully retracted. Retracting both at the same time could cause the part to shift or be thrown out, creating a safety hazard and risking part damage.

To maintain proper order during both extension and retraction, the circuit uses **two sequence valves**:

- The **first sequence valve** ensures the clamp cylinder extends before the drill cylinder.
- The **second sequence valve**, placed in the return line, controls the order of **retraction**, ensuring the drill cylinder retracts first, followed by the clamp.

This arrangement ensures a safe, controlled, and repeatable sequence in both directions, critical in many production and machining processes where part stability and precision matter.

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CHAPTER OVERVIEW

20: Pressure Reducing Valves

[20.1: The Function of a Pressure Reducing Valve and Application](#)

[20.2: The Operation of a Direct-Acting Pressure Reducing Valve \(PRV\) and Schematic Symbol](#)

[20.3: The Function of a PRV's Bypass Check Valve](#)

[20.4: Why a PRV Is Externally Drained](#)

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20.1: The Function of a Pressure Reducing Valve and Application

When working with multiple actuators in a single system, there are times when one part of the circuit needs to operate at a **lower pressure** than the rest. This is where a **pressure reducing valve (PRV)** comes into play.

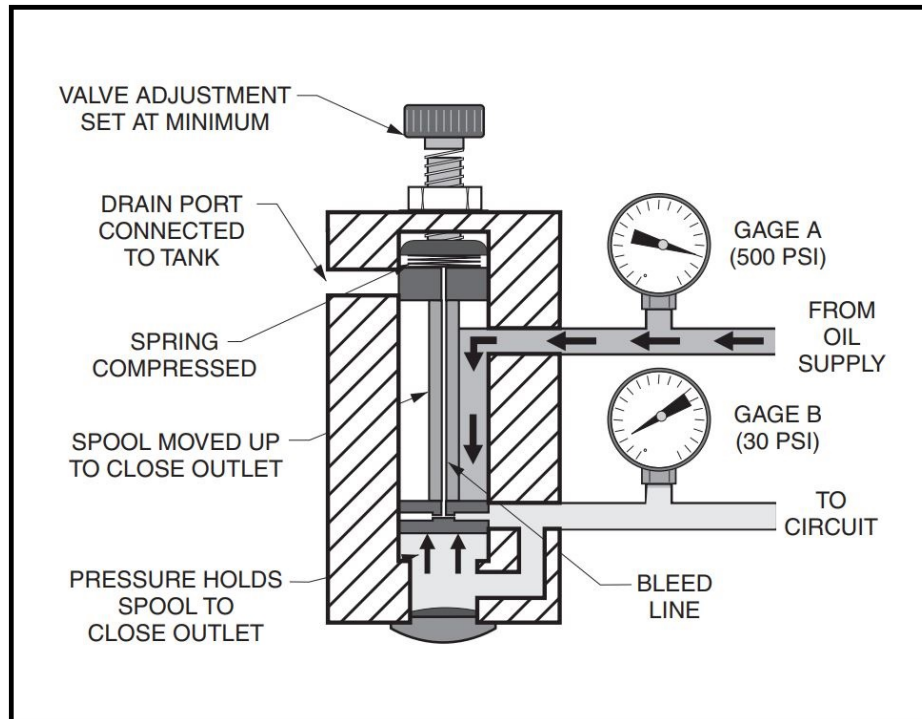


Figure 20.1.1: Diagram of a pressure reducing valve with the valve adjustment set at minimum.

The PRV is designed to **limit pressure downstream** of its location, protecting components or materials that could be damaged by higher forces. A common example is in a **clamp and drill circuit**, where the clamp holds a fragile or thin-walled workpiece, such as an aluminum or plastic tube. Applying the system's full pressure to the clamp could deform or collapse the part.

Here's the key concept: because of Pascal's Law, pressure in a system is uniform, and both actuators would receive the same pressure during parts of the cycle. So, if the system pressure is high enough to drive the drill cylinder, it might be too high for the clamp.

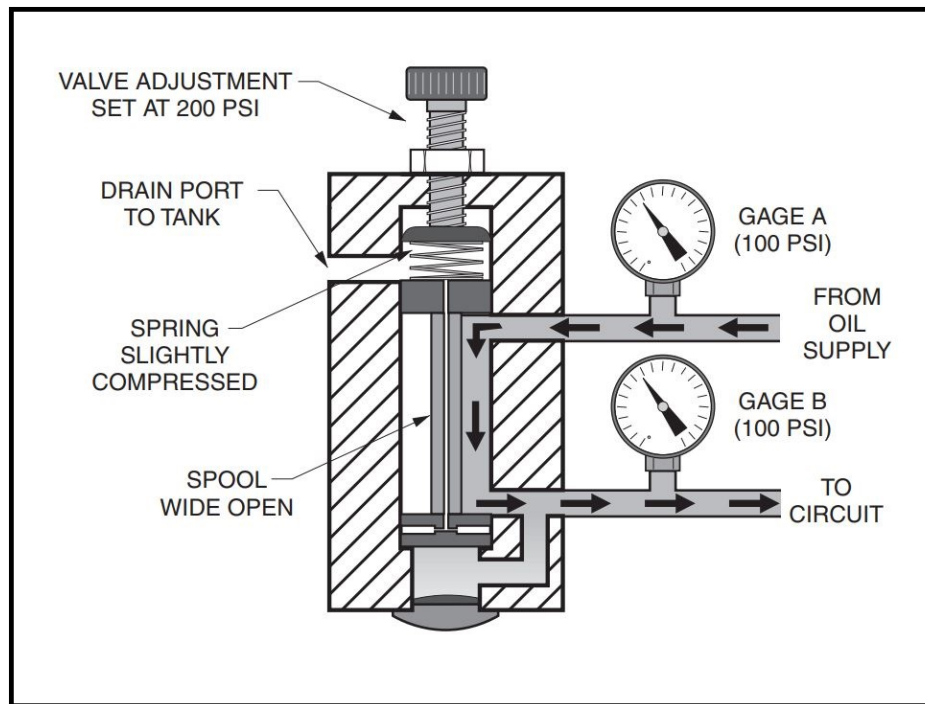


Figure 20.1.2: Diagram of a pressure reducing valve with the valve adjustment set at 200 PSI.

To fix this, a **pressure reducing valve** is installed in the clamp cylinder's branch of the circuit. It holds downstream pressure to a preset level, limiting the force applied by the clamp, regardless of the higher pressure in the rest of the system.

Physically, the PRV looks very similar to a relief valve. The critical difference is in **how it senses pressure**: the PRV responds to **downstream pressure**, whereas a relief valve responds to **upstream pressure**. This internal design distinction ensures the PRV holds the pressure in the clamping circuit at a safe and steady level throughout the operation.

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20.2: The Operation of a Direct-Acting Pressure Reducing Valve (PRV) and Schematic Symbol

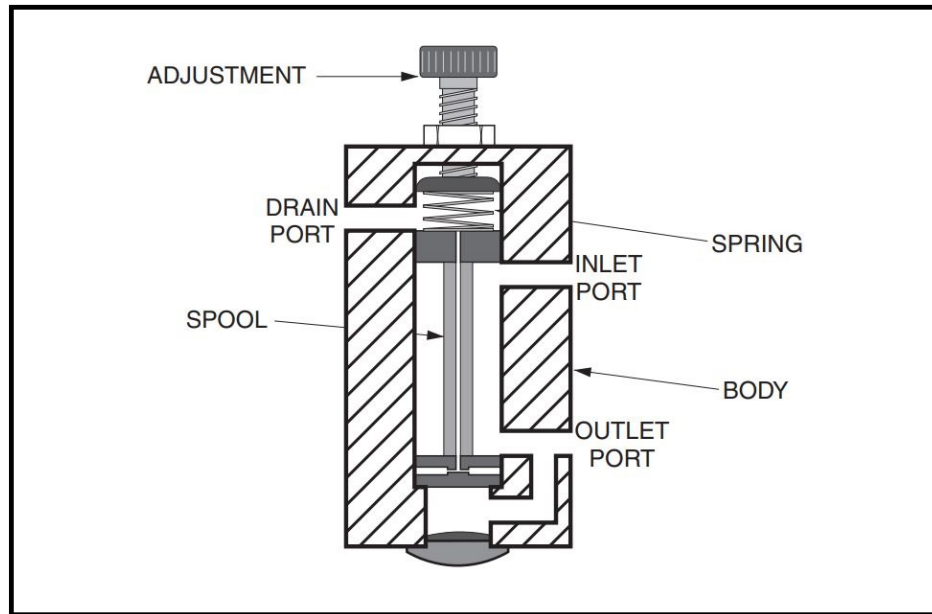


Figure 20.2.1: Diagram of a direct-acting pressure reducing valve.

Pressure reducing valves are essential components in circuits where pressure needs to be limited in just one part of the system. These valves are available in **direct-acting** and **pilot-operated** designs. Both types serve the same function, but the **direct-acting PRV** is simpler in construction and operation, making it easier to understand when you're first learning how pressure regulation works in hydraulics.

A **direct-acting pressure reducing valve** typically includes four main components:

- A valve body
- A spool or poppet
- A spring
- An adjustable screw or knob for setting pressure

Inside the valve body, you'll find **two main ports**: the **inlet**, which connects to the main hydraulic supply, and the **outlet**, which feeds a lower-pressure branch of the system. There's also a **drain port**, which plays an important role in valve function and reliability.

The valve is normally open, meaning that under no pressure, fluid flows freely from the inlet to the outlet. The spring holds the valve in this open position. As system pressure builds on the **downstream (outlet) side**, a sensing passage routes this pressure to the back side of the spool, opposite the spring.

As downstream pressure increases, it pushes against the spool. When this pressure force exceeds the spring force (as set by the adjustment screw), the spool begins to close the valve, restricting flow and maintaining the desired reduced pressure in that part of the system.

One detail that often trips students up: the **drain port**. Any internal leakage that enters the spring chamber needs a way to escape. Without proper drainage, this fluid would build pressure behind the spool, preventing it from moving freely. That's why the spring chamber must be **externally drained**—and this drain must connect directly to tank, not to any pressurized line.

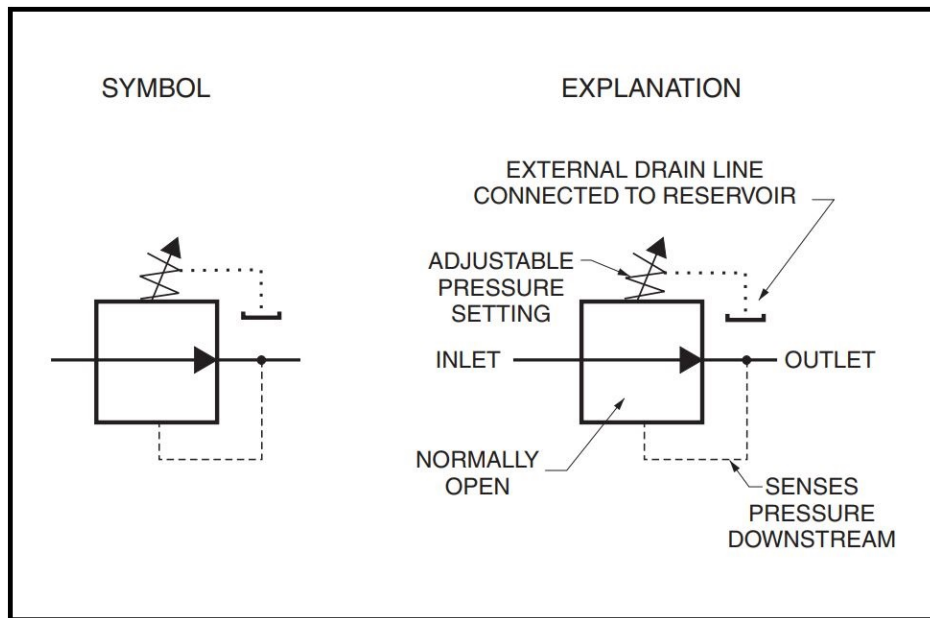


Figure 20.2.2: Schematic symbol for a direct-acting pressure reducing valve.

The **schematic symbol** for a direct-acting pressure reducing valve looks similar to a relief valve but with key differences:

- It is shown as **normally open**.
- It includes a pilot line that senses **downstream pressure**.
- It has an **external drain line**, usually shown in shorthand as connecting back to the reservoir or the return line.

This symbol will be used when adding the PRV to the clamp-drill circuit you've studied previously. By regulating the pressure to the clamp branch of the circuit, the valve ensures that delicate components, such as thin-walled tubing, aren't crushed by excessive force.

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20.3: The Function of a PRV's Bypass Check Valve

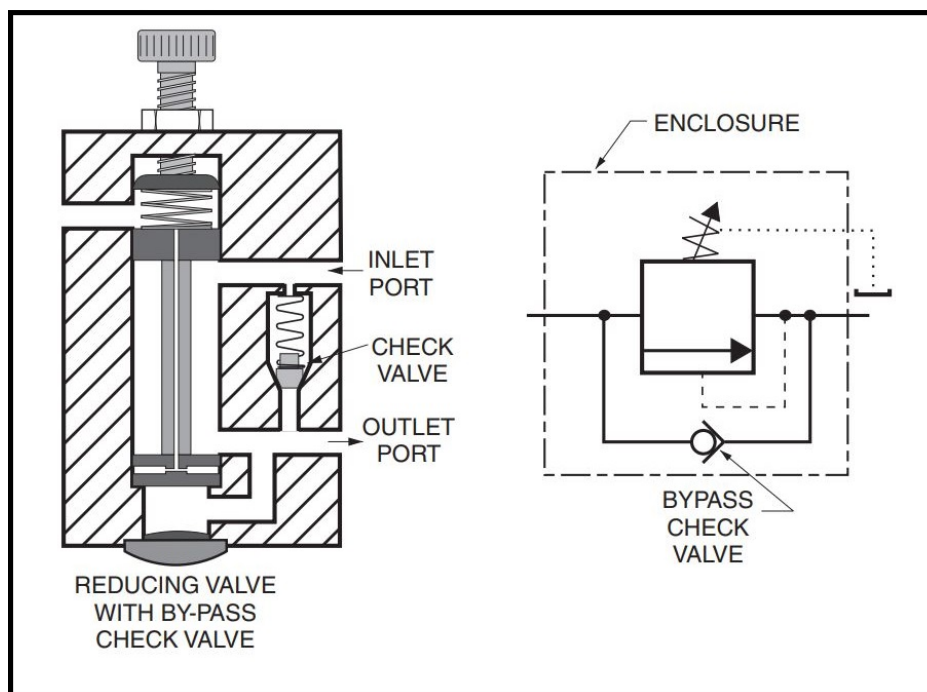


Figure 20.3.1: Diagram and schematic representation of a pressure reducing valve with by-pass check valve.

Even though a pressure reducing valve is normally open, **reverse flow through it isn't always reliable**. Under certain conditions, especially in **fast-cycling circuits**, pressure pulses can appear at the outlet. If these pulses are higher than the valve's set pressure, the valve may suddenly snap shut—even when you don't want it to. This unintended closure can **block return flow**, potentially causing system malfunctions or unwanted actuator behavior.

To prevent this, many systems include a **bypass check valve**. This check valve is connected **in parallel** with the pressure reducing valve and allows fluid to flow freely in the **reverse direction**, bypassing the PRV altogether.

There are two common ways to include this check function:

1. **Externally** – By plumbing a standalone check valve around the PRV.
2. **Internally** – By using a pressure reducing valve that has a **built-in (integral) check valve**, which is more compact and efficient.

The integral check valve allows reverse flow without affecting the pressure-reducing function during normal forward flow. This is especially useful in circuits where actuators need to return quickly or where pressure pulses are unavoidable.

The **schematic symbol** for a pressure reducing valve with an internal check valve includes a check valve drawn in parallel with the main valve symbol. This visual cue tells you that the valve can control pressure in one direction and allow unrestricted flow in the other.

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20.4: Why a PRV Is Externally Drained

Like sequence valves, **pressure reducing valves need external drainage** to operate properly, especially under sustained pressure conditions.

Since the outlet side of the PRV is pressurized, oil tends to **leak past the spool or poppet and into the spring chamber**. If this leakage is allowed to accumulate, it creates pressure behind the spool. That pressure resists spool movement and interferes with the valve's ability to close properly.

If the spool can't move, the valve can't control pressure accurately.

This is why an **external drain line** is used. It provides a dedicated, unpressurized path for any leaked fluid to return directly to the tank. The drain line must never be blocked or routed into a pressurized return—doing so could trap oil in the spring chamber and disable the valve's operation.

In short:

- **Relief valves** don't need external drains because their outlet is already connected to an unpressurized tank line.
- **PRVs**, on the other hand, do require external drains because their **outlets remain pressurized**, and leakage must be properly managed.

This difference might seem small, but it makes a big impact on circuit reliability and safety.

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