Contents

Chapter 1: Overview

Objectives

The objective of this manual is to explain what solenoid valves are, how they work, and how HydraForce uses them. The manual begins with the basics and builds on concepts discussed in each chapter. Each of these chapters have their own objective which include:

- Understand the basic principles which govern the physics behind an electro-magnetic solenoid actuator.
- Learn how these basic principles interact and influence the efficiency of a solenoid actuator.
- Identify the various types and shapes of solenoid actuators such as push, pull and proportional type armatures as well as flat versus conical construction.
- Understand why certain actuators are used with certain types of valves.
- Understand coil construction used by HydraForce today.
- Learn how the various armatures are constructed.
- Understand basic valve design.
- Identify the forces acting on spool type valves and poppet valves.
- Recognize the difference between normally open and normally closed poppet valves, direct acting poppet solenoid valves and spool valves available from HydraForce.
- Discuss some common installation considerations that should be taken into account as well as alternative uses and modifications.

Summary of Chapters

Chapter two discusses basic electrical terms, amps, volts, ohms, watts, Ohms' Law and power. These concepts are needed as a basis to understand the components of the solenoid valve and how it works. An analogy between hydraulic and electric properties is shown in addition to the differences between AC and DC current and the function of a full wave bridge rectifier.

Chapter three also serves as a basis for understanding the solenoid valve and how it works. It discusses the basic magnetic terms, including magnetic flux, magnetic fields, induction, permeability, saturation and magneto-motive force.

The basics of solenoid force are reviewed in chapter four. These include discussions of the basic components of an electromagnetic actuator, armature and pole piece shapes, and parameters which determine solenoid force. A relationship of how these parameters affect the force available is also shown.

The remaining chapters detail HydraForce specific products. Chapter five discusses standard HydraForce coil and actuator construction. Waterproof coil construction is discussed in chapter six and explains the differences between it and standard coil construction.

Valve construction is reviewed in chapter 7 and identifies the two basic types of valves, poppet and spool as well as the components of each.

Valve design is the topic in chapter eight. Basic hydraulic components in spool and poppet valves are described. The springs used in valves, balance of forces and response time are also outlined.

The types of solenoid valves available from HydraForce are listed in chapter nine. These include a discussion on pilot operated poppet valves, direct acting poppet valves and spool type valves.

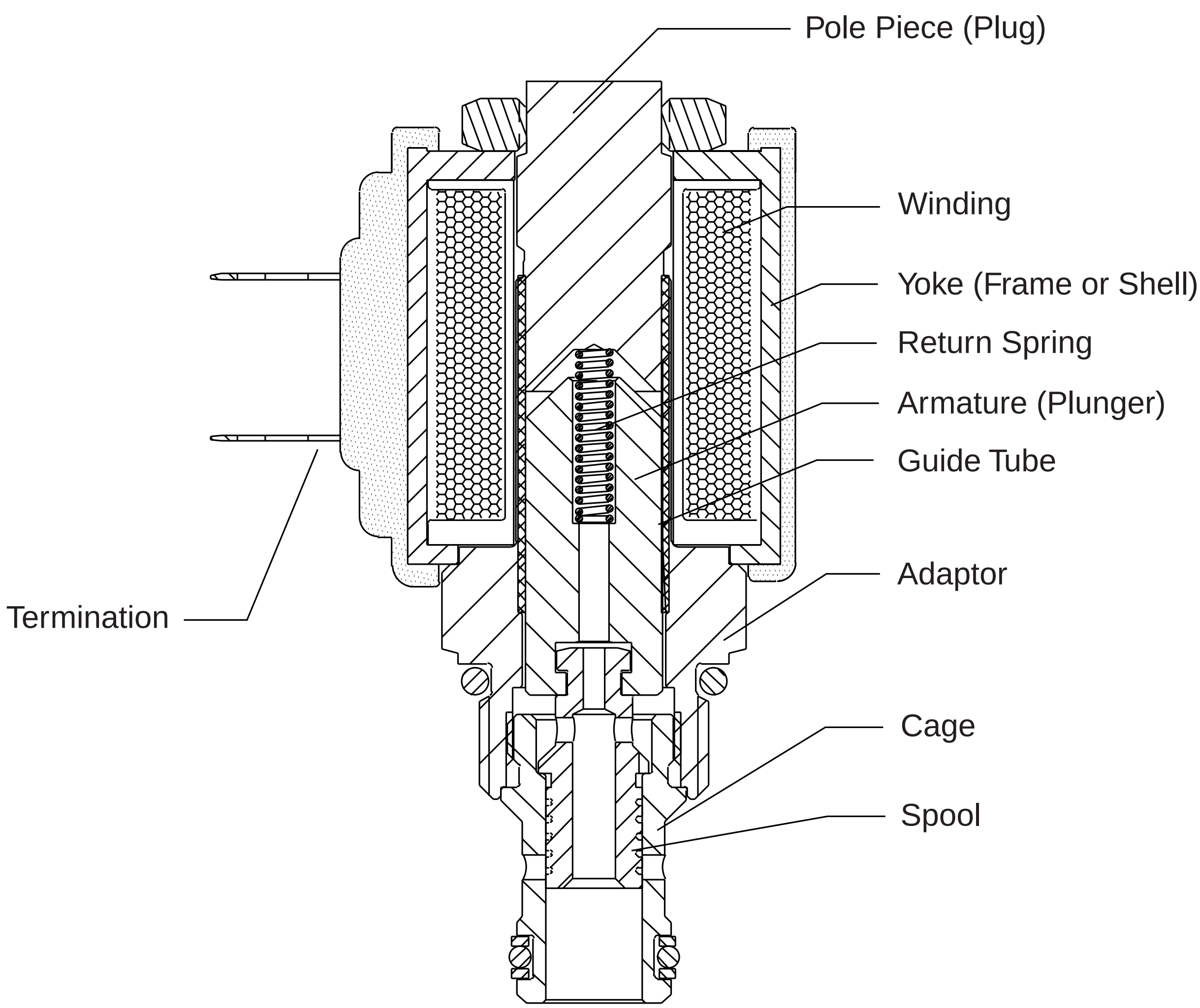
Installation considerations are mentioned in chapter ten and touch on fluid compatibility issues, environmental concerns, voltage considerations, back EMF, arc suppression and duty cycles.

What is a Solenoid Valve?

A solenoid valve is one which uses an electromagnetic actuator to move a hydraulic control element such as a poppet or spool.

An electromagnetic actuator takes electricity and converts it into magnetic force. Magnetic force is used to move the armature which in turn controls the spool or poppet and direction of flow.

Solenoid is a nickname given to a set of valves which use an electromagnetic actuator to shift the hydraulic control element.



De-Energized Solenoid Valve

Notes

Chapter 2: Basic Electrical Terms

Objectives

The objectives for this chapter are as follows:

- Understand the basic electrical principles of power, resistance, current and voltage.
- Draw an analogy between electric and hydraulic concepts.
- Display an understanding of the differences between AC and DC.
- Understand what a full wave bridge rectifier is, why it is used and how it works.
- Learn how resistors in series and parallel are added together.

Introduction

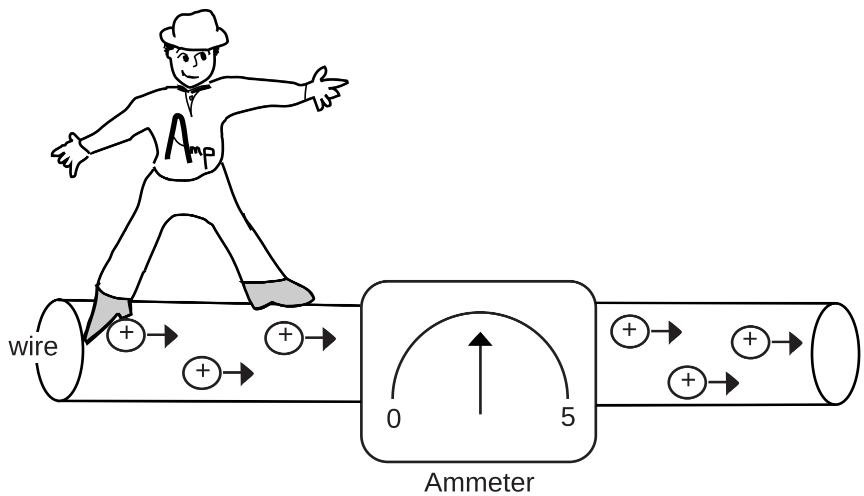
A basic knowledge of some general electric terms and concepts is necessary to understand the various components of the solenoid valve and how it works. These concepts will be defined in the following sections and will be used as a building block for the following chapters.

Amps

An ampere (amp) is the steady electrical current that when flowing in straight parallel wires of infinite length and negligible cross section, separated by a distance of one meter in free space, produces a force between the wires of 2 x 10^{-7} newtons per meter of length.

Another definition is the amount of charge that passes through a wire at a given point, in a given second. The measure of charge is a Coulomb, and one Coulomb per second is an Ampere.

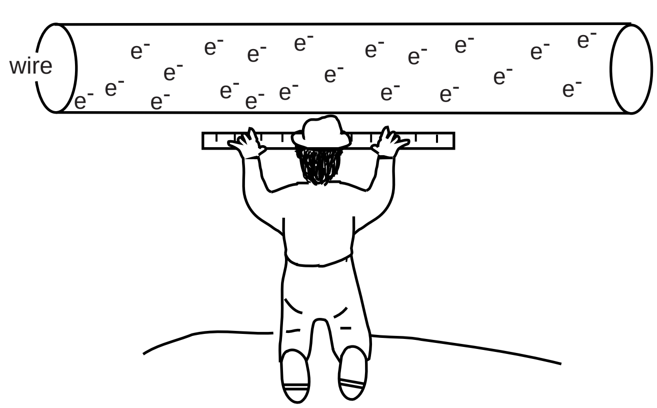
Throughout this manual, the flow of current will be designated as the flow of positive charges. These positive charges flow opposite to the flow of electrons.



Volts

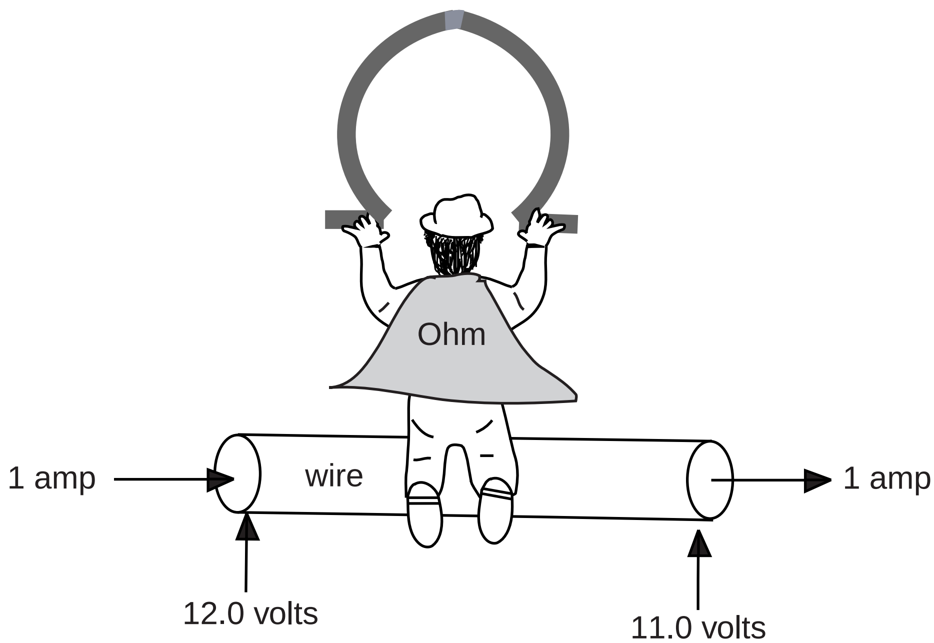
A volt is a unit of electric potential and electromotive force, equal to the difference of electric potential between two points on a conducting wire, carrying a constant current of one ampere when the power dissipated between the points is one watt. Electric potential is the amount of voltage available to flow from one end of circuit to another.

Simply stated, a volt is a measure of electric potential between two points on a wire. The term Electromotive Force (EMF) is used interchangeably with volts.



Ohms

An ohm is a unit of electrical resistance. It is equal to a current of one ampere produced by a potential of one volt across a conductor (wire). An ohm is represented by the Greek letter omega (Ω).



Watts

A watt is the measurement of power. Watts equals current multiplied by voltage (I x V), current squared times resistance (I^2 x R) or voltage squared divided by resistance (V^2 / R). One watt is the power used for one ampere to flow through one ohm.

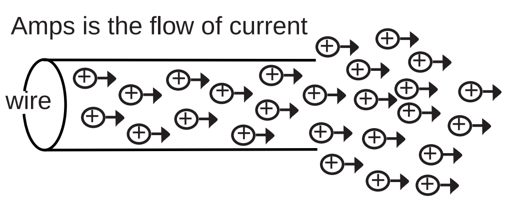
A watt can also be defined as one joule per second with one joule being a unit of energy.

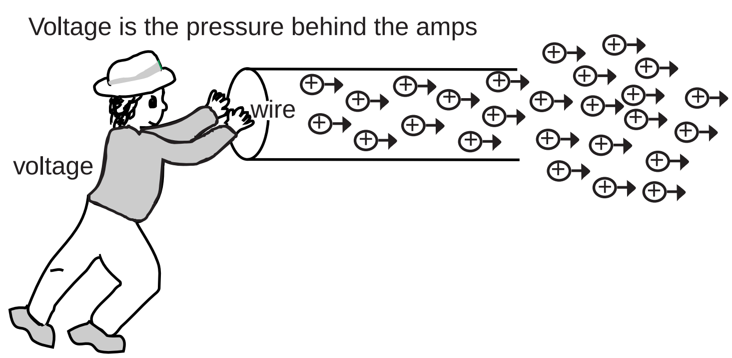
Analogy Between Hydraulic and Electric

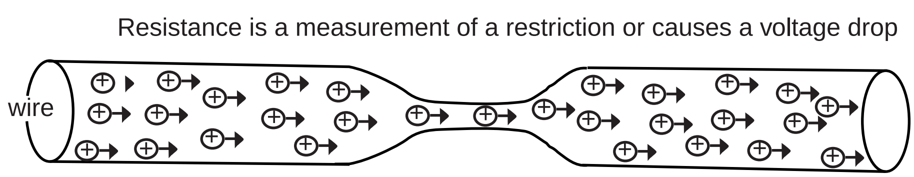
Amps (I) is the flow of current (the flow of electrons) and is analogous to the flow of fluid. One amp means that one coulomb flows past a point in a circuit every second.

Voltage (V) is the pressure behind the amps. This is the unit of pressure that pushes the current through a circuit. One volt will push one ampere through a resistance of one ohm.

Ohm (R) is the unit of restriction to the flow of current. One ohm is the quantity of resistance causing a potential drop of one volt when the current through it is one amp.





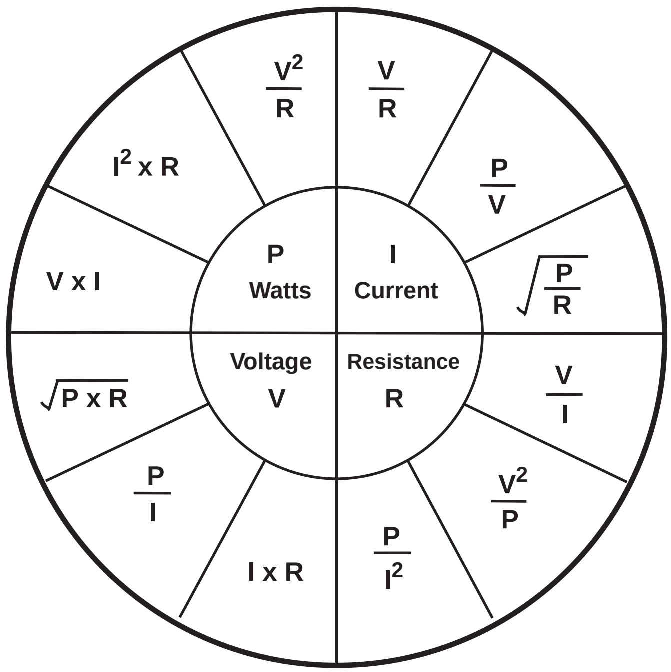


Ohm's Law

Ohm's Law is a relationship between voltage (V), current (I) and resistance (R) and can be defined by the formula V = I x R. This relationship shows that voltage is directly proportional to current multiplied by the resistance.

Formulas

The following wheel of formulas shows the relationship between power and Ohm's Law. If two of the following parameters, P, I, V or R are given, use the formula wheel below to find the other two.



Examples

Looking at several examples, we will see how varying one of the parameters, current (I), resistance (R), power (P) or voltage (V) will affect the others. To understand what will happen with each parameter in the following examples, refer to the formula wheel above.

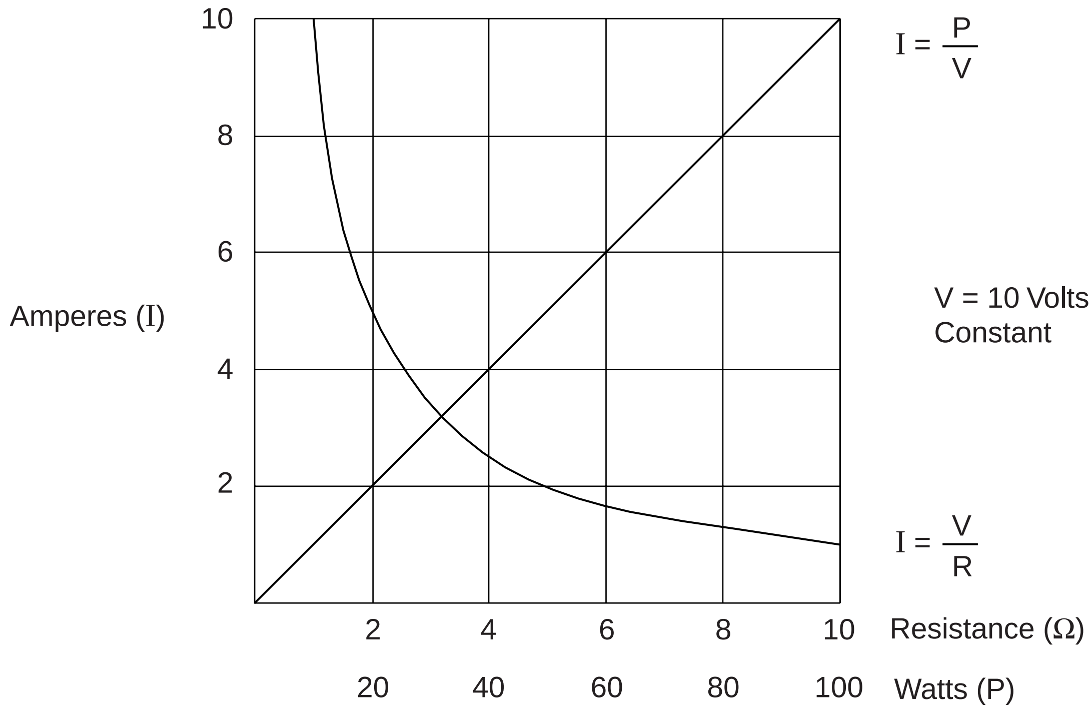
Example 1

Assume that voltage is held constant and current, power and resistance vary. Refer to the formula wheel and select the relationship for each parameter in the current section.

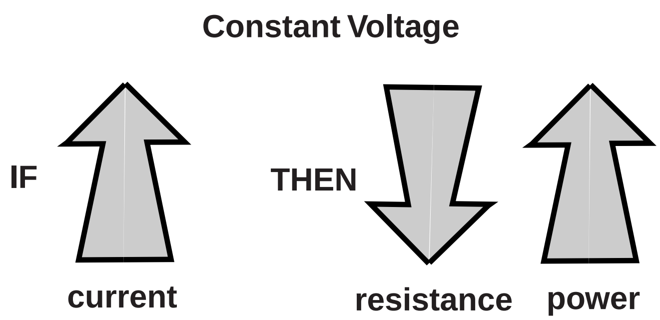
For current, I = V/R. If V is constant and the resistance varies, then I varies inversely. In other words, as resistance increases, current decreases.

In the relationship I = P/V, still assuming that voltage is held constant, power and current vary in direct proportion. In other words, as power increases, current increases.

Both of these relationships are shown graphically in the following diagram.



These concepts can be summarized as:



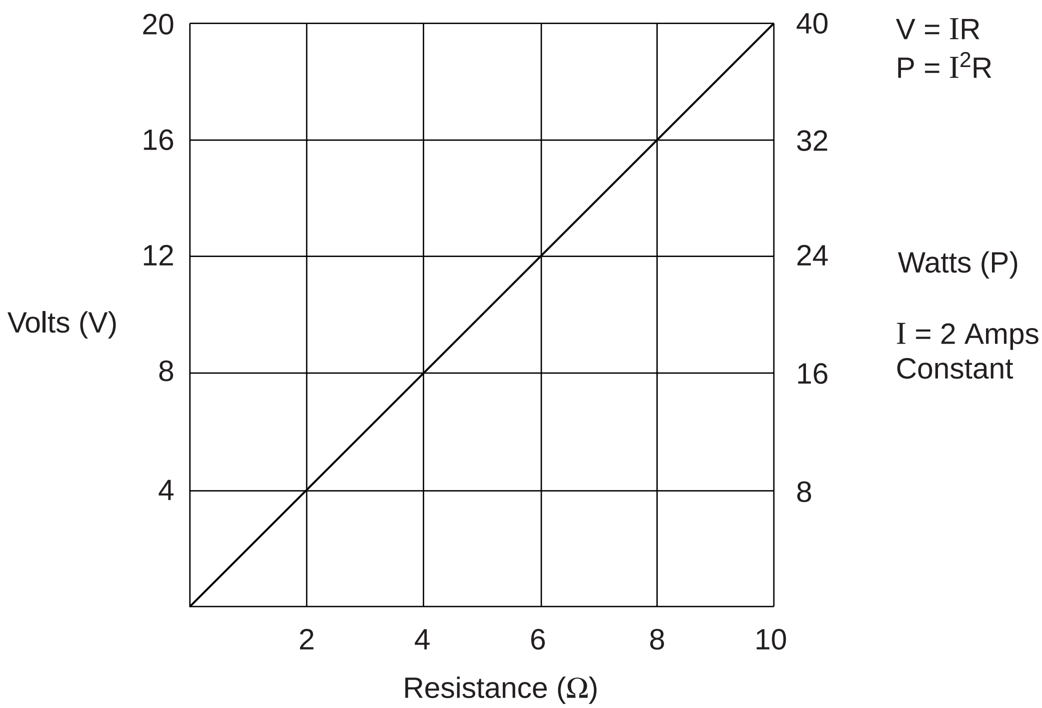
Example 2

Assume that current is held constant and voltage, power and resistance vary. Once again, refer to the formula wheel and select the relationship for each parameter in the voltage section.

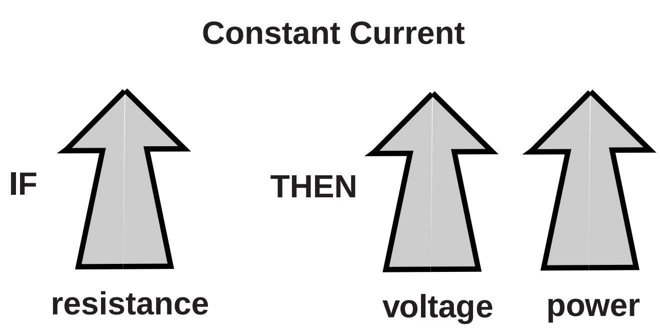
For voltage, V = IR. If I is constant and the resistance varies, then V varies proportionally. In other words, as resistance increases, voltage increases.

In the relationship $P = I^2 R$, still assuming that current is held constant, power and resistance vary in direct proportion. In other words, as resistance increases, power increases.

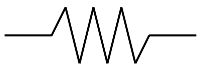
Both of these relationships are illustrated in the following graph.



These concepts can be summarized as:



Basic Electrical Symbols

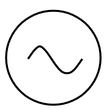


Resistor

A resistor is used to represent a part of an electrical circuit where a voltage drop occurs. A resistor typically dissipates electrical energy in the form of heat. It can represent a long wire, a coil or any device which causes a voltage drop.

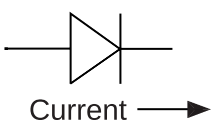
Battery Source

The battery source symbol is used to represent an electrical potential source that outputs DC (direct current).



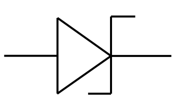
AC source

An AC (Alternating Current) source is associated with industrial applications where 110 volts and 220 volts AC are available.



Diode

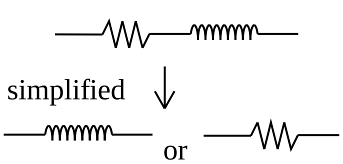
A diode is a device which allows current to flow in one direction only. The direction of the arrow shows the flow of current. The current is blocked from flowing in the opposite direction.



Zener Diode

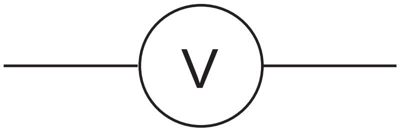
A zener diode is similar to a basic diode. The difference is that it blocks current until a certain voltage is reached, then passes current to maintain a voltage.

Resistor / Inductor



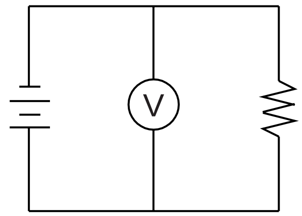
Solenoid coil

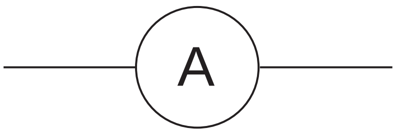
A solenoid coil is made up of two elements; an inductor and a resistor. The majority of applications require that only the resistance portion of the coil to be known. The inductance usually only needs to be known where solid state electronics are used in the application.



Voltmeter

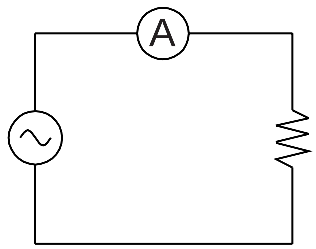
A Voltmeter is used to measure voltage or electromagnetic force. It is connected across a load (resistor) or source in parallel. See the following diagram for an example of a voltmeter connection in a circuit.





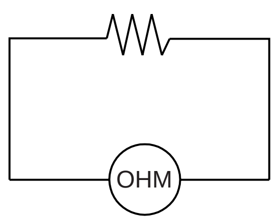
Ammeter

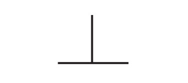
An Ammeter is used to measure current. It is connected in series between a load and a source. See the following diagram for an example of an ammeter connection in a circuit.



Ohmmeter

An Ohmmeter is used to measure the resistance of a conductor on a device.





Push Button Switch

A Push Button Switch and a Switch typically represent a mechanical on/off switch. They may also be used to represent a relay.

Switch

Resistors in Parallel and Series

Occasionally it is necessary to determine the equivalent resistance of a circuit. This may be done in order to determine the current, voltage and power available at the device which we want to actuate.

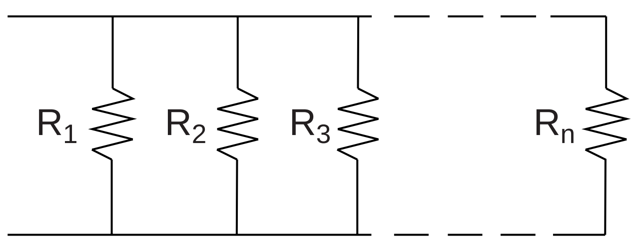
Resistors can be placed in series or in parallel. The following sections show how to calculate the equivalent resistance of several resistors in series or in parallel.

Resistors in Series

The equivalent resistance of resistors in series is found by adding each separate resistance. $R_{total} = R_1 + R_2 + R_3 + \ldots\ldots + R_n$

Resistors in Parallel

In parallel, the total resistance is found by summing the inverse of all the resistances. $1/R_{total} = 1/R_1 + 1/R_2 + 1/R_3 + \ldots\ldots 1/R_n$.

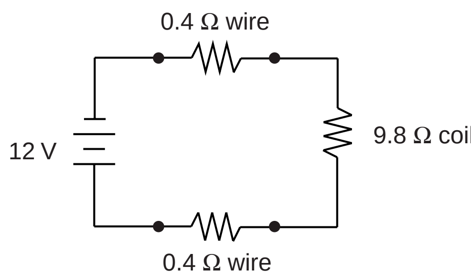


Example

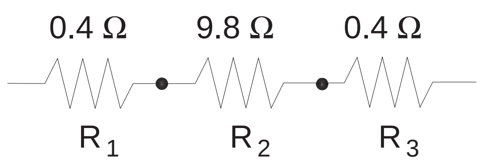
The following is an example of how to calculate the total resistance in a circuit in order to calculate the voltage and power across the load.

A 9.8 ohm coil has a 10 foot wire run between both ends of the coil and the battery. What is the power draw of the circuit? What is the voltage drop and power draw across the coil? Assume that the resistance of the wire is 0.4 ohms.

Step 1: Draw the required electrical circuit.



Step 2: Determine the equivalent resistance.



Recall that resistors in series add directly.

$R_{total} = R_1 + R_2 + R_3$

$R_{total} = 0.4 + 9.8 + 0.4$ ohms

$R_{total} = 10.6$ ohms

Step 3: Use Ohm's Law to determine the current draw.
Recall the formulas V=IR or I= V/R.

I = V/R

I = 12V / 10.6 ohms

I = 1.13 Amps

Step 4: Determine the power draw.

Recall $P = V^2/R$

$P = (12\ V)^2$ / 10.6 ohms

P = 13.58 watts

Step 5: Determine the voltage drop across the coil.

Recall V = IR

V = (1.13 Amp) (9.8 ohms)

V = 11.07 V

Step 6: Determine the power draw of the coil.

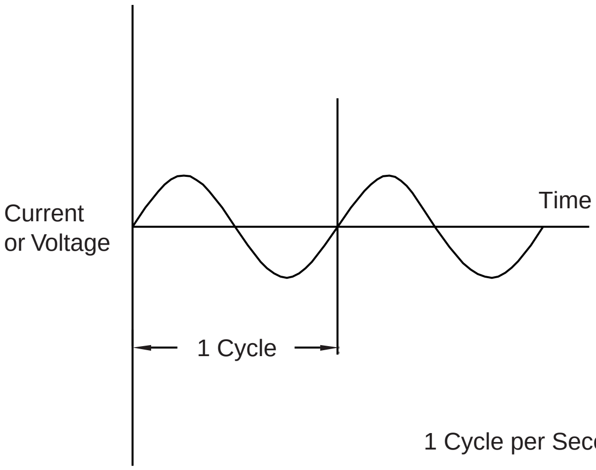
Recall P = IV

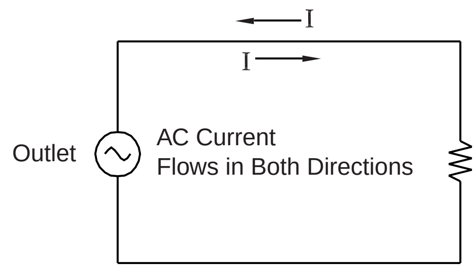
P = (1.13 Amp) (11.07 V)

P = 12.5 Watts

Alternating and Direct Current

Alternating current or AC is an electric current that reverses direction in a circuit at regular intervals. The following graph illustrates an AC sine wave. A representation of AC flow can also be seen in the following diagram.



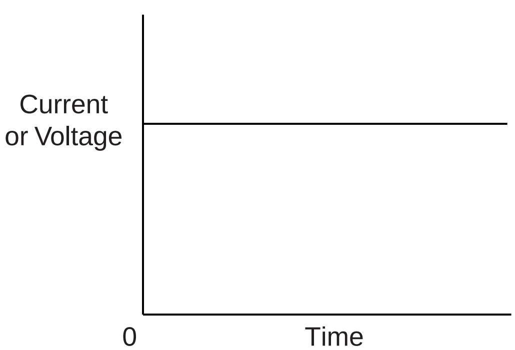


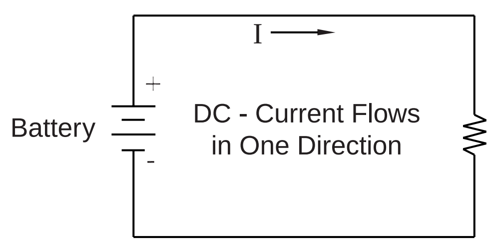
1 Cycle per Second = 1 Hertz (Hz)

USA: 60 Cycles per Second = 60 Hertz

Europe: 50 Cycles per Second = 50 Hertz

Direct current or DC is an electric current flowing in one direction only. DC can be shown graphically as a straight line with no sine wave as illustrated in the following graph. A representation of the current flow from a battery, can also be seen in the following diagram.





AC and DC are used in different types of applications due to their physical nature. DC is typically used in such applications as mobile construction equipment in which batteries are used. AC is typically used in industrial applications where 110 and 220 volts are available.

When DC is not available, AC can be converted into DC and typically is for the following reasons:

- DC is required for electronics because electronic devices work in an on/off state. AC is constantly changing direction and the electronic device would not know if the current were on or off.
- Solenoids are typically DC operated. The reasons for this are discussed in the following chapters.

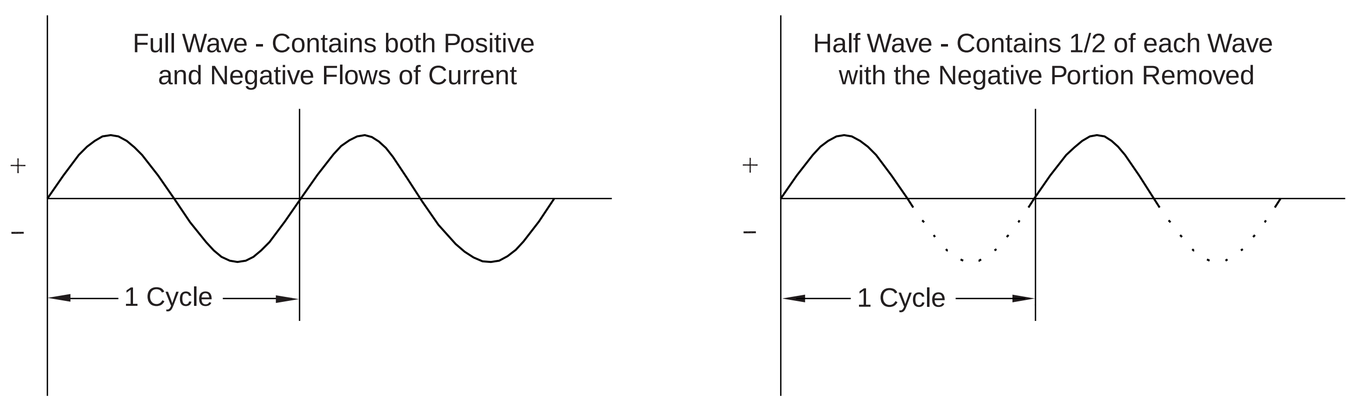
Rectifier

Current is converted from AC to DC by use of a rectifier. There are two types of rectifiers which will be discussed in the following sections, the full wave rectifier and the half wave rectifier. Both rectifiers operate on the full AC sine wave, however, the half wave rectifier has the negative portion of the wave removed. The type that is used in the majority of solenoids is the full wave bridge rectifier.

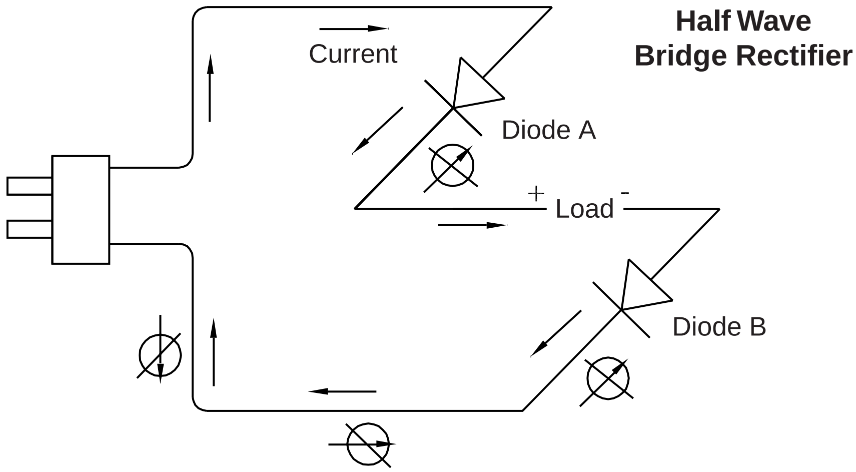
A rectifier consists of a series of diodes which invert the negative portion of the AC signal into positive current. This, in effect changes the current from AC to DC.

In a half wave rectifier the positive current is allowed to flow and the negative current is blocked by the use of the diode. Refer to the following illustration.

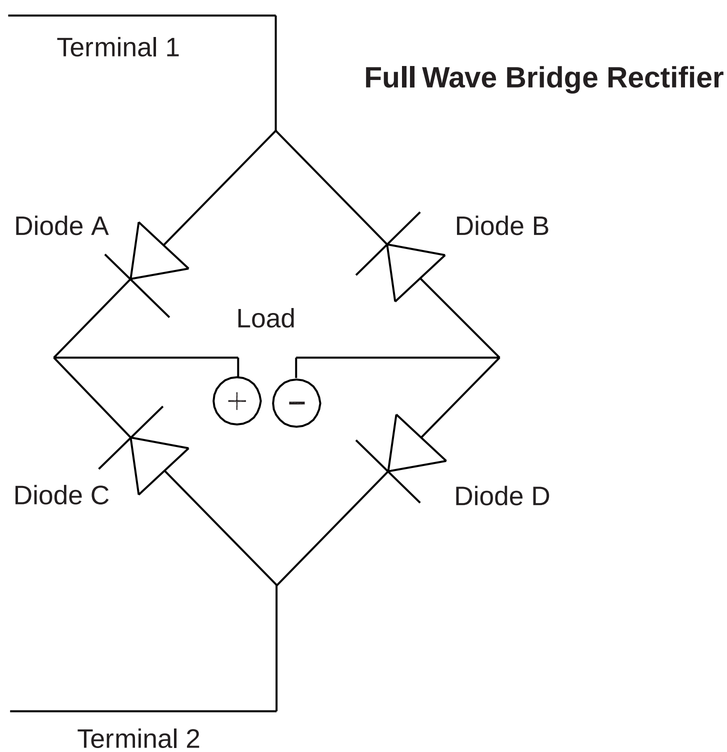
AC Sine Wave



This type of rectifier is typically not used because the average current would be too low for normal applications. The current is too low because it is off half of the time.



A full wave rectifier however, uses the full sine wave. Refer to the following illustration as the path of the current is outlined.



The AC current enters the circuit at terminal 1 and begins flowing through diode A. It then crosses the load, travels down through diode D and exits the circuit through terminal two. In the reverse direction, the current enters the circuit at terminal two, flows through diode C, back across the load, through diode B and then out through terminal 1.

Recall that DC current flows in one direction only. As we followed the path of the current, the load never saw a change in the direction of the current. Since the current did not appear to change directions, it never changed signs across the load, and is therefore converted from AC into DC through the use of the full wave bridge rectifier.

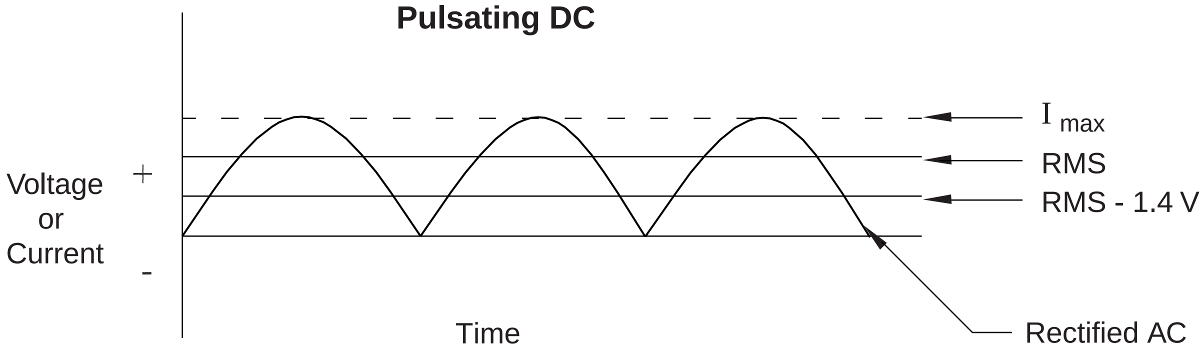
Pulsating DC

The AC is now rectified and the device, such as a solenoid, sees pulsating DC. Recall that DC has no sine curve and can be graphed as a flat line. It is continuous current and does not change signs across the load. The AC sine wave is a series of rises and drops from negative to positive. Rectified AC does not change signs from negative to positive. The pulsating is a result of the rise and drop in voltage and should not be confused with PWM (pulse width modulation).

Ammeters typically have a setting to measure the usable current for a given device. The usable current is referred to as the Root Mean Square Current. This current can be mathematically determined by the following formula:

$$I_{RMS} = \sqrt{1/2\,(I_{MAX})^2} = 0.707\,(I_{MAX})$$

Pulsating DC



While referring to the figure above, notice that the RMS current is approximately 30% less than the maximum current of the sine wave. There is another 1.4V decrease due to the resistance or the voltage drop of the diodes.

Summary

In this chapter the following concepts were learned:

- We discussed the flow of electricity through a circuit and introduced the concepts of AC and DC.
- Electrical potential (voltage), how and where to measure it, was covered.
- We learned about resistance and how to calculate the equivalent resistance in a circuit.
- The basic symbols used in an electric schematic were listed.
- We determined how the change in power, resistance, current or voltage affects other parameters.

Review Questions

Use the following review questions as a measure of your understanding of the chapter material. Answers are provided in the appendix.

1. What is the unit of measure for electrical resistance? ________________________

2. Draw the symbol for a diode. Which direction does the current flow? ________________________

3. If the resistance increases due to temperature and the voltage remains constant, does the power increase? Does the current increase? ___________/___________

4. What device would you use to measure Electromotive force? ________________________

5. What device(s) would you use to measure power? ________________________

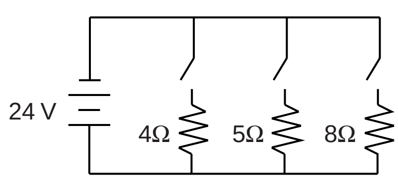
6. The voltage from a battery is 14 volts at the beginning of the day. At the end of the day the voltage has dropped to 9 volts. What is the current available for a resistor of 10.2 ohms at the beginning and the end of the day? (Assume that resistance remains constant.) ___________/___________

7. An application requires 30 ft of wire between the battery and the coil. (Assume that the resistance of the wire is 0.02 ohms / ft.) If the battery is 12 V with 40 amps available, what is the current draw of the system? What is the voltage drop across the coil if the resistance is 7.2 ohms? ___________/___________

8. If a system can provide 10 watt, what is that a measure of? ________________________

9. If a 6 ohm coil draws 2 amps from a 12 volt battery and there are only 20 watts available, is there sufficient power to drive the coil? ________________________

10. In the following circuit, if all three switches are closed at once, what is the current? ________________________



11. What device would you use to change AC into DC? ________________________

Notes

Chapter 3: Basic Magnetic Terms

Objectives

The objectives for this chapter are as follows:

- Understand the basic concept of a magnet, the magnetic field surrounding it and how to calculate this field.
- Determine the strength of the magnetic field of a wire and apply this concept to a solenoid.
- Learn what magnetic flux is and how to calculate it, as well as what the relationship between the magnetic field and flux is.
- Understand the basic concepts of magneto-motive force and magnetic induction.
- Learn what the terms Ferromagnetism, permanent magnetic moment and paramagnetic materials mean, and how they affect the solenoid.
- Discover what a domain is, how it is aligned, and how the material and magnetic field is affected by an aligned domain.

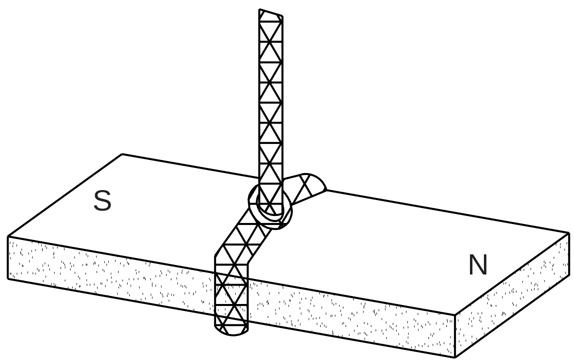
Introduction

In this chapter, basic magnetic theory and terminology will be presented.
The terms and examples discussed will provide an insight into the operation of the electromechanical actuator portion of the solenoid valve. The topics presented in this chapter will also illustrate how a strong magnetic force can be created with little electrical power. The terms mentioned above will be tied together to describe the movement of a solenoid armature moving in a magnetic field.

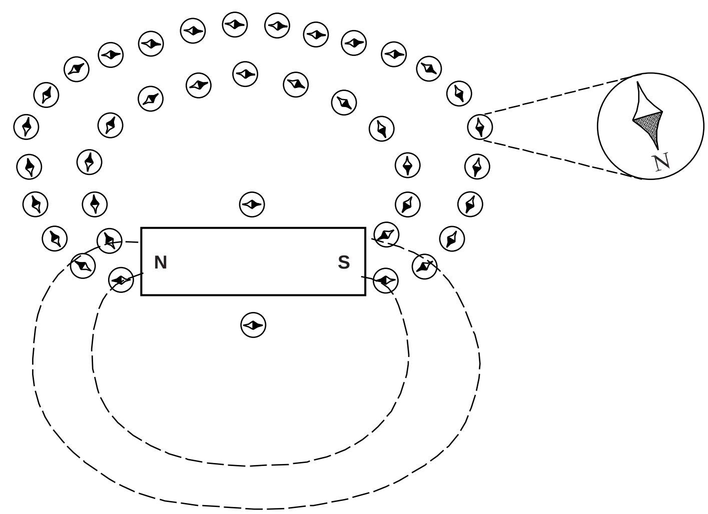
Magnetic Fields

A magnetic field is a condition found in the region around a magnet characterized by the existence of a detectable magnetic force at every point in the region and by the existence of magnetic poles.

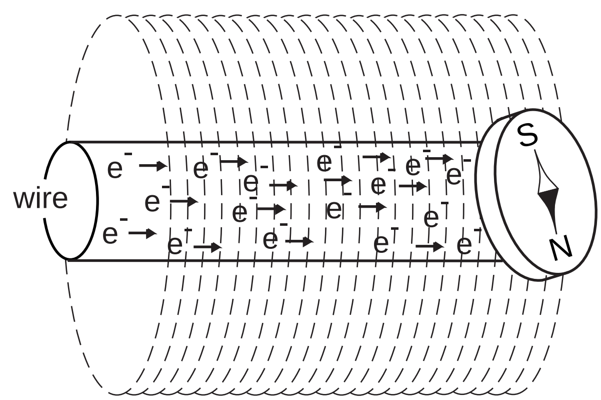
A simple bar magnet has a north and south pole. If two magnets are held end to end, like poles repel (north to north) and opposite poles attract (north to south). To determine which end of the magnet is north or south, the magnet can be suspended from a string. The end that points toward the geographic North Pole (of the earth), is considered the north pole of the magnet. This same principle applies to a compass which is also basically a magnet.



Magnetic field lines are used to describe the path in which the magnetic field flows. The magnetic field lines indicate the direction in which the magnetic force is exerted. One way to plot these field lines is by using a compass. A standard bar magnet and several compasses are shown in the following diagram. The direction in which the compass needle points is the direction in which the magnetic field flows. Notice that the two compasses closest to the magnet, point towards the south pole. This illustrates the concept of opposite magnetic poles attracting each other.



A magnetic field is also formed around a wire carrying a current. In chapter two, amps was defined as the amount of current or electrons flowing through a wire. The moving electrons create a field around the wire. This field is known as the *magnetic field*. The following diagram illustrates the magnetic field surrounding a long, straight wire.

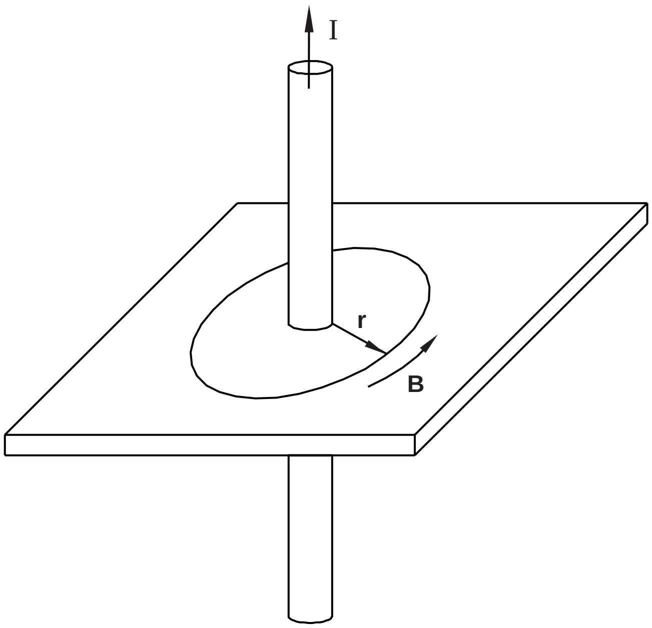


The units of measurement for the magnetic field is a Tesla (T) or a Gauss (G) where $1T = 10^4$ G. These units are a measure of the force created by a moving charge flowing through a given length of wire. The following relationship illustrates this principle:

$$1T = \frac{1\text{Newton}}{\text{Ampere x Meter}} = \frac{N}{A\ m} = \frac{\text{Force}}{\text{Moving Charge x Length of Wire}}$$

Magnetic fields are typically measured in Gauss because the unit of a Tesla is very large. To illustrate how large the Tesla is; the magnetic field of the earth is 0.6 G or 0.00006 T.

Strength of Magnetic Field of a Straight Wire



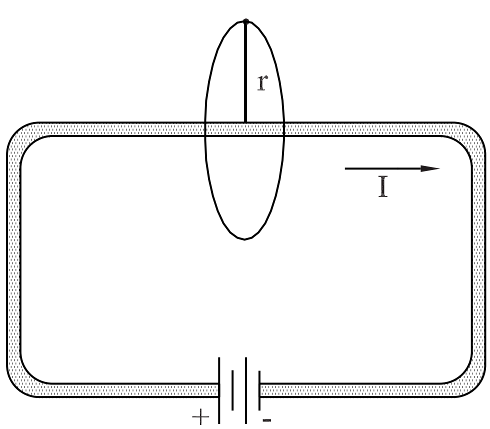
The figure to the left represents a straight wire with current (I) running through it. Perpendicular to the wire is the magnetic field (B). The strength of the magnetic field (at distance r from the center), can be found by using Ampere's Circuital Law where:

$$B = \mu_0 \frac{I}{2\pi r}$$

The constant μ_0 (which is the Greek letter Mu) is known as the permeability of free space. Permeability, by definition, is the ability for something (i.e. a gas, liquid, or in this case a magnetic field) to pass through a material. The permeability of free space, μ_0, is a physical constant, just as gravity is, and is equal to $4\pi \times 10^{-7}$ N / A^2 (where N is Newtons and A is Amps).

Example

In the following example, the magnetic field flowing through a wire will be determined. Refer to the diagram which represents a long straight wire connected to a battery, while working through the problem:



If $\mu_0 = 4\pi \times 10^{-7}$ N / A^2
$I = 1A$
$r = 2.54cm = 0.254$ m (1 inch)

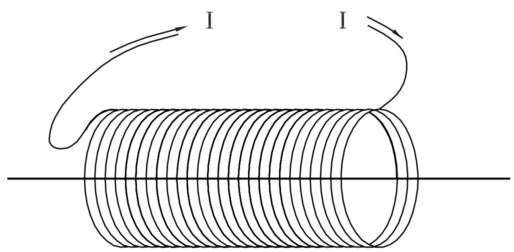
Then $B = \mu_0 I / 2\pi r$
$B = (4\pi \times 10^{-7})(1) / (2\pi)(0.0254m)$
$B = 0.00000394T$

Or $0.00000394T (10^4 G / 1T) = 0.0394G$

Or fifteen times less than the strength of the magnetic field of the earth.

Magnetic Field of a Solenoid

A wire wound into a helix (a spiral form similar to a cork screw or a spool of thread), is called a solenoid. It is used to produce a strong magnetic field in a small space. A set of identical coils, as shown in the following diagram, are placed side by side and on top of one another.



The magnetic field inside a solenoid coil can be calculated as:

$$B = \mu_0 (n I) / l$$

where **n** is the number of coils and **l** is the length.

Example:

The following example shows how to calculate the magnetic field inside a solenoid:

If $N = 1000$, $I = 2A$ and $l = 0.04m$
$B = \mu_0 (n I) / l$

Then $B = (4\pi \times 10^{-7})(1000)(2) / 0.04$
$B = 0.063T$
$B = 630$ G

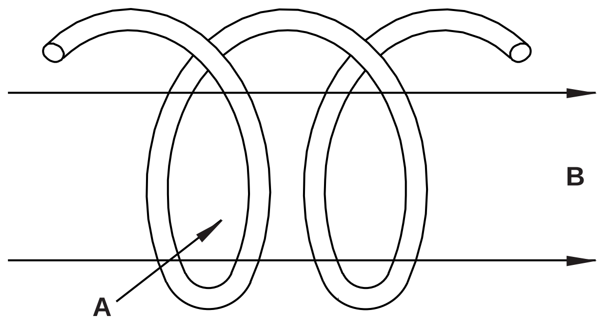
This is roughly 1000 times the strength of the magnetic field of the earth.

It is apparent from this example that the magnetic field of a coiled wire is greater than one around a single wire.

Magnetic Flux

Magnetic flux is a term which is associated with the magnetic field. It is a measure of how many field lines pass through a specific area, and can be calculated by using the following formula:

Flux = magnetic field x area which the field passes through
Flux = B x A



Recall the formula to calculate the magnetic field inside a solenoid:

$$B = \mu_0 (n\ I) / l$$

The general formula to calculate flux though a solenoid is:

$$\text{Flux} = \mu_0 (n\ I) / l \times nA$$

The flux through the simple two turn solenoid shown above, can be calculated by the following:

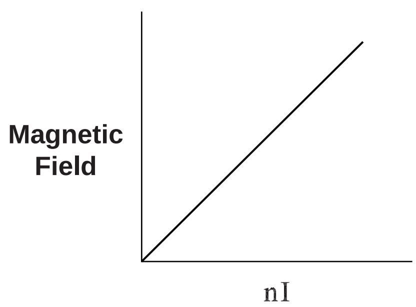
The magnetic field (B) passes through two identical areas (A) of the solenoid coil. The number of turns is shown as (n). The flux through the coil above is:

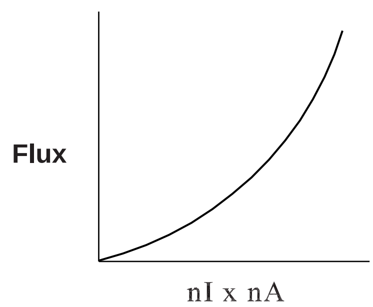
$$\text{Flux} = B \times 2A$$

or

$$\text{Flux} = \mu_0 (2\ I) / l \times 2A$$

These relationships for B and flux illustrate one of the reasons that solenoids are able to develop strong magnetic forces. Simply adding turns of wire increases the magnetic field strength or flux. The following graphs show that the magnetic field grows proportionally with the increased number of turns and the magnetic flux grows quadratically or by n x n.





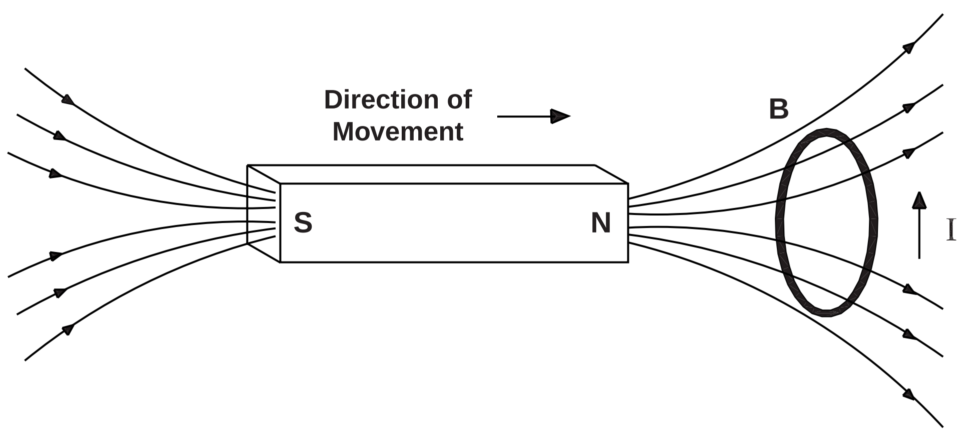
Magneto-motive Force

Magneto-motive force is the energy required to form the magnetic field in a solenoid. Recall the formulas to calculate the magnetic field or flux. The magneto-motive force is given by the term nI which is used in these calculations.

The number of turns on the solenoid multiplied by the current in the solenoid is known as the amp turns. This term is used interchangeably with magneto-motive force. The term amp turns (nI) is frequently used in industry to designate the strength of a solenoid.

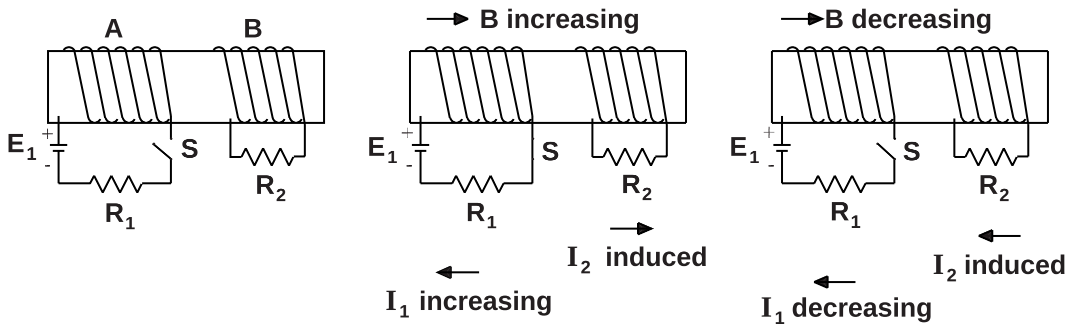
Induced Current

The process in which current is induced is described in the following section. The diagram below represents a bar magnet passing through a single coil of wire.



When the magnet moves through the coil, the magnetic field around the wire changes. When the strength of the magnetic field changes, a current is induced in the coil as shown in the diagram.

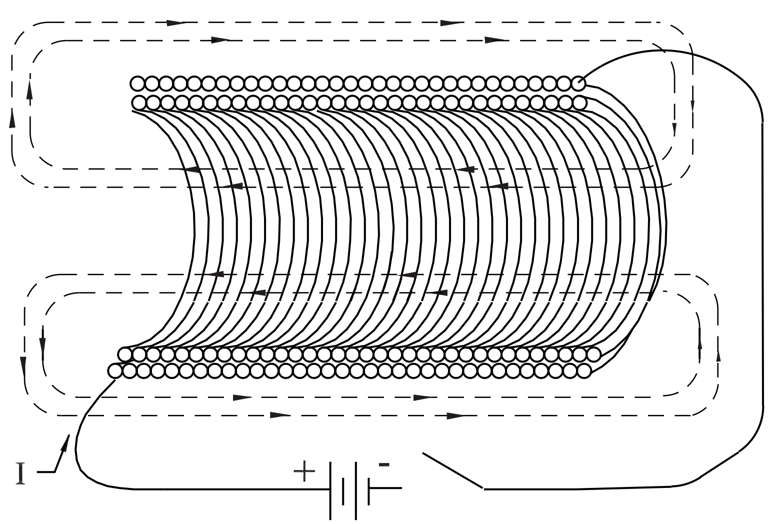
The following three diagrams show what occurs as the magnetic field increases and decreases. This change in current induces or creates current through the second coil.



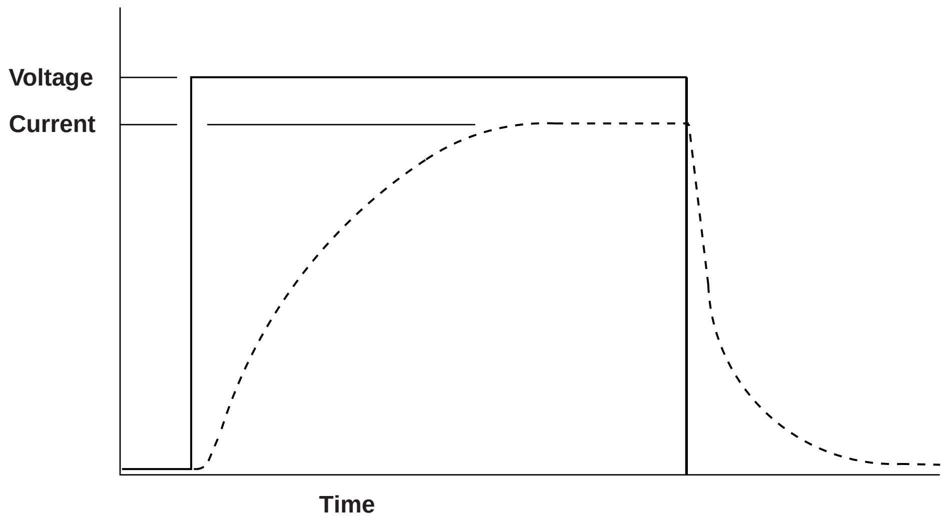
There are two coils of wire wrapped around a piece of iron in each of the diagrams above. When the switch is closed, current begins to flow through the coil at A. As this occurs, the steel becomes magnetized, or the magnetic field begins to change. This is similar to the earlier example of when the bar magnet was moved toward the single loop of wire. In this example, the current is induced by the increase in magnetic field through the piece of steel in coil B. This induced current is flowing opposite to the flow of current in coil A. When the switch is opened, the current in circuit A decreases to zero, causing the magnetic field to decrease and inducing another current. The current is now flowing in the opposite direction since the magnetic field is decreasing.

Note that because there is (induced) current flowing in circuit B, there must be voltage or electromotive force (EMF) present. EMF is produced when the magnetic force induces current or voltage in a coil of wire.

This concept can be extended to a solenoid coil. As we have learned, the solenoid creates a magnetic field when connected to a battery (switch closed). This is illustrated in the following diagram.



As the current flows through the coil, it creates a magnetic field. This magnetic field creates or induces an EMF or current opposite to the one from the battery. The graph below shows the voltage and current from the battery. The voltage measured across the coil builds instantly, but the current builds slowly. This occurs because the induced current flows opposite to the battery current. When the switch is opened, the voltage immediately drops but the current decreases slowly. Again, this is due to the self induced current flowing through the coils as the magnetic field decreases or collapses.



Magnetic Induction

The magnetic field of a bar magnet or a solenoid can cause adjacent material to become magnetic. This concept is known as *magnetic induction*. For example, if iron shavings were randomly scattered on a piece of paper, and a bar magnet was placed underneath, the iron shavings would align themselves in a pattern similar to the one shown for the magnetic field around the bar magnet. Each shaving becomes magnetized with an internal north and south pole and aligns itself in this pattern. This concept is magnetic induction at work.

Magnetic induction can change the degree to which surrounding materials exhibit their own magnetic field. Every material has its own magnetic field. Just as electrons flowing through a wire create a magnetic field, the electrons spinning around the atom itself create a magnetic field. The field around the atom created by the spinning electrons is known as the *permanent magnetic moment*.

Different materials behave differently in the presence of an external magnetic field. Some materials are not affected by the magnetic field and others do not affect it. Some materials can actually intensify the strength of the magnetic field.

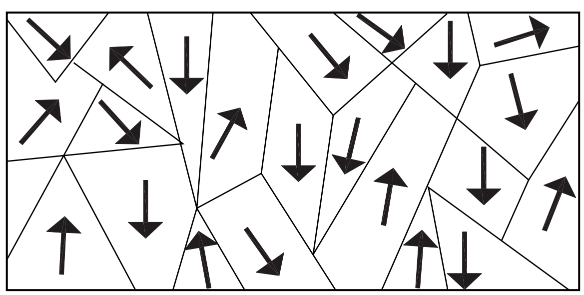
Paramagnetic Materials

Paramagnetic materials neither change the magnetic field nor are affected by it. These types of materials exhibit a very small magnetic moment, even in the presence of a very strong bar magnet. Copper or aluminum, which are materials typically used in wire, are paramagnetic materials. The amount that copper or aluminum become magnetized, or their permeability, is so small that it is comparable to air.

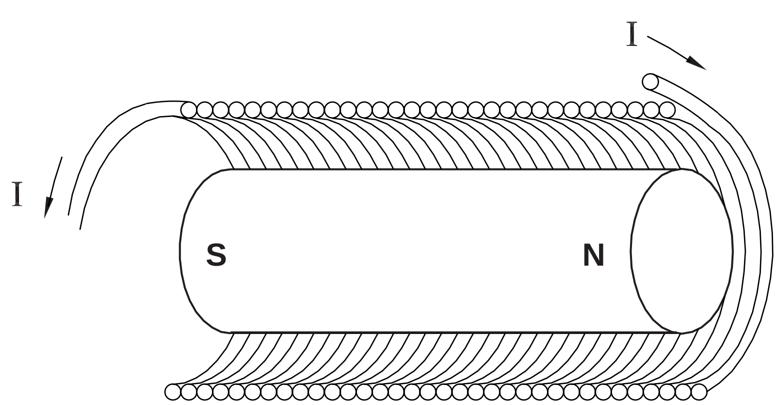
Ferromagnetism

Ferromagnetism is a concept which occurs in materials such as iron, nickel and various materials which exhibit extremely high magnetic permeability. These materials have the ability to acquire high magnetism in relatively weak external magnetic fields.

The external field aligns the permanent magnetic moments within the atoms. A group of atoms polarized (aligned) in the same direction forms a domain. The domain can be conceptualized as a tiny bar magnet. Shown below is an unmagnetized piece of iron. Notice that the domains (magnets) are pointing in random directions.



If the iron core is inserted into a solenoid and the solenoid is powered (current is applied), these domains begin to align.



The strength of the magnetic field of the solenoid and iron together is given by:

$$B = K_m \mu_0 \frac{nI}{l}$$

Where: B is the magnetic field strength

K_m is the relative permeability of the material

μ_0 is the permeability of air

n is the number of turns in the solenoid

I is the current in the solenoid

l is the length of the solenoid

K_m, the relative permeability of the material is not a constant. It changes relative to the increase in magneto-motive force, (nI). As the current increases, so does K_m. Eventually, K_m reaches a constant value. This constant value is 2T or 3300 times the magnetic field strength of the earth.

Recall the iron core in the solenoid, as we discuss what happens while the current in the solenoid is increased and the iron becomes magnetized. The figures below correspond with the points on the graph which also follows.

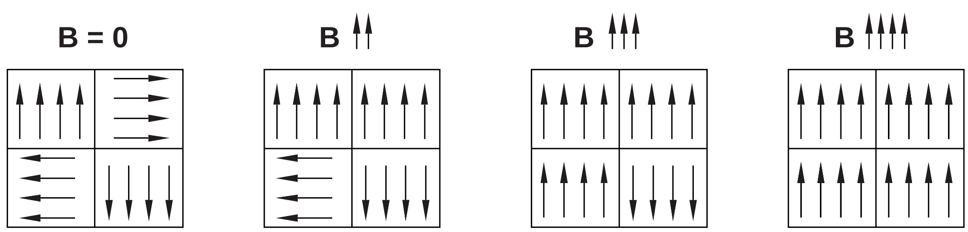
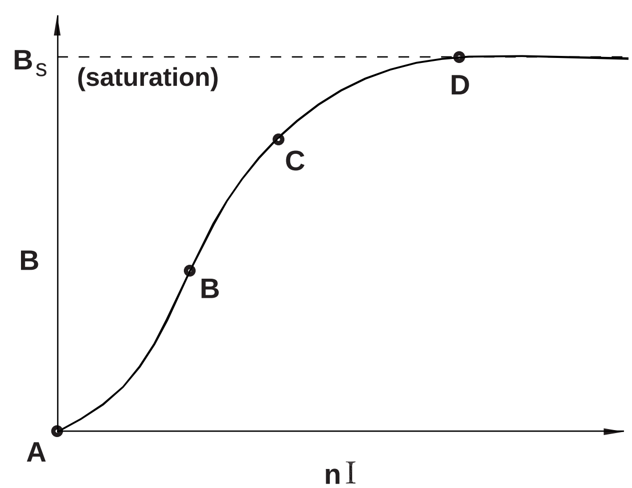


Figure A **Figure B** **Figure C** **Figure D**



At point A, there is no external field applied and therefore no alignment of the domains. The current has been applied at Point B and some external field is present. A small amount of alignment of the domains occurs as a result. The current and magnetic field have been further increased at point C and the domains are almost completely aligned. This is called the knee of the curve and is considered the optimal point for solenoid design. The maximum amount of domains have been aligned with the least amount of electrical current. Saturation occurs between points C and D. Between points C and D very few domains are left unaligned. More external field is required to align these fields than in the previous domains. It is therefore inefficient to continue applying the external magnetic field. Beyond point D any increase in magnetic field comes from increasing the magnetic field created by the flow of current through the solenoid.

Saturation

Saturation can be defined as the state of a ferromagnetic material in which an increase in applied magnetic field strength does not produce an increase in magnetic intensity. In other words, when saturation occurs, all the domains are aligned. Further, it doesn't matter how much the NI is increased, the steel will not become a stronger magnet.

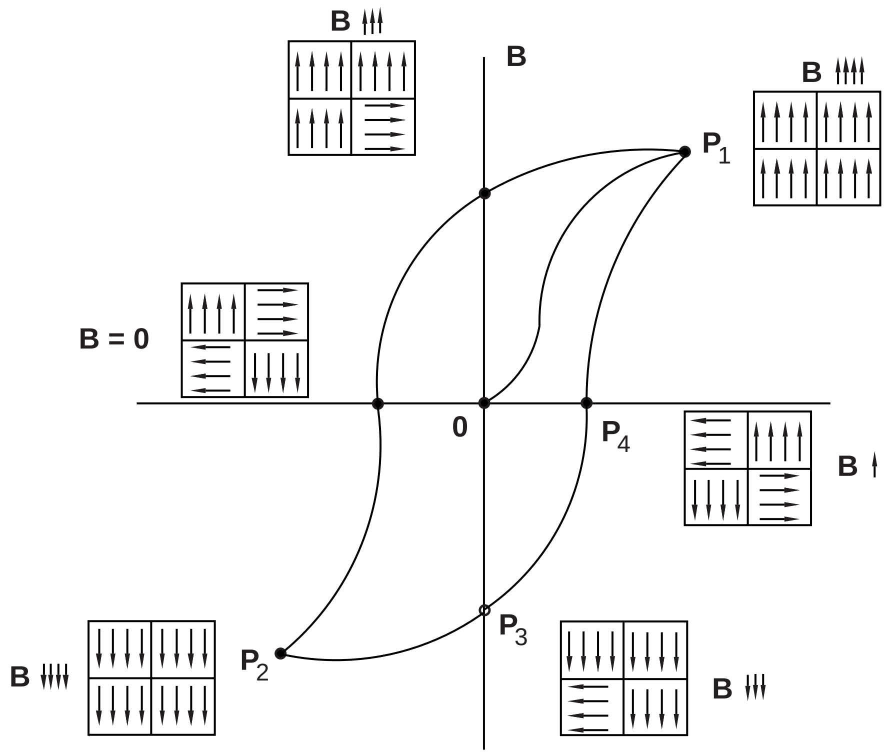
Magnetic Hysteresis

The alignment of the domains occurs because there is a strong interaction between the neighboring atoms that make up the material. There is a draw back to this strong interaction which is known as *magnetic hysteresis*.

Magnetic hysteresis is observed when there is a change in the external magnetic field and the change in the field of the magnetized material lags behind. In a sense the material has a memory. It remains in its changed state rather than reverting back to the original state. The graph shown on the following page depicts what is known as *hysteresis loop* for a Ferromagnetic material.

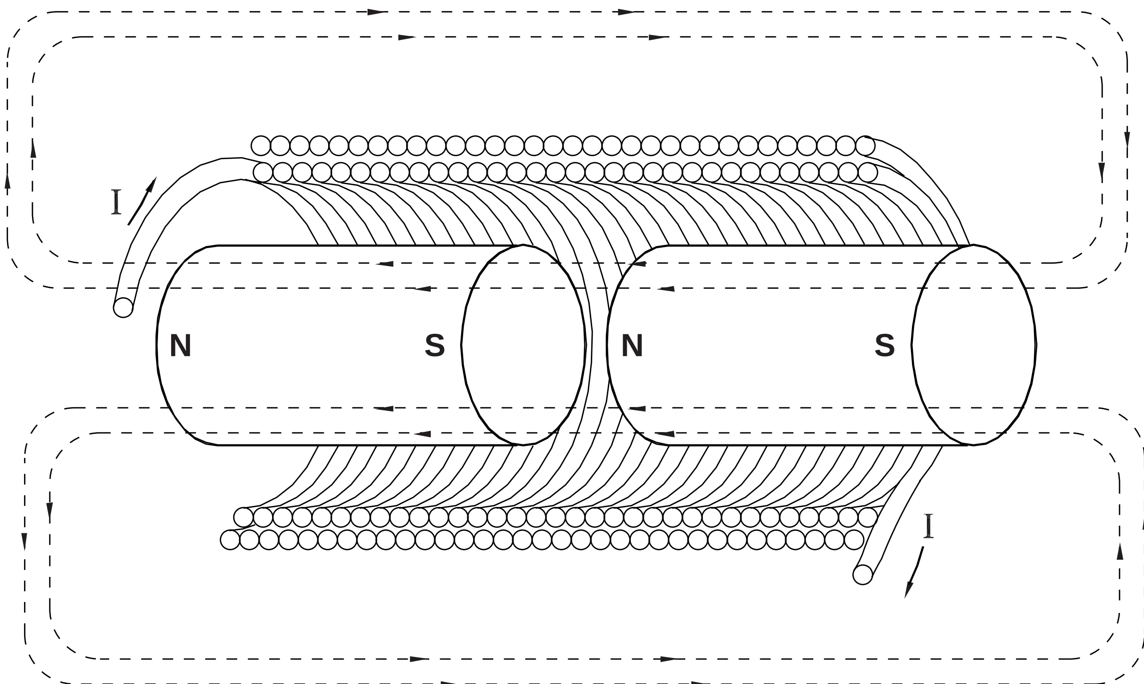
Assume that there is a round piece of Ferromagnetic material (iron) inside a solenoid coil. As the current through the solenoid is gradually increased from zero, the magnetic field in the iron increases along the curve (shown in the following diagram), from the origin to point P_1. The flattening of the curve indicates saturation (complete alignment for the domains) of the iron. If the current in the solenoid is now slowly decreased to zero the domains remain somewhat aligned at the level of P_r. This amount of magnetic field remaining in the iron is known as *residual magnetism*. If the current is now reversed (perhaps by switching the connection to the battery), the magnetic induction (magnetic field strength) in the iron is gradually brought to zero.

The remaining part of the curve is obtained by continuing to reverse the current until the saturation point P_2 is reached. Decreasing the current back to zero shows that the residual force for the current flowing in the opposite direction is equal and opposite. Upon reversing the current again, back in the positive direction, the curve goes from point P_3 to P_4 where the magnetic field of the iron goes to zero. If the current is again increased the curve will continue to follow from P_4 to P_1.



Review of Concepts

The concepts discussed in this chapter are needed as a basis for understanding solenoids and how they operate. Use the following section to tie all these concepts together, as a summary of the physics behind the magnetics of a solenoid valve. Refer to the following diagram while reviewing.



The current flowing through the coiled wire of the solenoid is the magneto-motive force (ampere turns). This magneto-motive force creates a uniform magnetic flux through the cross section of the solenoid. Magnetic field lines represent the flux and direction of magnetic force. The magnetic field of the solenoid induces a magnetic field in the two pieces of iron. Because iron is a ferromagnetic material the permanent magnetic moment of the atoms align in domains and intensify the magnetic field of the solenoid. These domains continue to align as the current or magneto-motive force is increased. Eventually, the iron becomes fully magnetized or saturated. North and south poles are created in both pieces of iron. The two pieces of iron are attracted to each other just as two bar magnets are and will move together until there is no gap separating them. Assume after the two pieces of iron come together, the current is turned off. Magnetic hysteresis causes the two pieces of iron to stick together. It is also due to hysteresis that a residual magnetism remains in the parts, and the parts remain attracted to one another.

Summary

In this chapter the following concepts were presented:

- The concept of how to plot the magnetic field surrounding a bar magnet or solenoid.
- How to calculate the strength of the magnetic field.
- Applying the magnetic field concept to the solenoid.
- Understanding the concept of Ferromagnetism, domains and how they become aligned.
- Determining what magnetic flux is and how to calculate it.
- What the terms permeability, saturation, residual magnetism and hysteresis are.
- How the above terms are related to one another.
- Learning what magneto-motive force, magnetic induction and parametric materials are.
- The basic operation of a solenoid actuator.

Review Questions

Use the following review questions as a measure of your understanding of the chapter material. Answers are provided in the appendix.

1. List one reason to increase the number of turns on a solenoid. ________________________

2. What do magnetic field lines represent? ________________________

3. Does current flowing through a wire affect the direction a compass points? Why or why not? ____________/___________

4. If a piece of iron was in a solenoid and the current was turned on, would a steel (iron) wrench be attracted? ________________ ________

5. If the current in question 4 were turned off, would the wrench remain attracted to the iron? If so, why? ________________________

6. What is Ferromagnetism? ________________________

7. What is residual magnetism? ________________________

8. What is the magnetic field proportional to? ________________________

Chapter 4: ElectroMagnetic Actuator Basics

Objectives

The objectives for this chapter are as follows:

- Discover what the components of an electromagnetic actuator are, how they are constructed and how the components interact.
- Learn about the pancake and tubular shaped armatures as well as the three variations on the tubular shape.
- Understand the concept of Force vs Air Gap and when to use the flat face, conical and proportional style actuators.
- Learn what parameters affect Solenoid force and how the process of solenoid design must juggle these parameters depending on the application.

Introduction

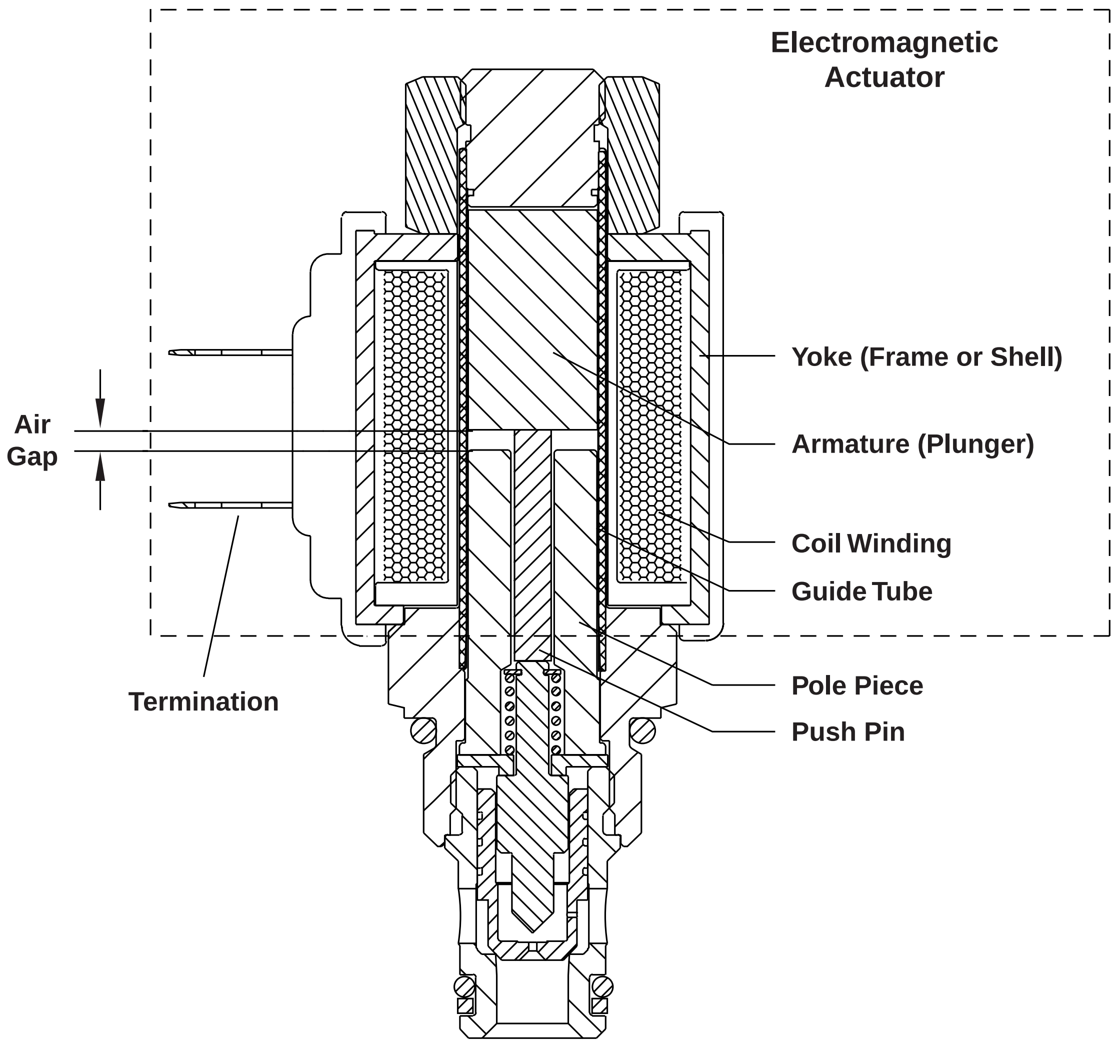
In the previous chapters we learned about the basics of magnetics and electronics. In this chapter we will use these basics to describe the construction and operation of an electro-magnetic actuator. Various designs of actuators will be compared, as well as a description of how the performance of each varies.

Electromagnetic Actuator

Recall the definition of an electromagnetic actuator from Chapter 1. A solenoid valve is one which uses an electromagnetic actuator to move a hydraulic control element such as a poppet or spool.

An electromagnetic actuator takes electricity and converts it into magnetic force. Magnetic force is used to move the spool or poppet which in turn controls the direction of flow.

The actuator portion of the solenoid valve is highlighted in the following diagram.



Actuator Components

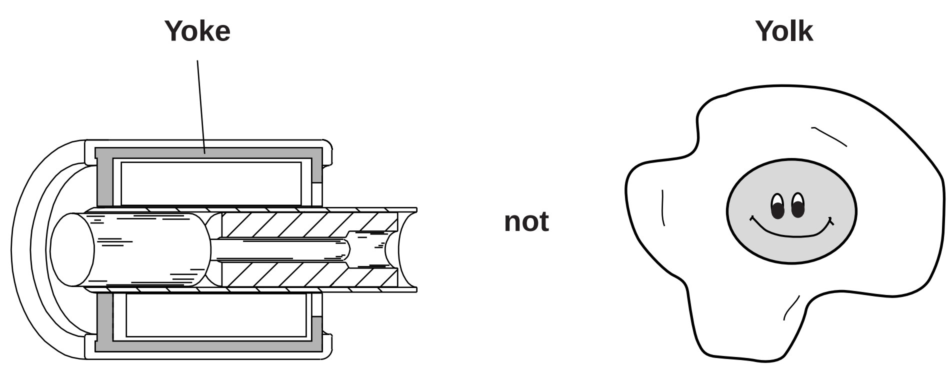
Coil winding

The coil winding is the solenoid that we learned about in the previous chapter. As we learned, it creates an electromagnetic field when the current is applied across the terminals. It is typically made from copper which is the most cost effective and efficient conductor of electricity.

Yoke

The yoke, also referred to as the shell or frame, concentrates the magnetic field. It surrounds the outside of the solenoid coil and is typically made from low carbon steel. Recall from chapter three that steel or iron is a Ferromagnetic material. The flux created by the solenoid can flow easily through this Ferromagnetic material. A Ferromagnetic material can also intensify the magnetic field. If the yoke did not exist, the flux lines or magnetic field would be loosely spaced, and the actuator would be inefficient.

Low carbon steel is used for most electromagnetic actuators. It has a high permeability (good conductor of magnetics), and a relatively low cost. There are better magnetic materials, but the increase in efficiency does not justify the increase in cost. The components of the actuator which are made from iron are, the yoke, pole piece and the armature.



Guide Tube

The guide tube acts as a guide for the armature. It is typically made from a nonmagnetic material such a stainless steel. The material needs to be nonmagnetic to avoid the armature being attracted to it.

Pole Piece

The pole piece acts as a magnet when the current is applied to the winding. It is a fixed Ferromagnetic part of the armature. Refer back to the summary diagram in Chapter 3, in which two pieces of iron are shown. When the coil is energized, a magnetic field forms a north and south pole in these pieces of iron. The pieces are attracted and move towards one another. Similarly, in the pole piece, as the coil is energized, the pole piece and corresponding armature are attracted to one another. The pole piece however, is fixed into place and draws the armature toward it.

Armature (Plunger)

As mentioned in the pole piece description, the armature is the piece of iron which the pole piece attracts. This part is allowed to move freely, constrained only by the guide tube. If nothing opposes the movement of the armature, it will be attracted to, and move towards the pole piece. However, if something does oppose the movement of the armature, it will exert a force on that object.

Air Gap

The air gap is the distance between the pole piece and the armature. The size of the air gap depends on the product which the electromagnetic actuator is coupled (hooked up) to, such as the stroke of the spool or pilot pin.

If the actuator was not connected to anything, the air gap would not exist, because the parts would remain attracted to each other once the current was applied. There would be no force to break the magnetic attraction between the pole piece and the armature.

Push Pin (Connecting Element)

The push pin is the element that transfers the magnetic force to the part outside of the actuator. In addition, any forces which oppose the magnetic force will be transferred to the armature through the push pin.

The push pin is typically made of a nonmagnetic material such as stainless steel so that it is not attracted to the pole piece.

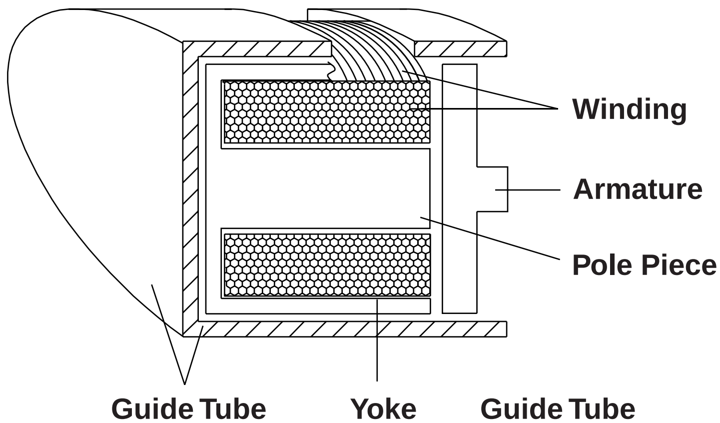
Armature Shapes

There are two basic shapes of armatures; pancake and tubular. The tubular style has three variations; flat, conical and proportional. The following sections describe each.

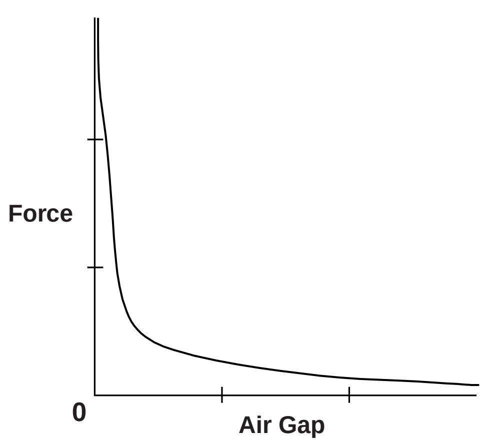
Pancake

The pancake style armature is used in applications where a high holding force is required but the air gap initially separating the plunger and pole piece is small. The name *pancake* comes from the shape of the flat armature which is the same diameter as the outside of the yoke. *Holding force* refers to the magnetic force between the pole piece and armature, when the air gap is zero.

The following diagram shows a cross section of a pancake style actuator.



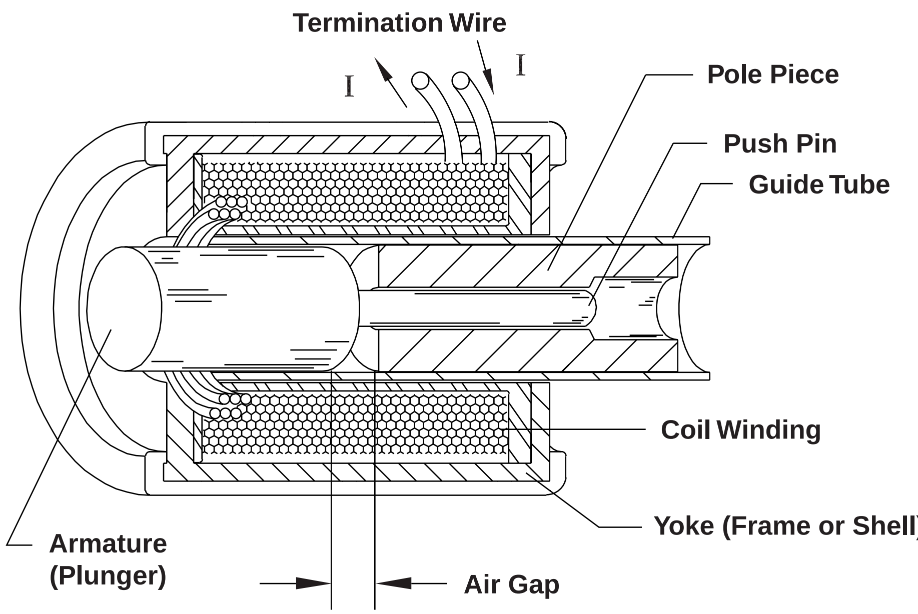
The graph below shows force vs. the air gap. This represents the magnetic attractive force between the pole piece and the armature when a constant current is applied and the position of the armature changes. Notice that the force is high when the air gap is zero (pole piece and armature are in contact), but decreases sharply as the air gap is increased.



Tubular

The tubular shape armature is used in hydraulic valves and pneumatic valves. There are three variations on the tubular shape, based on the shape of the pole piece and armature; flat, conical, and proportional.

A diagram of a tubular shaped actuator is shown below.



As with the pancake shape actuator we can plot a force vs air gap graph (see the following graph). The tubular shaped armature gives flexibility in controlling the shape of this graph. Three basic types of armature and pole piece designs are outlined and described in the following sections. Refer to the following comparison graph while reading through the descriptions of each shape.

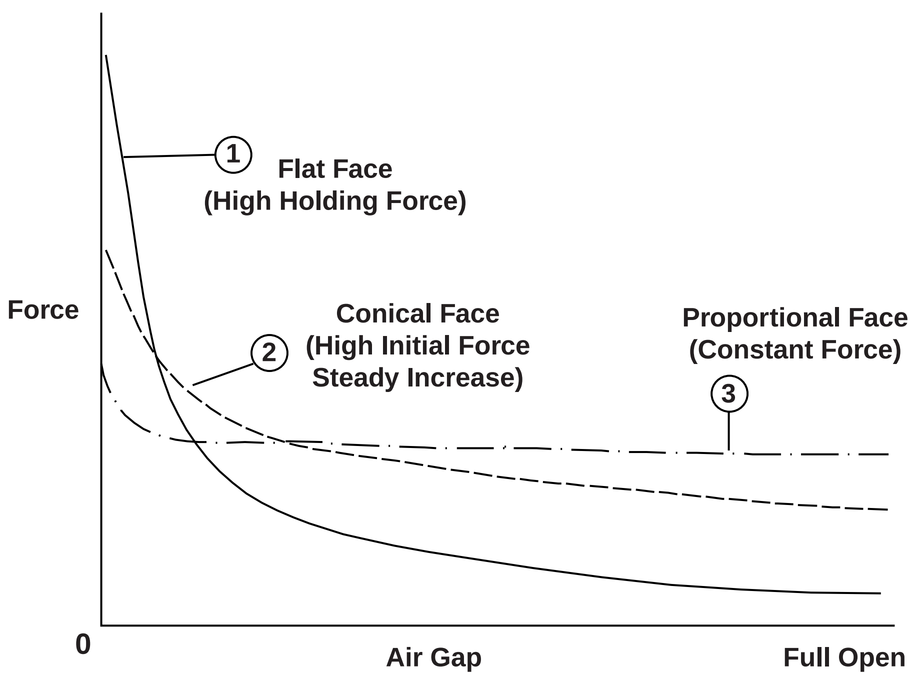
The *flat face* armature (number one on the graph) has a high holding force (magnetic force between the pole piece and armature, when the air gap is zero). This style of actuator is characterized by a low force at the full open point and a high force when the air gap is zero.

The *full open* point is the initial position of the product which the armature is connected to. This point varies depending on the application of the solenoid. It is defined by the distance the armature will be required to move

The *conical face* armature (number two on the graph) has a high initial force with a steady increase. The curve for this actuator shows that the initial force at full open is higher than the flat face, but the holding force is lower.

The *proportional face* armature (number three on the graph) has a constant force. The graph shows a constant or level force for the majority of movement (change in the air gap) of the armature.

The application (what the solenoid will be hooked up to) usually dictates which force versus air gap curve will be used. Not only is the performance of the solenoid or actuator force considered, the cost is as well. Each style discussed requires a better manufacturing process with the flat face being the least costly and the proportional being most costly.



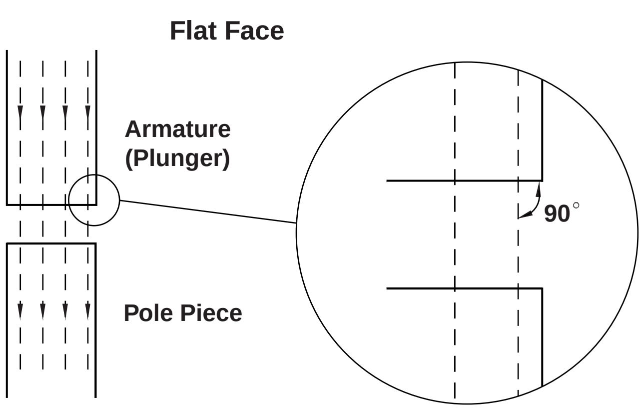
Flat Face

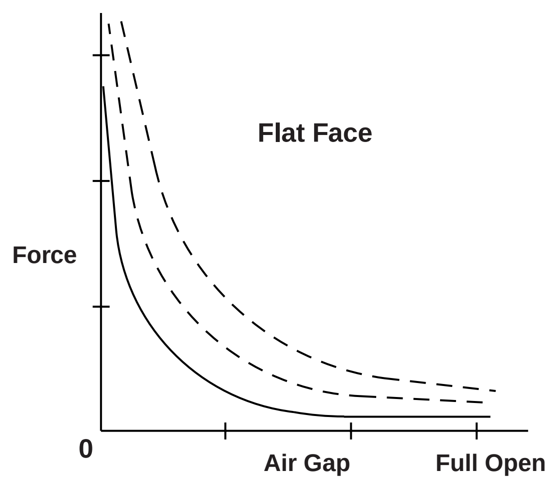
The illustration and graph below show a flat face plunger and pole piece. Magnetic field lines are overlaid on top of these parts. These indicate that magnetic field lines jump directly across from the plunger to the pole piece. The tendency of the field lines is to exit through the armature face and enter through the pole piece face at a right angle or perpendicular to the surface.

Recall from the previous chapter that the flux, or strength of the magnetic attraction between the parts is based on the magneto-motive force (nI), multiplied by the area through which the field flows (in this case the circular area of the armature and pole piece). The graph to the right represents the same actuator with various current levels applied. Each curve represents a different current value or a different value of ampere-turns (magneto-motive force). The lowest curve represents the lowest current level. The shape of the curve is based on the shape of the pole piece, armature (the area which the flux passes through), and the amount the domains within the material are aligned (the amount of nI).

When the armature is at the full open point, the force is low because the magnetic field has a greater distance to travel from the plunger to the pole piece. Recall that the permeability of air is low, so the magnetic field is reluctant to flow through the air. At this point very few domains are aligned in the pole piece and plunger. As the plunger and pole piece move closer together, the attraction increases as more domains align. While the parts are moving closer together, the magnetic field has a decreasingly smaller distance to travel. This results in an increase in force, because it can align more domains.

The cost of this shape actuator is relatively low due to the simplicity of the parts. There is very little machining time required to manufacture these parts and are therefore inexpensive to make.



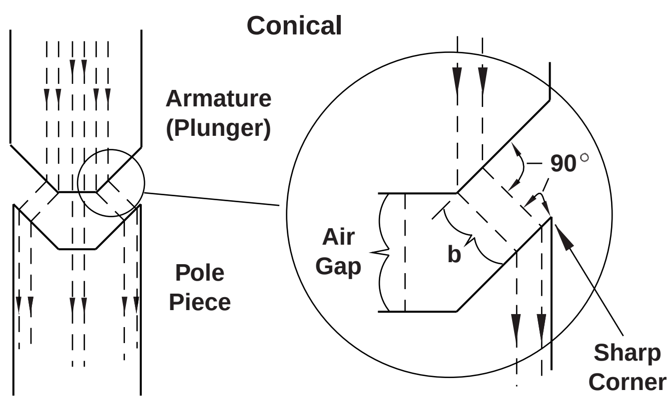


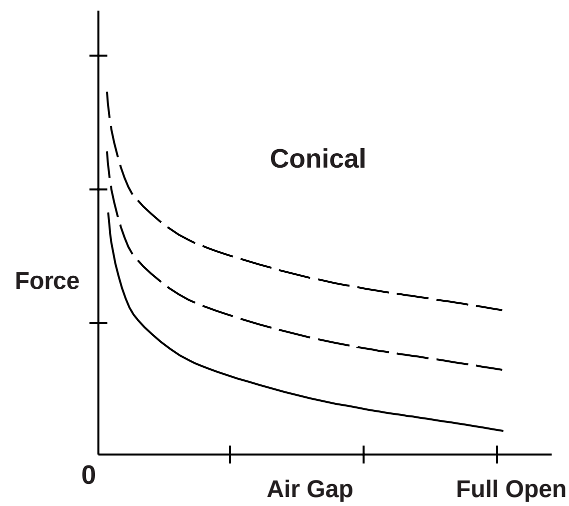
Conical

The following section describes the conical shape actuator. Refer to the diagram and graph below.

As in the flat face armature, the magnetic field in the conical armature still flows perpendicular from one face to another. The force when the armature is at the full open point is higher than in the flat face for two reasons:

1. The area of a conical surface is larger than that of the flat face even if the diameter of both is the same.
2. Although the air gap is equal on both the flat and conical, the distance the magnetic field must jump is less on the conical. Notice distance ***b*** shown in the diagram below is less than the air gap. This is simply a property of the conical surface which is triangular in shape.



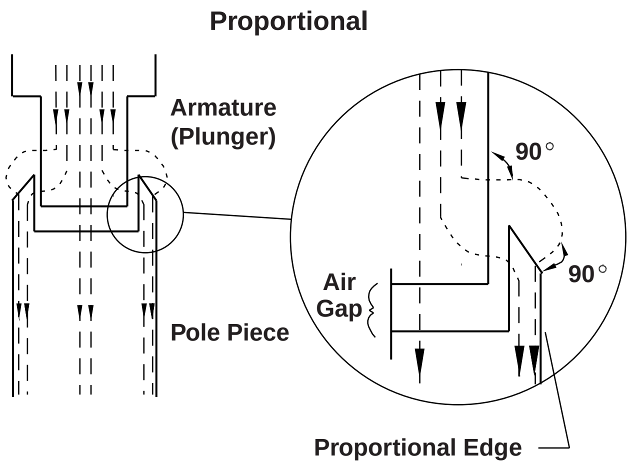


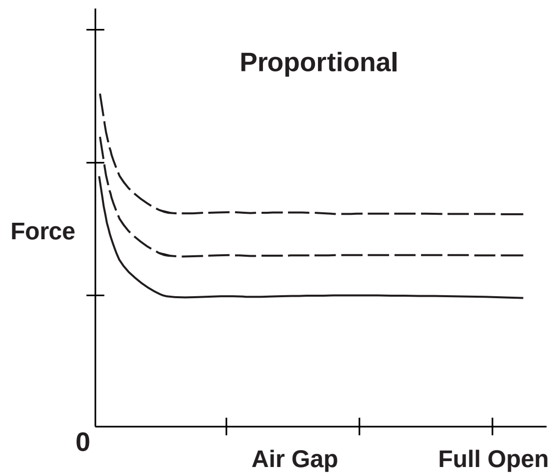
The graph above shows three curves for various current levels. The curves are similar to each other because the shape of the pole piece and plunger remain the same. The force is lowest at the largest air gap. As the distance between the pole piece and the armature decreases, the force increases and more domains become aligned. This happens because the magnetic field aligns almost all the domains at the sharp corners of the pole piece even before the air gap is zero. Since there is less material at the corners of the pole piece, a lower amount of flux at a larger air gap, can align these domains (saturate the material). As more and more domains become aligned, the change in magnetic force decreases. Therefore, since the domains at the corners align at larger air gaps, the change in force is less dramatic than with the flat face.

The conical shaped armature and pole piece are slightly more expensive than the flat parts because the shape is more complex and requires more machining.

Linear Proportional Face

The following section describes the linear proportional shape actuator. Refer to the diagram and Force vs Air Gap graph below.





As with the other two styles of armatures, the magnetic field lines leave and enter the surface of the steel or Ferromagnetic parts at a right angle. In this case, the magnetic field lines exit from the side of the plunger and enter the pole piece at a protrusion called the proportional edge (see diagram above).

The three curves shown in the graph above are a result of different current levels applied to the solenoid, and the area the magnetic field lines pass through. In the proportional armature, the force remains constant even after the air gap has changed, because the amount the domains are aligned in the proportional edge does not change. In addition, the distance the field lines jump from the plunger to the pole piece does not change.

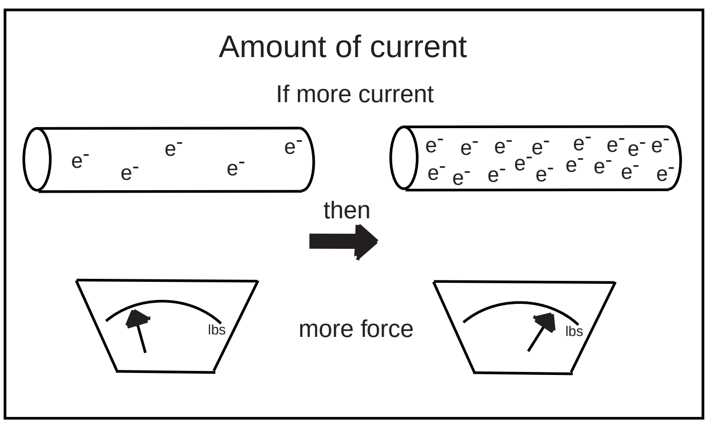
When the plunger is very close to the pole piece (near the zero point on the graph), the force begins to increase. This happens as the flat portion of the plunger approaches the flat face of the pole piece. At this point the graph of the flat face armature and the proportional armature are similar.

Relative to the two other styles, the proportional armature is much more costly to make. The shape of this armature is more detailed and the tolerances must be kept very tight to ensure that the performance does not vary.

Parameters which affect Solenoid Force

There are several factors which affect the force developed by the solenoid. These factors include:

- Current applied to the coil
- Coil resistance
- Ambient (room) temperature
- Number of turns on the solenoid coil
- Magnetic field density and construction (amount of iron used)

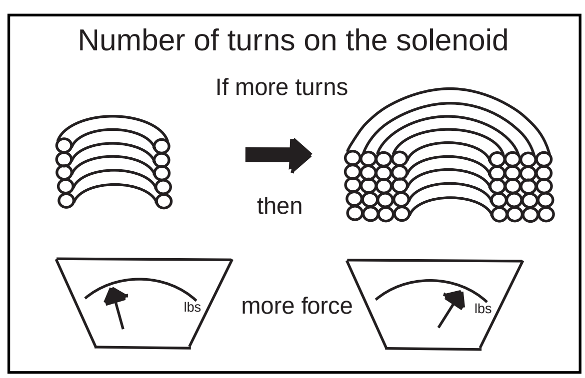


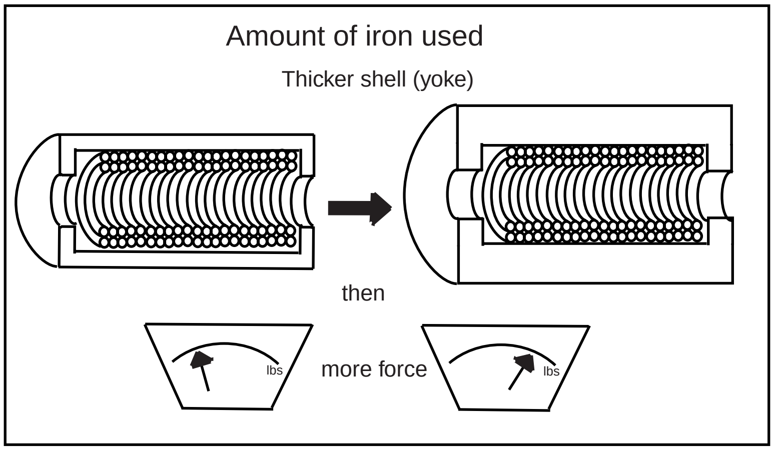
Amount of Current

Recall from the previous chapter that the magnetic field strength is dependant on the magneto-motive force (ampere-turns). Therefore, increasing the current, also increases the magneto-motive force. This in turn increases the magnetic field strength or the attraction between the armature and the pole piece.

Number of Turns

Again, as with the increase in current, increasing the number of turns increases the magneto-motive force.





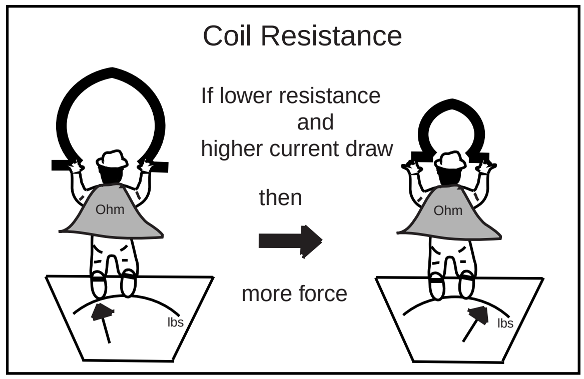
Amount of Iron

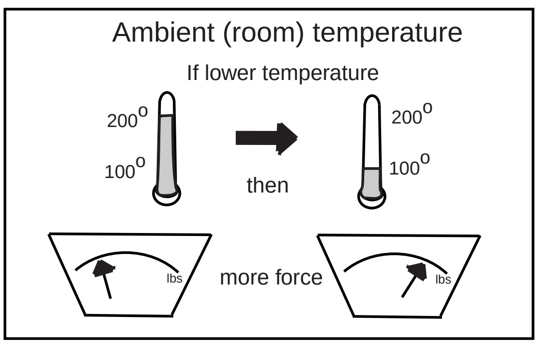
The amount of iron in the yoke affects the strength of the magnetic field. The frame is in the coil to concentrate the magnetic field. If it is too thin, the iron becomes saturated (all domains aligned) at a current level which is too low.

Resistance

Recall Ohms law V = IR. If resistance decreases while the voltage remains constant, the current will increase.

An increase in current results in an increase in nI (ampturns), which increases field strength.





Temperature

As the ambient (room) temperature increases so does the resistance of the coil.

The change in the resistance of copper due to the change in temperature can be determined by using the following equation:

$R_F = R_{20}(1 + 0.00393(T_F - 20))$

R_{20} = the resistance of the coil winding at 20° C

20 = 20° C

0.00393 = a physical constant of copper representing the change in resistance due to change in temperature

T_F = the operating (ambient) temperature

R_F = the resistance at the operating (ambient) temperature

Example

What is the resistance of a coil that is 9.8 Ω at 20° C, if it is used outside when the temperature is 95° F?

The conversion for ° F to ° C is:
° F -32 / 1.8 = ° C
95 - 32 / 1.8 = 35 ° C

Calculate the new resistance:
$R_F = R_{20}$ (1+ 0.00393 (T_F - 20))
R_F = 9.8 (1 + 0.00393 (35 - 20))
R_F = 10.4Ω

Each of the parameters listed can increase the magnetic force. Therefore, it appears that it is easy to develop any level of force desired for an application. This however is not the case.

If, for example, we wanted to increase the force, but were restricted by the size of the coil, would the solution be to increase the number of turns? Recall that the magnetic force is proportional to the number of turns times the current. At the same time, increasing the number of turns increases the resistance. If the voltage remains constant, by Ohm’s Law, the current drops. Therefore, increasing the turns does not necessarily increase the force.

The next parameter involves the thickness of the frame. Does increasing its thickness increase the magnetic force? The answer is, not necessarily. If there is not enough magnetic field created by the solenoid, then the domains will not align, regardless of the thickness of the frame. The added material and cost are therefore wasted.

Lowering the resistance to increase the magnetic force also has problems. If the resistance is lowered by removing turns of wire, then although there is more current, the magnetic force may not increase. This is because the magnetic field strength is a product of both turns and current. It is possible to maintain the number of turns and lower the resistance by using thicker wire. However, this solution may have a problem. The increase in current results in an increase in power or energy (recall P = IV). The energy is dissipated in the form of heat. As the current flows through the wire, it heats up. When the coil gets hot, the resistance increases. Increasing the resistance decreases the current, as does the magnetic force.

Each of the scenarios described indicates that there are many solutions and many right and wrong answers. Good solenoid design requires a balance between these factors.

Summary

In this chapter the following concepts were presented:

- The parts of the Electromagnetic Actuator were listed and discussed.
- We learned about the two styles of armatures, the pancake and tubular.
- The three variations on the tubular shape were presented; flat, conical and proportional.
- A discussion on force versus the air gap showed when to use the flat, conical and proportional shapes.
- The various parameters which affect solenoid force were presented along with what happens when the parameters are varied.
- The method to calculate the resistance of a coil when there is a change in temperature was displayed.

Review Questions

Use the following review questions as a measure of your understanding of the chapter material. Answers are provided in the appendix.

1. Name the parts of a solenoid electromagnetic actuator. ________________________

2. Why would a flat face armature be used? ________________________

3. What factors determine the shape or level of force for Force vs Air gap curve? ________________________

4. If the domains in the shell are all aligned (material is magnetically saturated) and there is excess magneto-motive force, will increasing the shell thickness increase the force? ________________________

5. What does increasing the current do for the magneto-motive force? ________________________

6. If it is 20° F outside, what is the current draw for a coil that is 7.2 Ω at 20° C? ________________________

7. How can lower resistance increase the magnetic force? ________________________

8. If the force applied to the push pin opposing the movement of the armature was constant, what type of armature could be used against this force. ________________________

9. Which style of tubular actuator is the most expensive? Why? ___________/___________

10. Which style of tubular actuator is the least expensive? Why? ___________/___________

11. What would happen if the force applied to the push pin holding the armature in place were suddenly removed? Why? ___________/___________

Notes

Chapter 5: Standard Coil Construction

Objectives

The objectives for this chapter are as follows:

- Identify the parts of a coil and understand the function of each of these parts.
- Learn how the size of the bobbin, core, flange and number of turns is determined.
- Recognize terminations and connectors used at the end of windings and understand what they are used for.
- Learn what an encapsulant is and where it is used.
- Apply the concept of an encapsulant to the molding process to learn what the single mold and double molding processes are.
- Compare the molding processes and understand how HydraForce made its choice.
- Recognize the HydraForce coil designations and their applications.
- Understand the parameters followed in designing a coil.

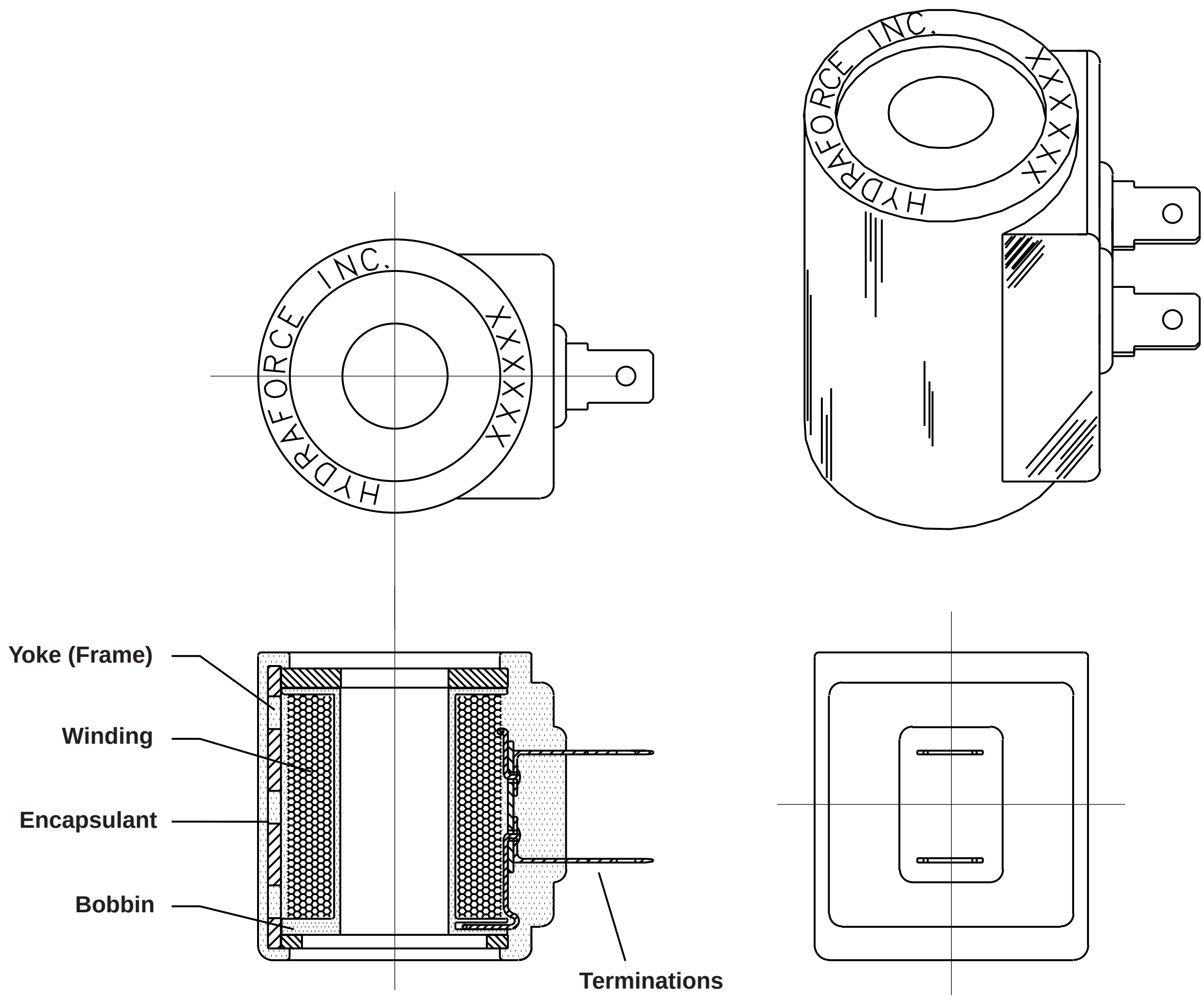
Introduction

The first four chapters in this manual are general information needed to understand how the solenoid coil and its parts work. The following chapters use the concepts learned in the previous chapters and apply them to HydraForce specific products.

Chapter five discusses the coil construction which HydraForce uses, the coils components and how the coils are wound. Topics such as magnet wire, encapsulation, start slots, wire insulation and terminations are also introduced.

HydraForce Coil Construction

The coil shown below is a HydraForce 08 size coil. Refer to this diagram while reading through the descriptions of each part. The coil, or solenoid, consists of a yoke or frame, winding, terminations, bobbin and encapsulant. The yoke and frame were introduced in the previous chapter.



Coil Materials

Magnet Wire

The winding consists of copper wire known as magnet wire. It is called magnet wire because it is processed specifically for use in electromagnetic actuators such as solenoids. As described in previous chapters, the solenoid is made from winding multiple layers of copper wire side by side and directly on top of one another. In order to wind the copper in this manner, each turn must be separated from the next. This prevents the current from jumping from one turn to the next, rather than flowing through the winding. Each turn is separated from the next by insulation on the wire. The insulation is a material which does not allow electricity to pass through.

There are several levels of insulation available. Each subsequent level is either a little thicker than the previous or uses a higher grade material. As the level of insulation increases, the level of protection increases and unfortunately, the cost as well. The insulation classes and their thermal rating are listed in the chart below.

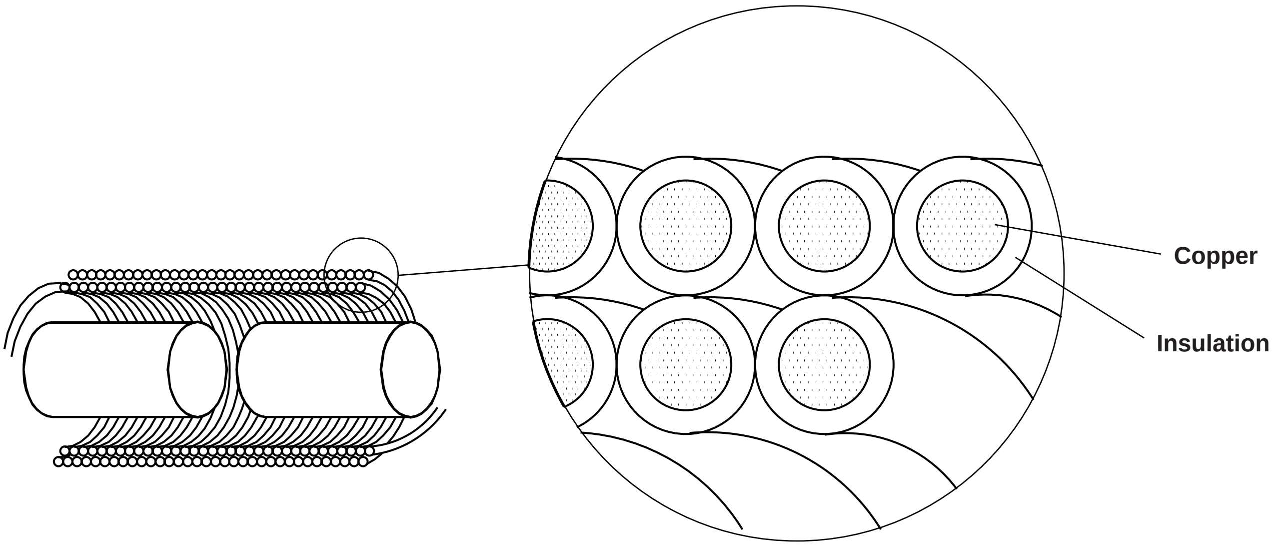
Thermal Rating (° C)	Class
105	A
130	B
155	F
180	H
200	N
220	C

The insulation for each class has a temperature rating at which the wire can be subjected for 20,000 hours before it begins to degrade. Historically, the industry standard was class F wire. However, early on, HydraForce opted to use the next higher level, class H wire with a thermal rating of 180° C, to ensure quality.

Applications exist in which the environmental temperature plus the increase in the winding temperature due to voltage applied, exceed the thermal rating of the class F wire. If this were to occur while the class F wire were in use, the insulation would degrade and ultimately fail. The current would jump from turn to turn and the coil would short out. Since the industry standard was the class F wire, this would occur frequently. The manufacturer would then supply the customer with the higher rated class H wire. HydraForce on the other hand, chose to eliminate this step to ensure reliability and a higher quality coil, by providing the class H wire as a standard.

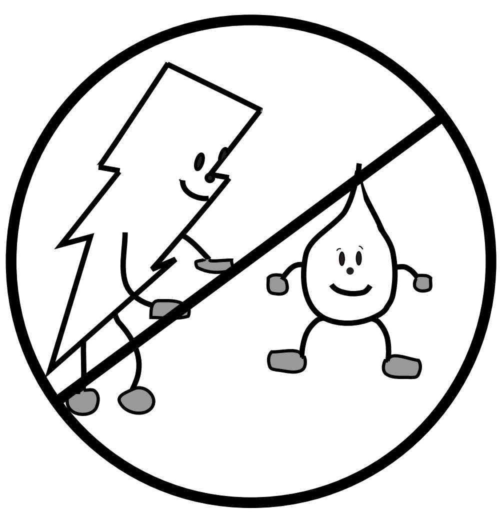
The current industry standard is class H. Since the winding temperature of the majority of the applications does not exceed 180° C, the cost of using a higher class wire is not justified. However, HydraForce can provide 200° (class N) wire if the application requires it. An example of this type of application is valves which are mounted directly in the engine compartment. In addition, some transmission manufactures prefer this type of wire.

The following diagram represents insulation surrounding the copper wire in the winding.

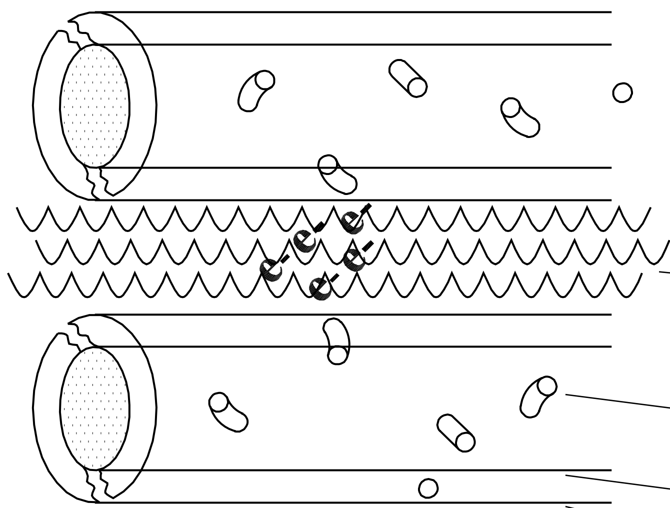


Magnet Wire and Water

It is common knowledge that water and electricity don't mix. Even though the magnet wire is insulated, imperfections still exist. While it is very effective in separating the turns of wire from one another, it cannot protect against water. Small pin holes or imperfections exist along the surface of the insulation where water could seep through. It is therefore important to waterproof the coil. If water gets on the winding and between the turns of wire, the electricity can flow from turn to turn.



Shown below are two sections of wire. Assume that these wires are from two different layers which lay on top of each other, as shown on the previous page. Due to the length of the wire needed for the winding, there is a difference in voltage between the two points. The potential difference and the water seeping through the pin holes could conduct electricity, and allow current to flow through the pin holes. As the current continues to flow, the wire gets increasingly hotter in those areas, which could cause the insulation to melt. If the insulation does begin to melt, the pin holes become larger and allow more current flow. Eventually the magnet wire will burn, causing the coil to short.



Magnet Wire and Nominal Voltage

Different applications provide different voltage levels. For example:

Mobile Construction Equipment:	12 & 24 VDC
Material Handling Equipment:	36 & 48 VDC
Industrial Equipment:	110 & 220 VAC

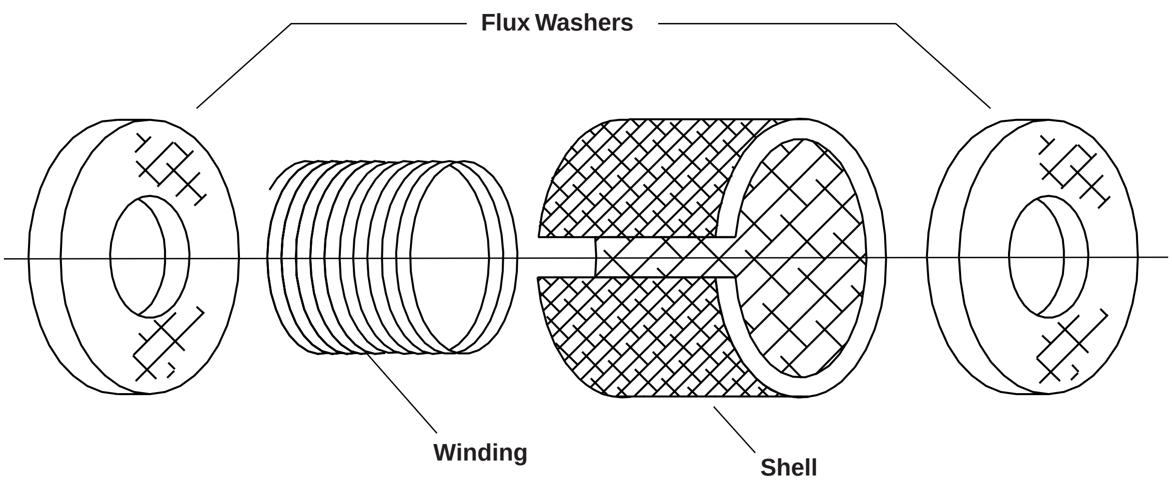
One valve could be used in any of these applications. This valve would require only one level of NI or power. Recall that $P = V^2 / R$. If V increases, then R must also increase to maintain the same P. R could also increase by $R = V^2 / P$. The resistance can be increased in the winding, by using more turns with thinner wire. Recall that as more turns are added, the NI increases. At the same time however, the resistance increases and current decreases. NI therefore, remains unchanged. In order to accomplish this, thinner wire has thinner insulation so the correct number of turns can fit on the winding.

Frame

As mentioned in previous chapters, the frame is present to concentrate the magnetic field of the winding. This increases the strength of the magnetic field passing through the armature and pole piece. The frame is made up of three parts, the shell and two flux washers.

The shell is a tubular shaped element which encloses the winding. The two washers at either end of the winding are the flux washers. They are referred to as flux washers because the magnetic field passes through the thickness or area of the washer. As we've learned, the area multiplied by the magnetic field is flux. Without these washers, the flux would not be concentrated and the solenoid would be inefficient or weak.

The following diagram shows an exploded view of the washers, shell, and winding.



The frame is typically made of a low carbon steel. Low carbon steels are used because they have high permeability, relative to other, more costly Ferromagetic materials. They are also used because steels with a small amount of carbon are preferred, to eliminate residual magnetic effects. As we learned in chapter two, when an external field passes though iron (steel), the domains align. Even after the solenoid (external field) is turned off, some of the domains remain aligned. This alignment or residual magnetism is greater for steels with a higher carbon content.

HydraForce uses a standard 1018 steel. The number designates the components or chemical elements that make up the steel, including carbon. The carbon content of this steel is 0.15% maximum, compared to higher carbon steels such as 1095 which has a carbon content of 0.90 - 1.03% by weight. HydraForce further treats the steel by annealing and plating it.

Annealing is a heat treating process which softens the material. This is done because the surface of the steel becomes hard as it is formed into the shape of the washers or shell. The hardening of the material could increase the residual magnetism, however, the process of annealing reverses this effect.

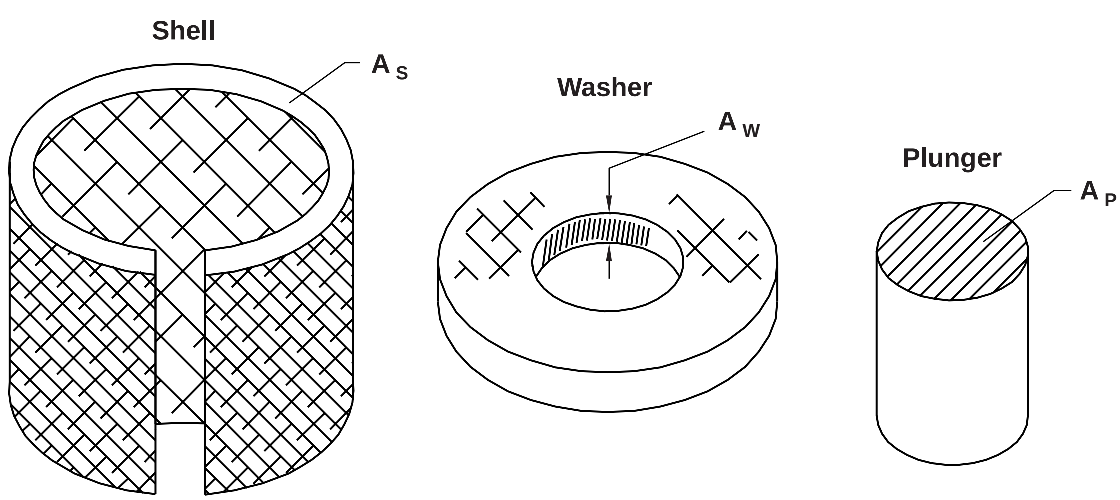
The parts are plated with zinc after they are annealed. This gives the parts their shiny appearance and provides resistance against corrosion (rust)

Frame Size

Below is a comparison of the surface area of the various parts the magnetic field must pass through. For optimum solenoid design, the area in the washer and shell must at least be equal to, or greater than the area of the plunger.

$$A_s = A_w = A_p$$

Where: A_s = cross sectional area of shell
A_w = cross sectional area of washer
A_p = cross sectional area of plunger



Bobbin

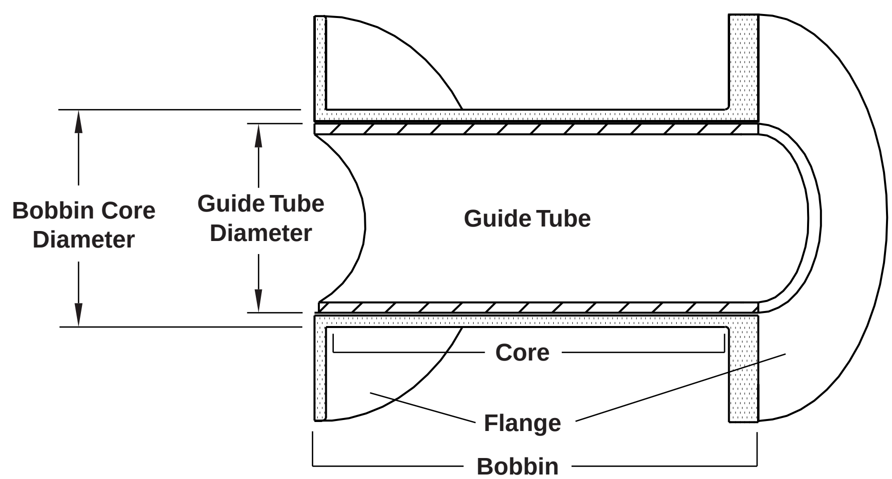
The bobbin is the portion of the solenoid on which the wire gets wound. It is made from a plastic known as Rynite$_{TM}$, or Nylon, available from DuPont. Both materials are thermoplastics, and are glass filled to make them stronger and stiffer. Thermoplastics, and specifically Rynite or Nylon, are used in coil manufacturing because their consistency or stiffness remains the same in the presence of heat. In addition, these materials resist cracking due to extreme temperature changes.

HYDRAFORCE POLICY

-HydraForce used glass filled Rynite or Nylon for its bobbins.

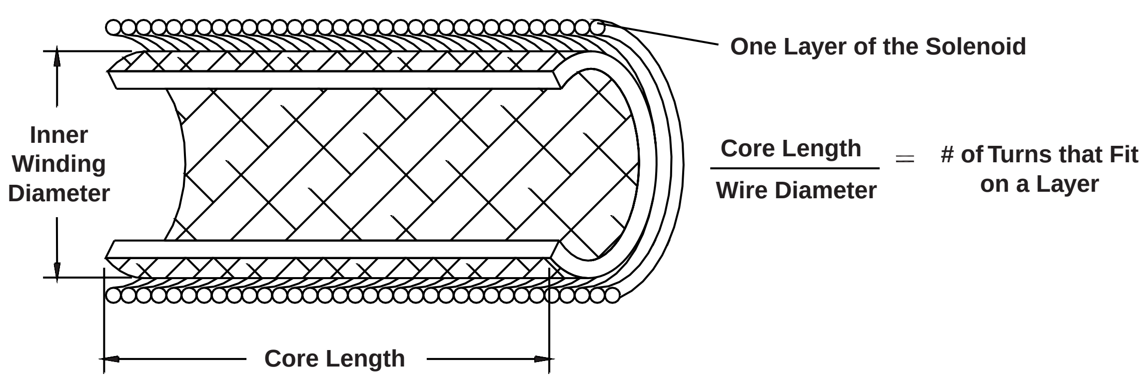
Bobbin Size

The size of the bobbin is determined by the outside diameter of the guide tube as well as the number of turns of wire required to develop the magneto-motive force for the actuator. Refer to the diagram below.

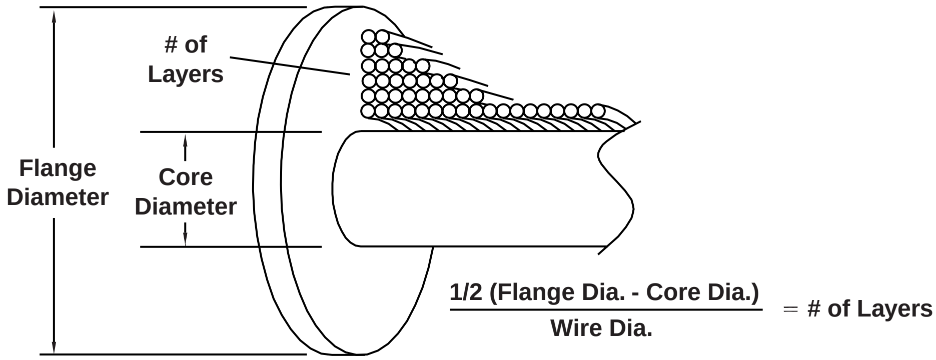


The number of turns of wire which fit onto a bobbin is determined by the core diameter and the flange diameter.

The diameter of the core defines the innermost diameter of the winding. The length of the core determines how many turns of copper can be laid next to each other. The diagram below illustrates this concept.



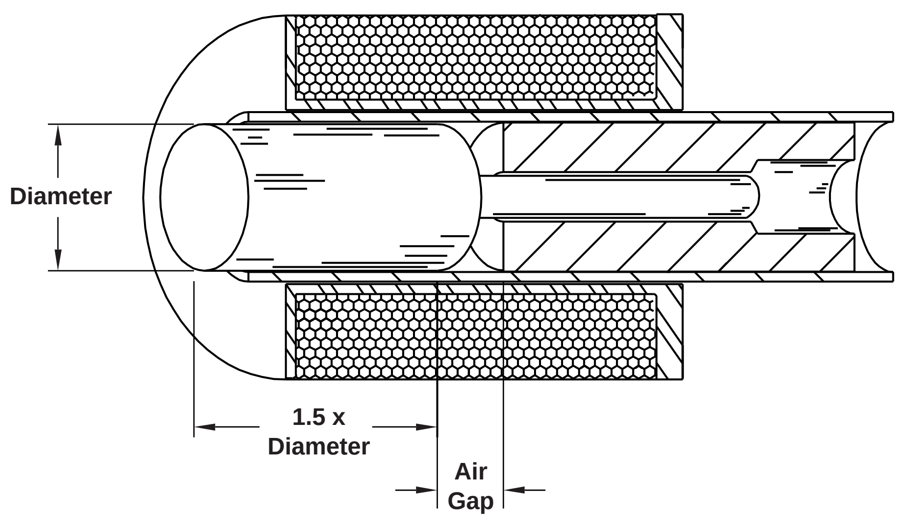
The area between the core diameter and the outside diameter of the flange, determines the number of layers that can fit onto the bobbin. Refer to the following diagram.



There is no rule which defines the ratio between the length of the core to the flange diameter. A solenoid could be wound with one layer (a very long core and a small flange), or it could be wound with one turn per layer (very short core and very large flange). However, both of these examples are extreme and would use too much space in one direction or the other. A compromise somewhere in the middle is usually the best solution.

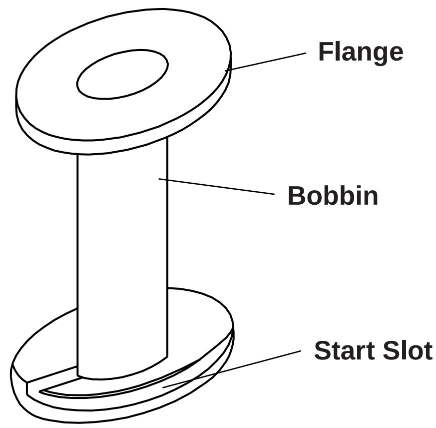
The diameter and length of the plunger are among the factors which influence the ratio between the length of the core to the flange diameter. In order for the plunger to slide freely in the guide tube, the length of the plunger should be a minimum of 1.5 times the diameter.

Another factor to consider is the air gap, which is typically in the middle of the length of the winding. Since the air gap is in the middle, this means that the portion of the pole piece and plunger within the bobbin, must be of equal length. This ensures that the two pieces meet in the middle and still extend beyond the coil.

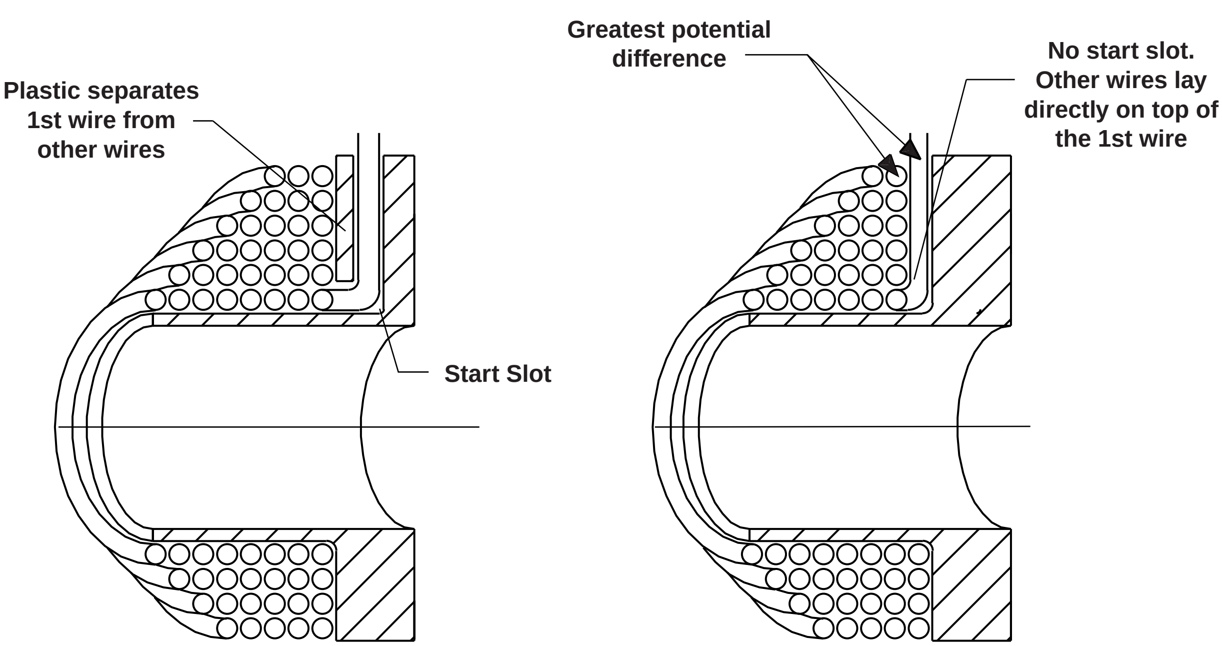


(in the middle of winding length)

The first turn of wire wound onto the bobbin is inserted into a slot in one of the flanges and is known as the *start slot*. The start slot can be seen in the following illustration.



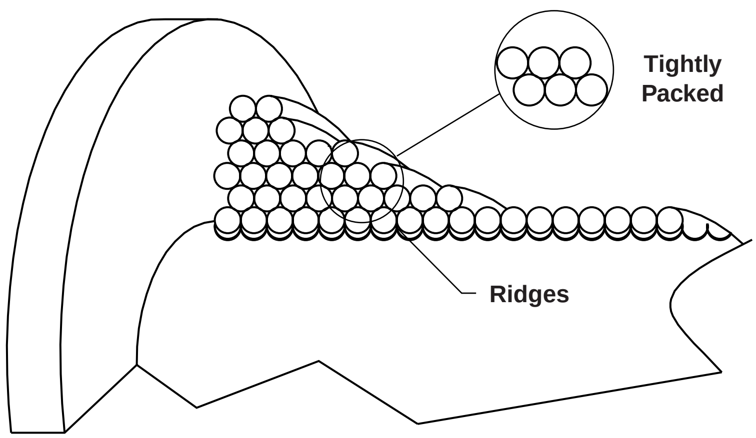
The slot is used to protect the insulation from being rubbed off while additional turns of wire are wound onto the bobbin. If there is no insulation on the wire, the current could jump from wire to wire, or short. The diagram below shows a bobbin with a start slot and one without. In addition to protecting the wire, the start slot also protects the coil during operation. When power is applied to the coil, the copper expands. In its expanded state, it could rub against the first wire, breaking the insulation, causing the wire to short. This problem is predominant at the start slot because of the potential voltage difference between the start wire and the wire on the outermost layer (*see diagram below*). A large voltage drop exists because current flows through the entire coil from the start wire to the end.



Winding Method

Perfect Wound

There are two types of winding methods available, perfect wound and random wound. The perfect wound (or sometimes referred to as layer wound) method is shown in the following diagram.



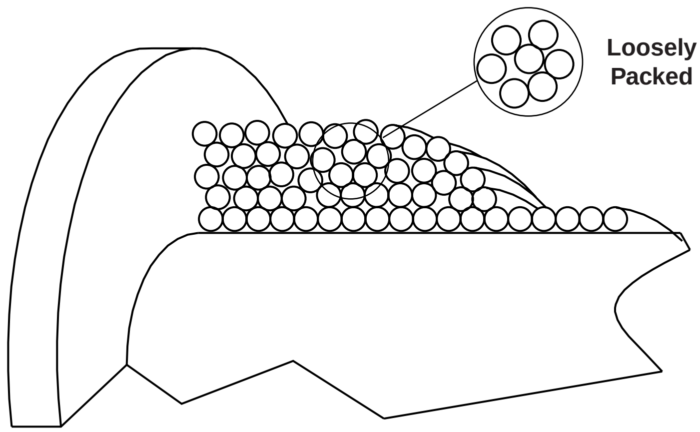
Notice that the bobbin is different from the ones shown in previous diagrams. There are small grooves or ridges, to ensure that the first layer on the bobbin fills the space completely. The subsequent layers of wire are wound between the previous ones as shown in the diagram. One drawback to using bobbins with grooves is that a special bobbin is needed for each voltage. The reason for this is that a different thickness of wire is required for each different voltage or winding and therefore the size of the grooves varies.

It was once thought that layer wound coils were needed to enure the wires were tightly packed. If the wires were loosely packed, they could vibrate and rub against one another in the application. This could potentially cause the insulation to be rubbed off, causing the coil to short. However, both random wound and perfect wound wires stay in place because during the winding process the wire is held taught by a tensioning device on the winding machine. Therefore, each layer is pulled tight against the next in either method.

Another reason to layer wind a coil is to ensure that the outer layer of the winding closest to the shell is even. If it becomes uneven, there is the potential that the wire could touch the shell and cause the coil to short. In order to overcome this problem, a little extra space is allowed between the winding and the shell.

Random Wound

An example of a random wound coil is shown below.



The turns in a random wound coil are just that, random. They do not necessarily lay tightly inside the previous row, as seen in the diagram. The example above however, is an extreme case. The winding process does not become random until the first seven to ten layers. This is because winding machines today are programmed to move from one flange to another. Modern machines are designed to wind perfect wound coils. The machines are programmed with the wire diameter so that they will move smoothly across the length of the core, minimizing the space between each turn of wire.

In the perfect wound process, the possibility exists that the wires begin to lay randomly after fifteen to twenty layers. The winding machines may skip slightly causing a gap to occur between the wires.

HydraForce uses the random wound process for the following reasons:

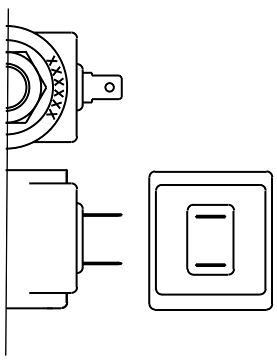
1. The cost of the bobbin is lower with the random wound process. One bobbin is used for any size wire.
2. The random wound process provides layer wound coils for at least the first 7-10 layers.
3. The perfect layer wound coil has the potential to become random after 15-20 layers.
4. There is no concern that the outer winding layer will come in contact with the shell, because extra space for winding high spots is designed into the coil.

HYDRAFORCE POLICY

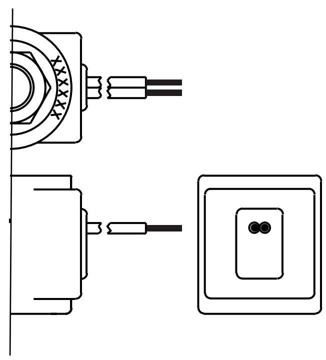
- *HydraForce uses the random wound process as its standard.*

Terminations

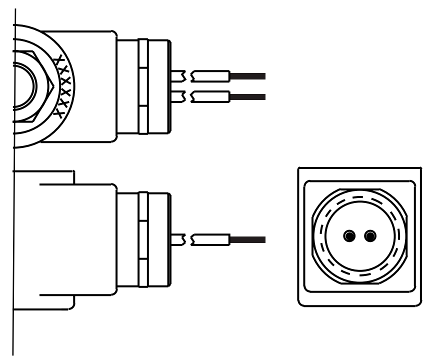
In the previous chapter, the current was applied to the winding through a pair of wires. There are various types of conductors that can be connected to these wire at the end of the winding. Shown below are several styles available from HydraForce.



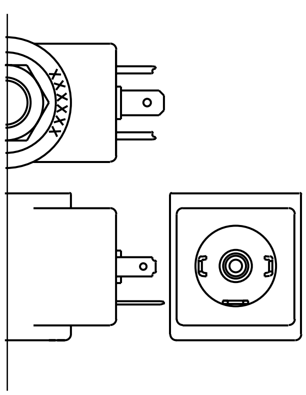
Dual Spades
SAE J858a
S



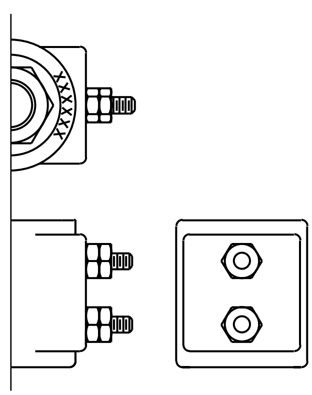
Dual Leads
18 gage
L



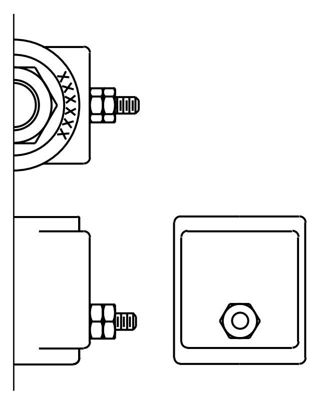
1/2" Conduit
& 18 gage Leads
P



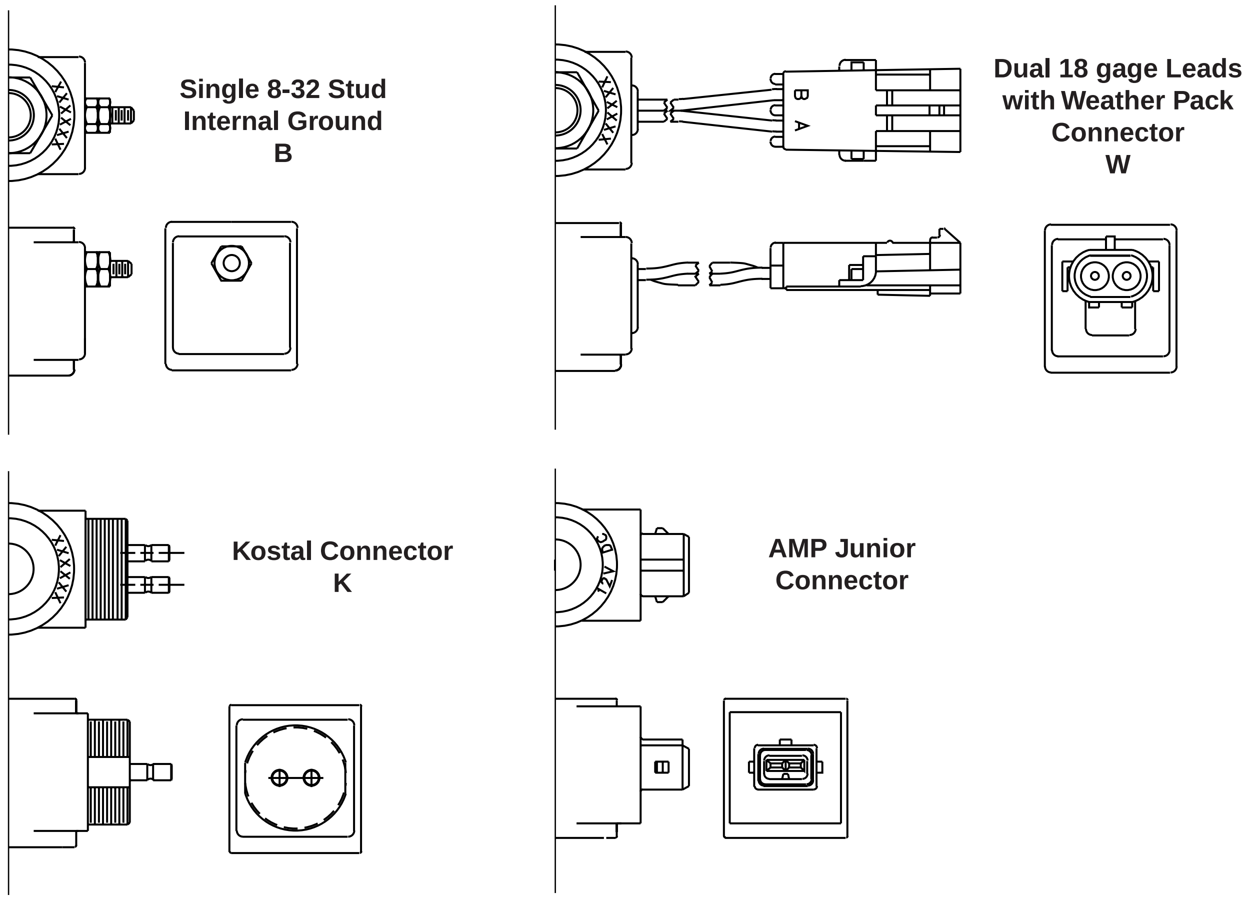
DIN 43650
Connector
G



Double
8-32 Studs
E



Single 8-32 Stud
Internal Ground
with Diode
D



Some of the terminations listed above and on the previous page have features designed into them which are worth noting:

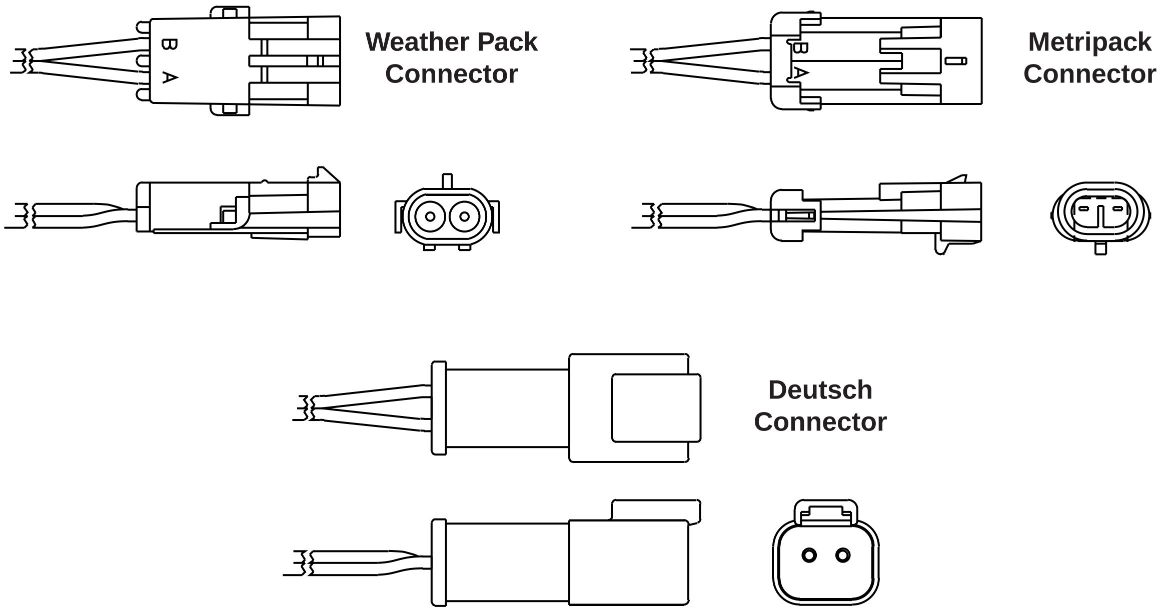
DL: The lead wires in any of the coils with Dual leads can be pulled on with 20 lbs of force without causing damage to them.

G: The third termination pin is grounded to the shell of the coil.

P: The third termination pin is grounded to the shell of the coil.

Junior AMP: This style is a weather resistant type of termination. The advantage of this connector over those on the following page, is that it is molded into the coil. While the connectors on the following page are considered weather resistant, they are connected on lead wires, where water is able to get in.

Special connectors for various conditions are available which can be attached to the end of the wire. Some examples of these are listed on the following page.



The connector selected depends on the customer preference and the application. For example, material handling applications such as fork lifts, scissor lifts and aerial platforms use the dual spade termination. Transmission and mobile construction equipment use the DIN or Dual Lead terminations with one of the above connectors.

Encapsulant

The encapsulant is the material which encases the bobbin, winding, shell, washers and terminations. The material used, as in the bobbin, is Rynite or Nylon. This thermoplastic is injected into a mold which temporarily holds the bobbin and other parts into place.

A mold is a tool which is used in forming plastic parts. The mold has an inverted image of the part cut into it so that when the it is filled with the molding compound, (thermoplastic in this case) the part will be formed. The molding process can be compared to a jello mold. Hot liquid plastic is injected around the other parts. Once the encapsulant (the jello or thermoplastic) solidifies around these parts, the assembly can be removed from the mold. The parts are then suspended in the plastic, as pieces of banana would be suspended in the jello.

Two methods can be used to encapsulate the coil assembly. These are the single mold method, and the transfer (double) mold method. Each of these methods are described in the following sections.

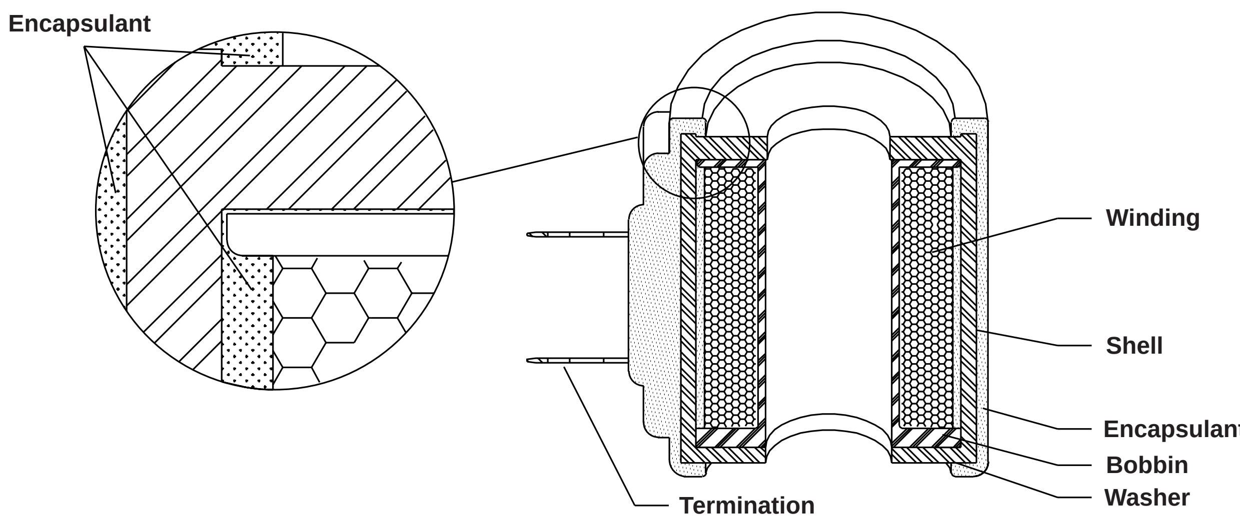
Molding Processes

Transfer Mold (Epoxy Resin)

Transfer molding is a term associated with the encapsulation of a coil by pouring epoxy around the winding. The winding and termination are loaded into a shell which is typically in the shape of a can that is open at one end. The epoxy is poured into the can and encases the winding and termination. This process is slow, costly and rarely used in the cartridge valve industry.

Single Mold (Thermoplastic)

In the single mold method of encapsulation, the winding, shell, washers and termination are molded in one operation. This can be seen in the illustration below.



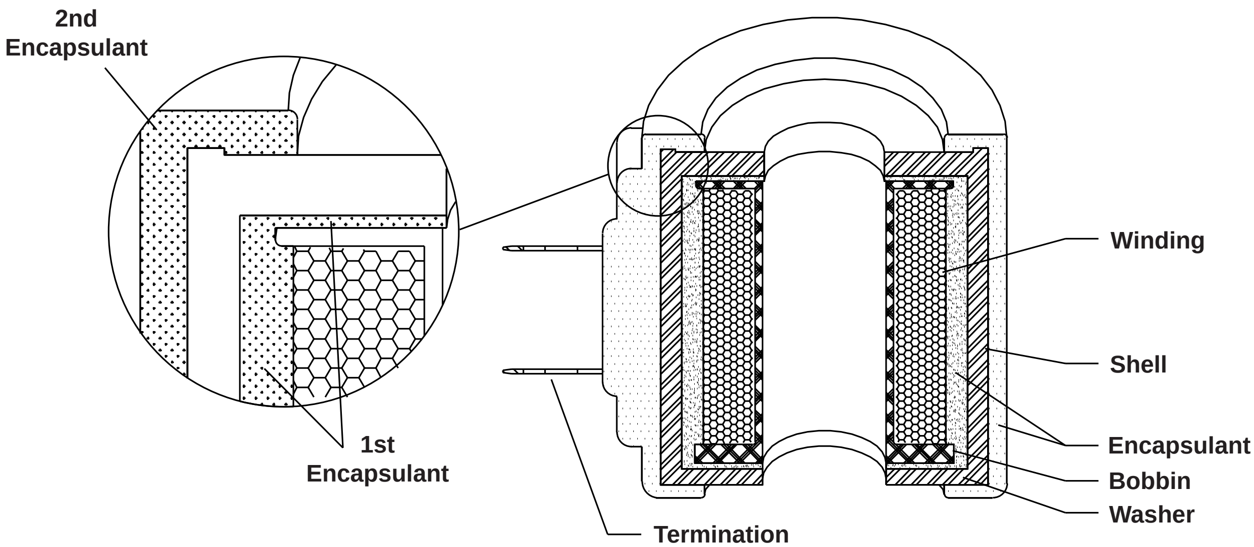
Transfer Mold

A second encapsulation process uses a material known as epoxy. This process does not involve injecting plastic into a mold. Instead, the material is poured into the shell and around the winding. This process is slow and seldom used today.

Double Mold (Thermoplastic)

In the double mold process, the winding and possibly the termination are encapsulated first. A second molding process is then done which encapsulates the shell and washer along with the first encapsulation of the winding and termination. This mold is larger than the single mold due to the extra plastic used in the two molding processes.

The double mold can be seen in the following diagram (note the first and second encapsulants which can be seen in the enlarged area).



Comparison of Single and Double Mold

The reasons for choosing one method over the other include: magnetic efficiency, cost, thermal cycle, waterproofability, and overall size. The arguments for each of these factors are presented in the following paragraphs.

The magnetic efficiency of the single mold process is typically greater than that of the double mold. The closer the steel shell is to the winding, the stronger the magnetic field. As we learned in previous chapters, when the plunger is far from the pole piece (at a larger air gap), the force is weakest. This concept holds true when the distance (air gap) between the shell and the winding is increased. Since the plastic is thinner (bringing the steel closer to the winding), in the single mold coil, its magnetic field is stronger.

The cost of the single molded process is less than that of the double molded. The single mold is done in one process, whereas the double mold is done in two. There is less time and material required to manufacture the single mold.

The thermal cycle, or temperature change from hot to cold is another factor to consider. In both processes, the plastic and steel expand and contract as the coil heats and cools. Not only do the steel and plastic expand and contract, they do so at different rates. As this happens, small cracks begin to form between the plastic encapsulant and the bobbin. Water can seep through the cracks and potentially short the winding. Since the plastic surrounding the bobbin in the double mold process is thicker, it is stronger than the single mold coil in this area. It can therefore sustain larger temperature changes and a greater number of these changes. However, a gap could eventually form between the bobbin and the encapsulant, even in the double molded coil, allowing water into the winding.

The size of the double molded coil is greater than that of the single molded. Due to the nature of the double molding process, more plastic is present on the coil. As a result, the steel is pushed farther from the winding. As mentioned previously, when the air gap is larger, the magnetic efficiency is less. To compensate for this loss in efficiency, the thickness of the metal is increased. The increased metal thickness, as well as the double layer of plastic, increases the size of the coil.

Keeping all these factors in mind, HydraForce chose to use the single molded process. The main reason for this decision was to improve the magnetic efficiency. The decision to use the double molded coil might have been made if it were fully water-proof. However, the cost, loss in magnetic force and possibility that water could get in with either process, lead HydraForce to the single molded coil. (Waterproofing of coils will be considered in Chapter 10.)

HYDRAFORCE POLICY

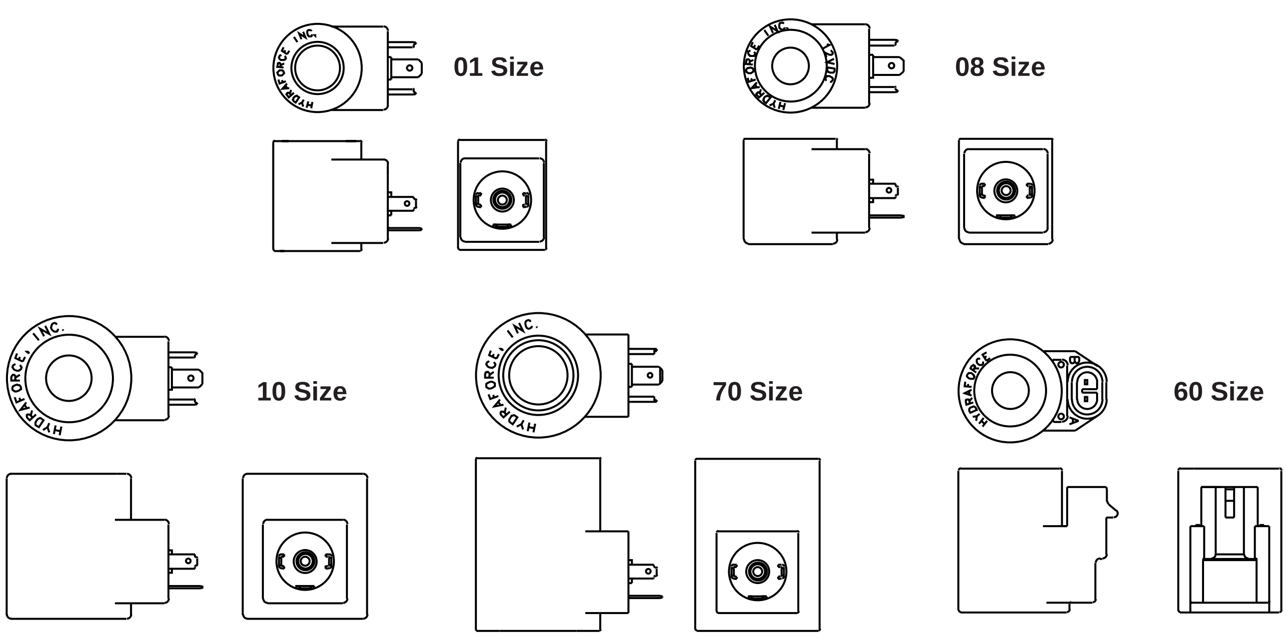
-Hydra Force uses a single molded process as standard.

HydraForce Coils

There are six sizes of standard HydraForce coils currently available. Theses are:

Size	**Typically Used On:**
01	Proportional pressure reducing valves
08	Solenoid valves
10	Solenoid valves
12	Solenoid valves *(shown in Ch 6)*
60	Solenoid valves
70	Proportional flow control valves

Each of these coils can be seen in the following diagram.



Each coil is designed with the following parameters in mind to ensure quality over a wide range of applications.

Storage temperature range:	-40° to 150° C
Operating temperature range:	-40° to 100° C
Duty cycle:	100% ON
Operating voltage:	+/- 15% of nominal voltage

Parameters Defined

Each of the parameters followed in designing a HydraForce coil, are defined in the following section.

Operating Voltage

The operating voltage is a range of voltage which can be applied to a coil. At the low end of the range, the coil can draw enough current to operate the valve. At the high end of the range, the coil will not fail due to overheating.

Storage Temperature

The storage temperature is the temperature at which the coil can be stored and subjected to. In this temperature range the material remains unchanged.

Operating Temperature

The operating temperature is the temperature the coil can be subjected to continuously during use. At this temperature, no degradation of the coil material will occur. The valve which the coil is mounted on will continue to operate per HydraForce catalog specification for flow and pressure. The coil can be operated in higher ambient temperatures, but the low voltage condition must be reviewed as well as the duty cycle. The voltage and temperature requirements will be further discussed in Chapter 10.

Duty Cycle

The duty cycle is defined as the percentage of time the coil is powered up while installed on a valve, for a given application.

HydraForce coils can be powered up for 100% of the time with 115% nominal voltage. For example, a 12V coils would be powered up at 13.8 V (12V x 1.15). This coil could be installed on a valve which was in a 100° C ambient environment. The coils can be subjected to these extremes for 20,000 hours with no degradation in material.

Summary

In this chapter the following concepts were presented:

- What magnet wire is.
- Why magnet wire is insulated and what class of insulation HydraForce uses.
- What type of plastic HydraForce uses in its coils.
- The name of the coil components.
- Why a start slot is present on the bobbin.
- How water can short a winding.
- The difference between layer wound and random wound coils.
- The various types of termination HydraForce offers.
- The six sizes of coils available from HydraForce.
- The design or operating parameters of the coils.

Review Questions

Use the following review questions as a measure of your understanding of the chapter material. Answers are provided in the appendix.

1. Why is magnet wire insulated? ________________________

2. What class magnet wire does HydraForce use in its coils?
   What is its continuous duty rating? ____________/___________

3. What is the HydraForce definition for continuous duty? ________________________

4. What are the components which make up the frame? ________________________

5. What is the temperature range that the coil can operate in? ________________________

6. What is the start slot used for? ________________________

7. What type of termination is used in the material handling industry? ________________________

8. What are the parts of the coil? ________________________

9. What type of plastic is used in HydraForce coils? ________________________

10. What are the four sizes of standard HydraForce coils? ________________________

11. What is the voltage range that standard coils can operate in? ________________________

12. What winding process does HydraForce use? ________________________

Notes

Chapter 6: Waterproof Coil Construction

Objectives

The objectives for this chapter are as follows:

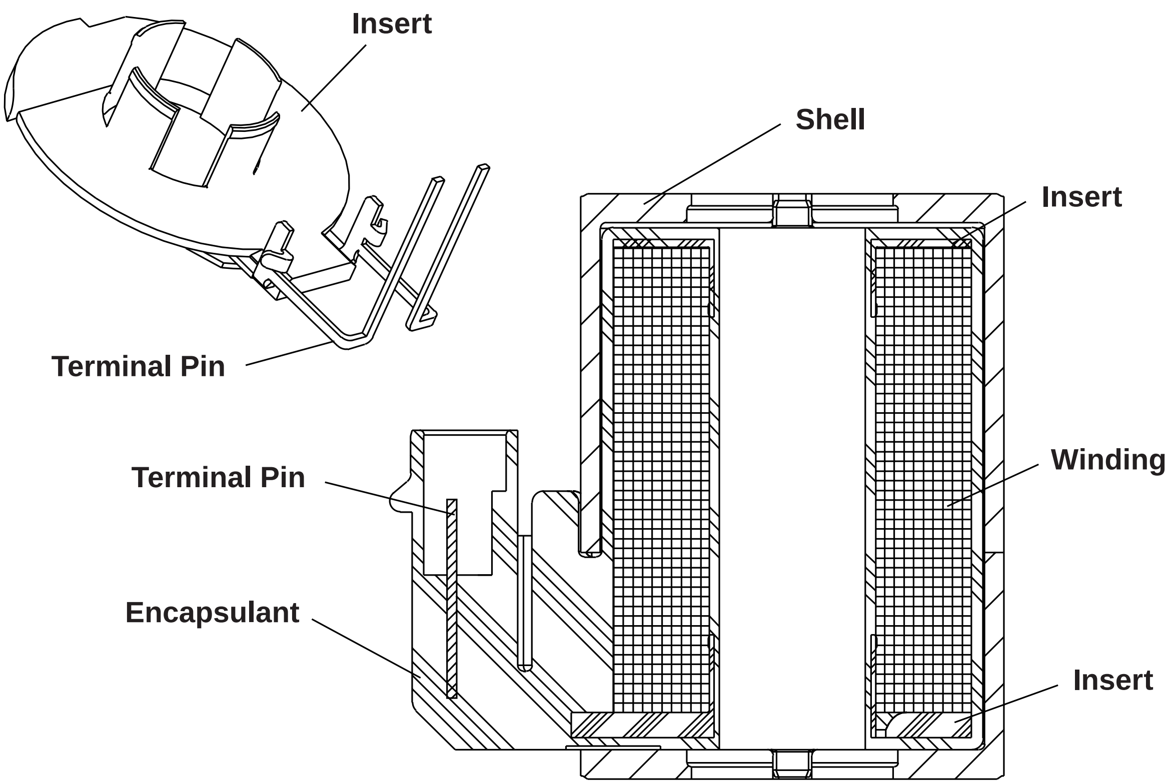
- To learn about the 12 size coil.
- Learn what a bobbin-less coil is.
- Discover what the IP67 rating is.
- Understand why the coil frame is on the outside of the encapsulant for this coil.
- Learn about retractable pin molding
- Learn about weather resistant connectors which are molded into the coil.

Introduction

In this chapter, the 12 size coil design for spool valves is introduced. The coil differs in both size and construction from any other type of coil. The waterproof version of this coil is unique because it does not require o-rings to seal it from the environment. In addition, no bobbin is used for the winding. This fact and the special molding process used, make the coil waterproof.

Waterproof Coil Construction

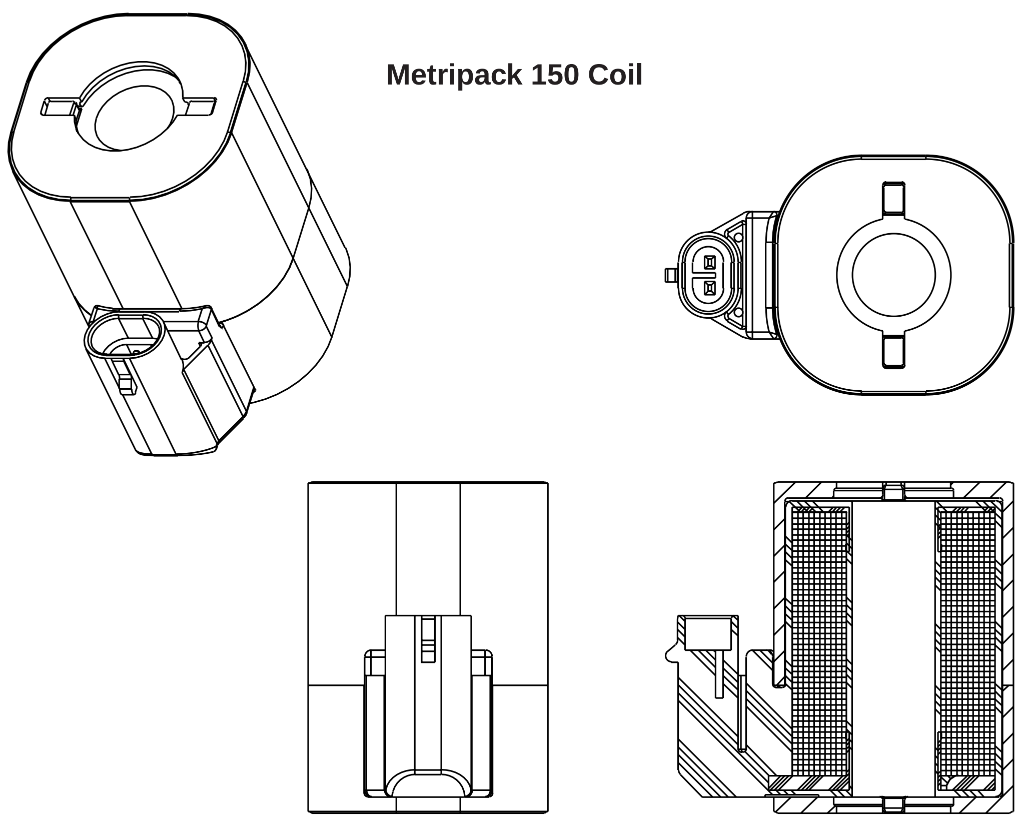
The 12 size coil is HydraForce's latest innovation in coils. While it serves the same function as the previous coils, this coil has no bobbin and an external shell. Shown below is the construction of the new waterproof coil used on the 12 size spool valves.



This coil was designed to answer some potential problems that exist with the current waterproof o-ring sealing assembly. The o-ring assembly requires proper installation of the components. Proper installation includes keeping the seals clean, not damaging the surfaces, and tightening the nut to the proper torque. While these issues do not cause any problems for the trained installer, they may cause problems to the untrained service technician.

In the standard coil construction, a bobbin is used to wind the coil. Recall the discussion of the bobbin from the previous chapter. In the waterproof construction, a bobbin is not used. Rather, the magnet wire is wound on a steel tube. The tube itself is part of the machine which winds the coil, and is not part of the coil. After winding, the coil is heated until a thin film of adhesive causes the magnet wire to bond to itself. The solid, free standing winding can then be removed from the winding machine, and end caps or inserts are installed at either end of the winding. This type of winding is known as a bobbin-less, or free standing winding, and it is considered to be perfect wound. The end caps serve two purposes. They provide a place to fix or locate the terminal pins prior to molding, and they protect the winding during the encapsulation process. During the molding process, small pins, known as retractable pins, hold the end caps and winding suspended. When plastic is injected into the mold tool, the pins are pulled away from the winding and plastic fills in where the pins were.

As with the standard coils, a variety of terminations can be installed. The three terminations that will be available initially, are the dual lead, dual spade and metripack 150. However, to take advantage of the fact that this coil is waterproof, a weather resistance connector which is molded into the coil itself should be used. This can be seen in the metripack connector shown below.



Metripack 150 Coil

The metripack coil meets the IP67 weather rating. IP67 is a British standard for the weather rating of an enclosure. Other coils with waterproof terminations are being designed to meet this standard. The standard specifies that the coil can be submerged in 1m of water for 1/2 hour. (The coil and water temperature remain constant throughout the test).

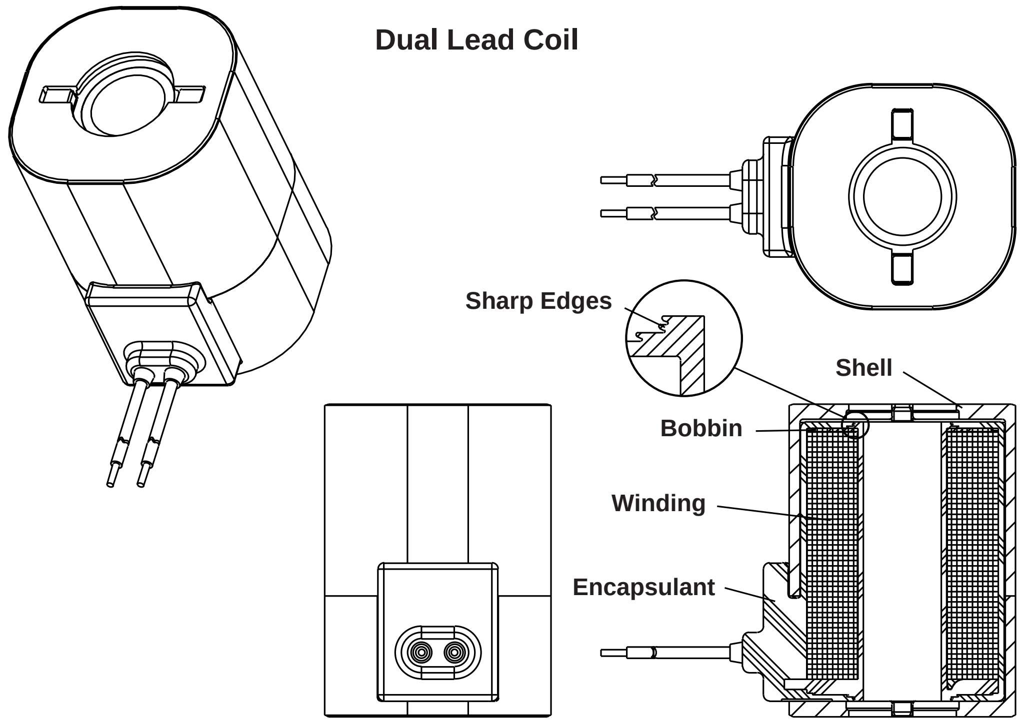
Another advantage of molding the connector in place rather than having it on dual leads is that no strain relief needs to be built in to the coil. A strain relief protects the lead wires from being pulled out of the encapsulant. This simplifies the coil construction.

The reason this coil can be submerged in water, unlike other coils, is that there are no seams or joints between the encapsulant and the bobbin, because there is no bobbin. Instead, the encapsulant completely encloses the winding on the outside, as well as the inside diameter as shown in the cross section on the previous page.

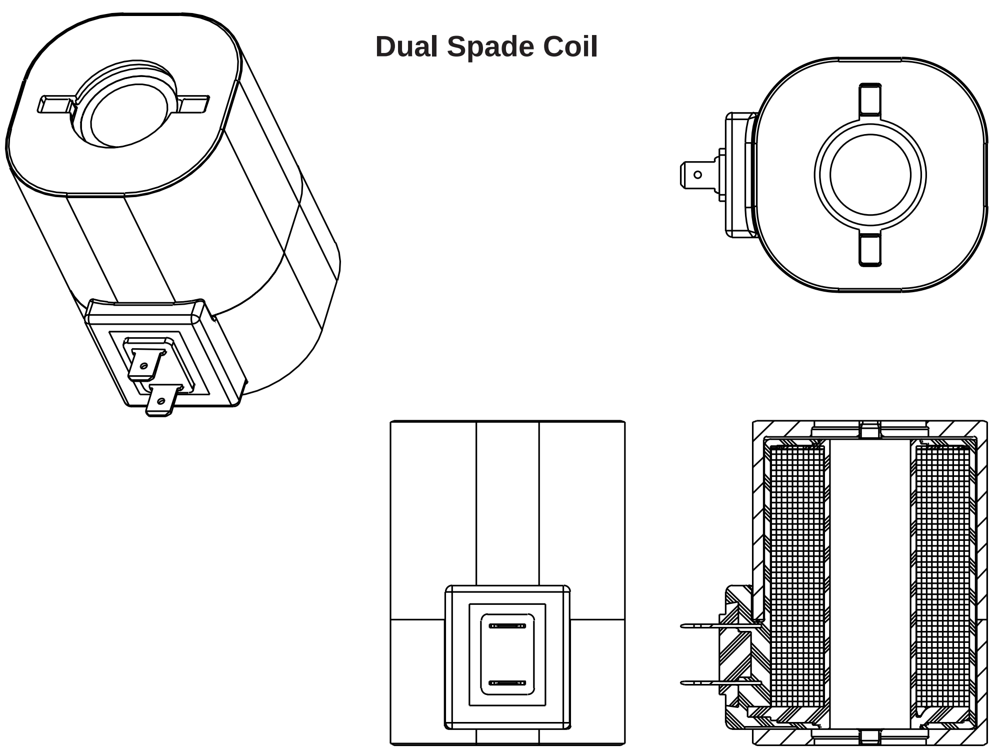
The diagram on the previous page shows the encapsulated coil inside of its shell. This shell or frame serves the same purpose as others, to concentrate the magnetic flux. The shell is located on the outside of the encapsulant to eliminate the problems noted in Chapter 5. As mentioned in the discussion of the single or double molding, when the steel shell inside non-waterproof coils expands or contracts, the plastic could crack. This may occur when the coil is used in an environment where the temperature change is drastic.

The following two coils are not considered fully waterproof because of the termination style. The point where the termination enters the encapsulant is not sealed. Since there is an entry point for the water, the free standing winding is not used in these two coils. Rather, the winding is wound on a bobbin. This is more cost effective, because the wire with adhesive and the process of winding the free standing coil are more expensive than the bobbin wound coil. The bobbin is slightly different than previous HydraForce designs. At the outer edges there are small, sharp corners. These corners of the bobbin re-melt during encapsulation. While the plastic may still crack in this area when it is subjected to drastic temperature changes, this feature will improve the weather resistance of the coil in many applications. The dual lead and dual spade coil are shown on the following page.

Dual Lead Coil



Dual Spade Coil



The same values for the design parameters mentioned in Chapter 5 were applied to this coil as well. These include:

- voltage range
- temperature range
- frame size
- materials
- duty cycle

While the coil still operates within the above criteria, it's power draw is slightly higher than if it were constructed with the frame inside the encapsulant. The 12 size coil, as shown on the previous pages, draws 40 watts when it is at room temperature, with nominal voltage applied. Recall the discussion of the double molded coil in Chapter 5. These coils, like the waterproof coils, push the frame further from the winding when compared to the single molded coil. This makes the coil a little less efficient. To compensate, the nI of the coil is increased by decreasing the resistance slightly.

Future 08 & 10 size coils

There are plans to introduce 08 and 10 size waterproof coils based on the design presented in this chapter. These should be available in late 1999 and will be designed to fit onto the existing cartridges. However, because the waterproof coil will not require the extra o-rings to seal the coil, the extra large adaptors to support the o-rings will no longer be needed. These coils may be slightly larger in diameter than their predecessors. Also, the power draw will be slightly higher for the reason mentioned above.

Summary

In this chapter the following concepts were presented:

- Construction of the 12 size coil.
- Construction of the waterproof coil.
- The bobbin-less winding.
- IP67 weather rating.
- Reasons for an external shell.
- Reasons for molding the connector into the coil.

Review Questions

Use the following review questions as a measure of your understanding of the chapter material. Answers are provided in the appendix.

1. Why is the shell external on the 12 size coil? ________________________

2. Why is the dual spade 12 size winding wound on a bobbin? ________________________

3. What are the inserts used for? ________________________

4. What are the advantages of molding the connector into the coil? ________________________

5. What are the advantages of the waterproof coil design? ________________________

6. What kind of winding does the waterproof coil use? ________________________

Chapter 7: Valve Construction

Objectives

The objectives for this chapter are as follows:

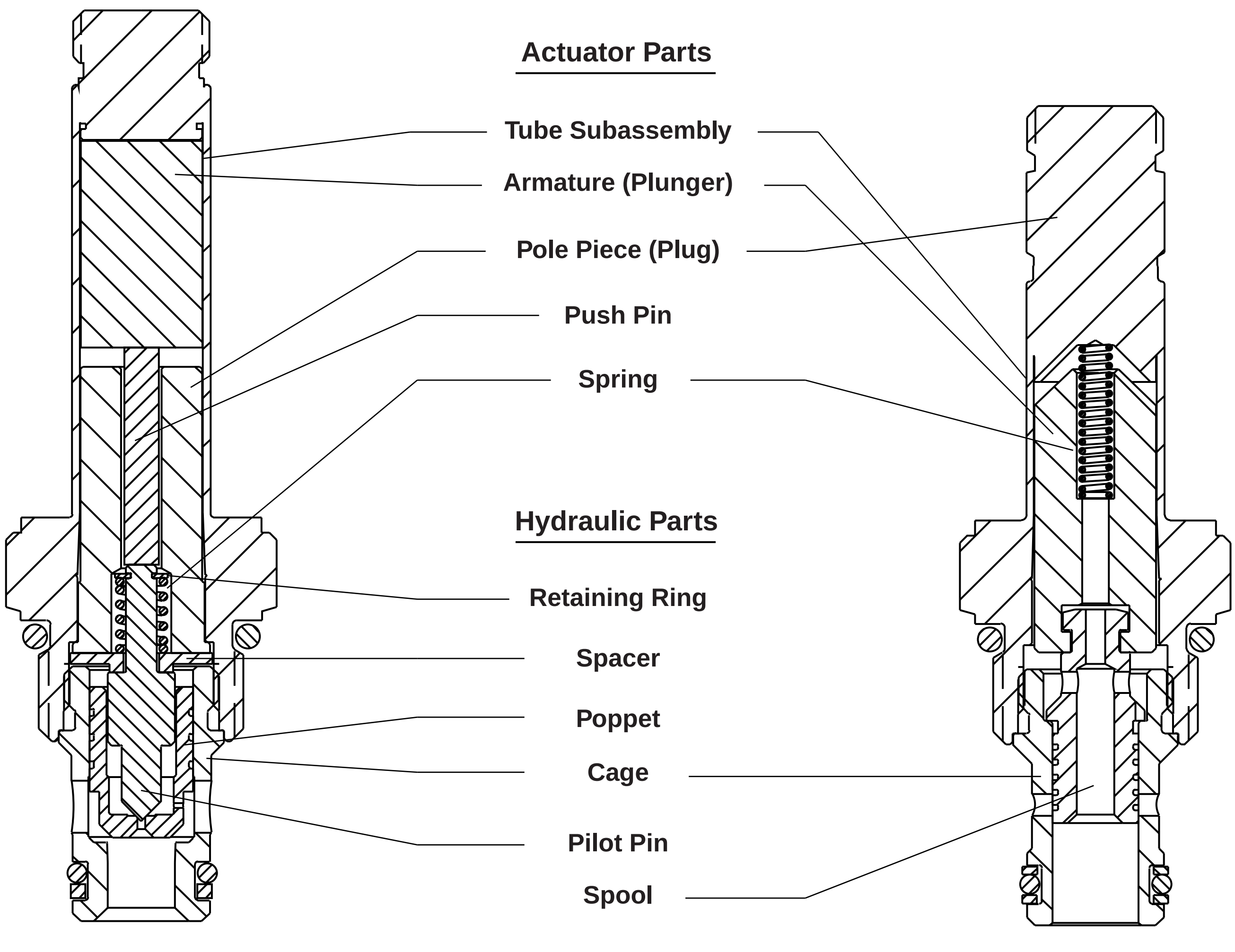
- Identify the two basic types of valves, poppet and spool, and become familiar with their components.
- Learn how the tube subassembly is constructed and what the pressure limitations are.
- Recognize the differences between the poppet and spool type cages.
- Learn the differences between the push and pull style armatures.
- Identify a “T” slot and discover what it is used for.
- Become familiar with the spring and its function in the solenoid valve.

Introduction

In this chapter, the two basic types of valves are introduced. The differences in function between the push style and the pull style armature and valve are outlined. A description of the components which make up the armatures and valves is provided as well as the materials and processes used to manufacture theses parts.

Valve Types

There are two basic types of solenoid valves available from HydraForce. An example of each type, the SV08-21 and the SV08-24 are shown and described in the following sections.

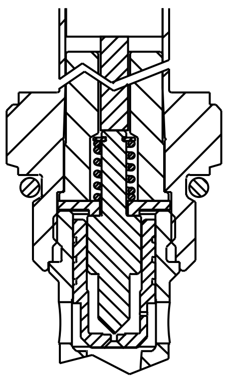


SV08-21
Push Style Armature

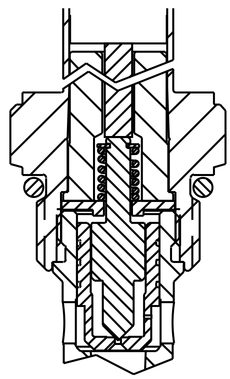
SV08-24
Pull Style Armature

The following diagram shows three stages of a poppet style push armature as well as the spool style pull armature, in use. While the diagrams show a flat face, push style armature working in the poppet valve, this is not limited to poppet valves. In the poppet style set of diagrams, the first stage shows that the valve is open and the coil is de-energized. In the second stage, the coil has just been energized and the valve/ poppet is in transition. The coil is energized and the valve is partially open. In addition, the plunger is pushing down on the push pin and the pilot pin. In the last stage, the valve is closed and the coil has been energized for at least one half second.

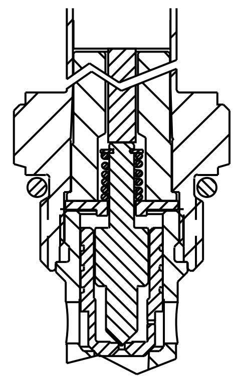
Poppet Style
Stage 1



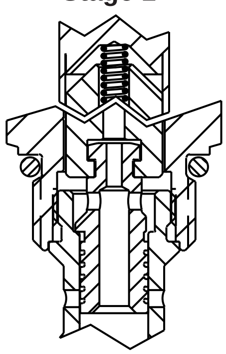
Poppet Style
Stage 2



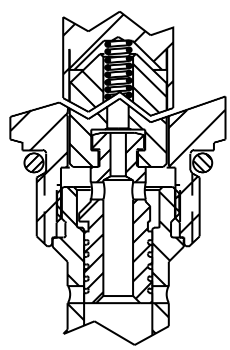
Poppet Style
Stage 3



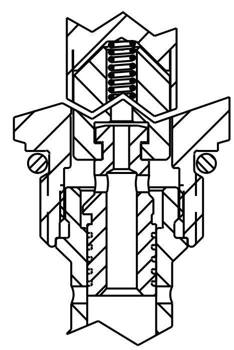
Spool Style
Stage 1



Spool Style
Stage 2



Spool Style
Stage 3



The second set of diagrams show the three stages of the spool style / pull armature in use. The first stage shows the valve when the coil is de-energized. In the second stage, the coil has been energized briefly and the plunger has begun to pull up on the coil. In the last stage, the coil has been energized for at least one half second and the plunger and spool have fully shifted.

Actuator Types

The two styles of valves are defined by their actuator type. There are two basic types of actuators, the push style and the pull style. Refer to the previous illustration, in which the first set of diagrams show the armature and pole piece for the SV08-21 valve. These make up a push style actuator. It is named a push style actuator because of the way it works. The armature *pushes* on the hydraulic parts (pilot pin & poppet) of the valve.

In the same illustration, the second set of diagrams show the armature and pole piece for the SV08-24 valve. These make up the pull style actuator. In this case, the armature *pulls* up on the hydraulic parts (spool).

In both styles, the plunger and pole piece are made from low carbon (SAE 12L14) steel for the same reason the shell is. It has high permeability (good magnetic properties) for a relatively low cost. The magnetic properties are further improved by annealing the parts.

Wet Armature

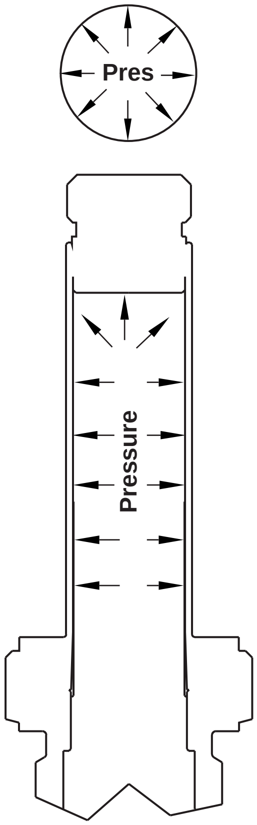
The plunger, tube subassembly and the pole piece make up the armature assembly. HydraForce uses a type of assembly known as a *wet armature*. A wet armature is simply an armature assembly in which the plunger and the inside of the tube are exposed to hydraulic fluid. On the other hand, a dry armature is separated from the hydraulic fluid entirely.

Tube Subassembly

The parts of the tube subassembly are joined together by a process known as brazing. Brazing occurs when a filler material is heated, melts and bonds the other two parts together. These parts are brazed together because the tube subassembly must be able to hold or contain the oil even when the oil is pressurized.

When pressure is applied to the inside of the tube, it pushes outward on the tube causing the tube to deform. Any amount of pressure on the tube, changes the shape of it, however, the change is so small that it is not noticeable. After the pressure is removed the shape of the tube returns to its original shape. At some point, the pressure is so great that the tube does not return to its original shape. Proof pressure is the pressure at which the tube begins to deform permanently. At the point of proof pressure and above, the tube deforms and remains deformed. Below the proof pressure, the tube deforms elastically and can snap back after the pressure is removed.

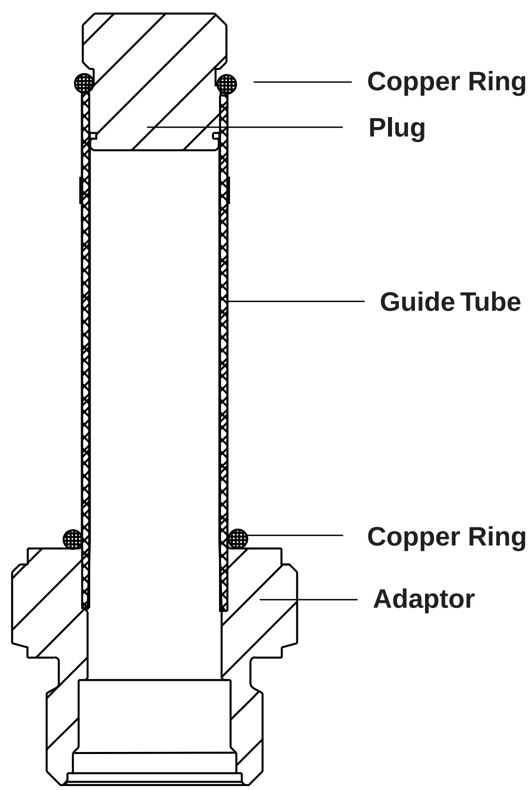
If pressure is continually applied above the proof pressure level, the tube has the potential to burst or fail catastrophically. The burst pressure is the pressure at which the valve or tube subassembly no longer contains the pressure or fluid.



The proof and burst pressures of several HydraForce subassemblies are listed in the following chart.

Subassembly	Proof Pressure	Burst Pressure
SV08	3500 psi	7000 psi
SF08	7000 psi	14000 psi
SV10, 12, 16, 38	5000 psi	14000 psi
EHPR	4000 psi	12000 psi
PV70 & 72	4000 psi	12000 psi

The tube subassembly is made up of three main components, the plug, the guide tube, and the adaptor, as well as two smaller parts, the copper rings. The diagram to the right illustrates this.

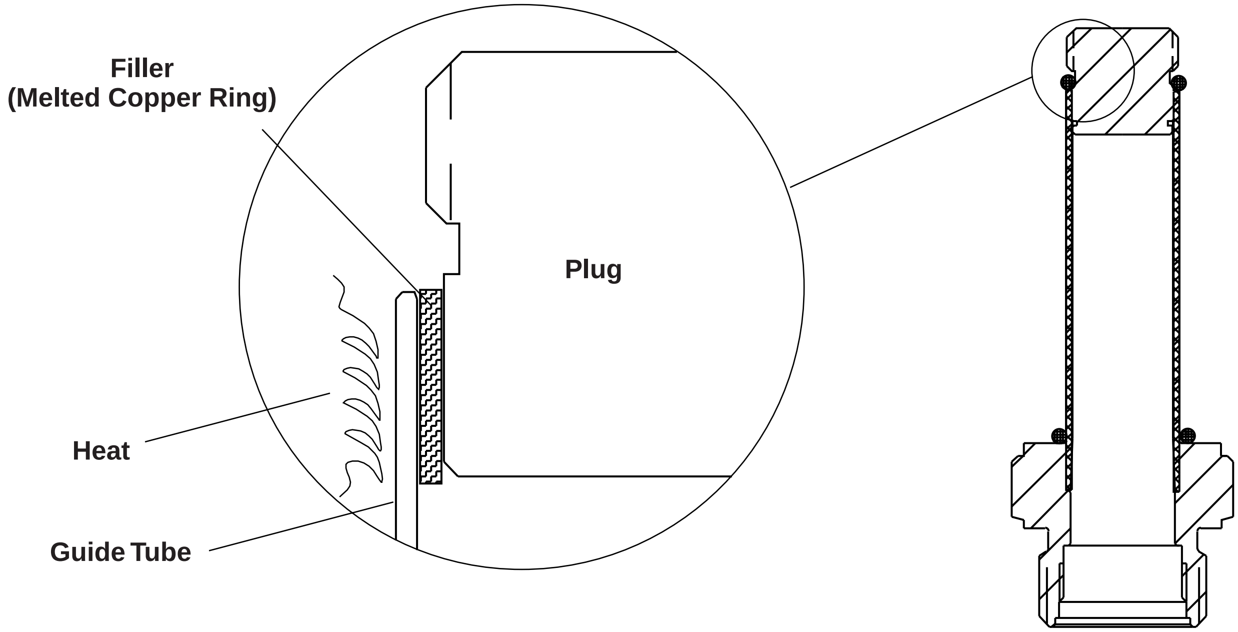


The guide tube is used to guide the plunger when it is attracted to the pole piece. As previously discussed, this tube is made of non-magnetic steel, to prevent the plunger from sticking to the guide tube.

The plug caps off, or plugs the end of the guide tube. In the push style tube subassembly, the plug is also made of a non-magnetic stainless steel. The reason for this is so the armature is attracted down towards the pole piece. Otherwise, the plunger would have a stronger attraction to the plug, since it is initially closer. The plug in the pull style tube subassembly also acts as the pole piece. It is therefore made of the same material as the shell and the flux washers. A low carbon steel such as SAE12L14 is typically used because it is easily magnetized as well as a low cost material.

The adaptor is the part of the tube subassembly which acts as the interface between the valve and the cavity. In addition, it attaches directly to the cage. It is made of the same high permeability steel as the shell and pole piece. This type of material is used to further concentrate the magnetic flux, therefore increasing the strength of the electro-magnet.

HydraForce uses a copper filler which is typically in the form of a ring. The tube, plug and adaptor are pressed together and the copper rings are placed near the seams they are intended to join. After assembly, the parts are placed in an oven or furnace at 1000° F. At this temperature the copper melts and fills between the plug and tube or between the tube and adaptor. The assembly is then cooled, allowing the copper to solidify and form a bond between the parts which is as strong or stronger than the parts themselves.



Plunger

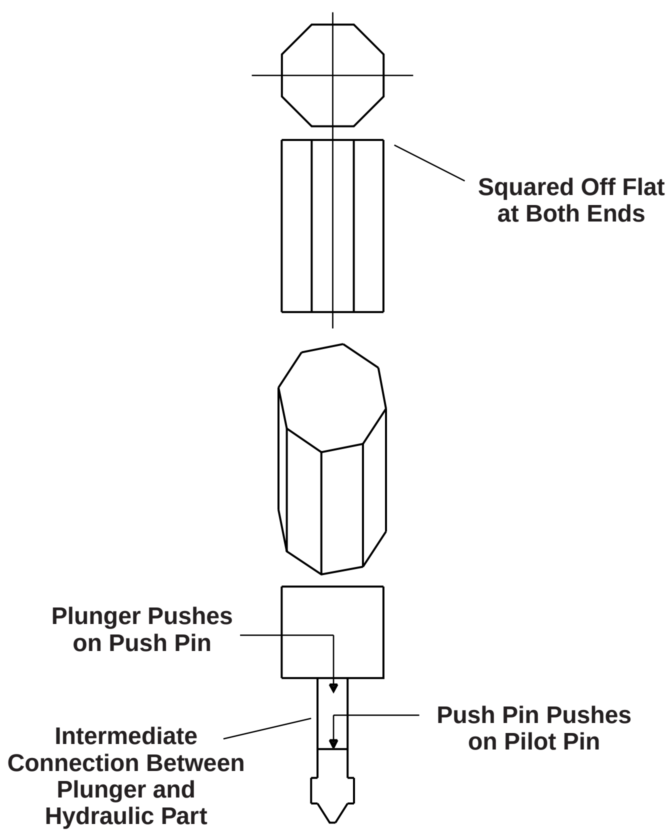
The plunger, much like the plug and the shell is made of a low carbon steel and is annealed. There are two basic styles of plungers, the push style and the pull style. They correspond with the push and pull style actuators.

The shape of the push style plunger is less complex than the pull style. Its armature face is typically flat, which requires less machining time to manufacture. In addition, the plunger is not directly connected to the hydraulic components. It simply pushes against the push pin which in turn acts on the hydraulic components.

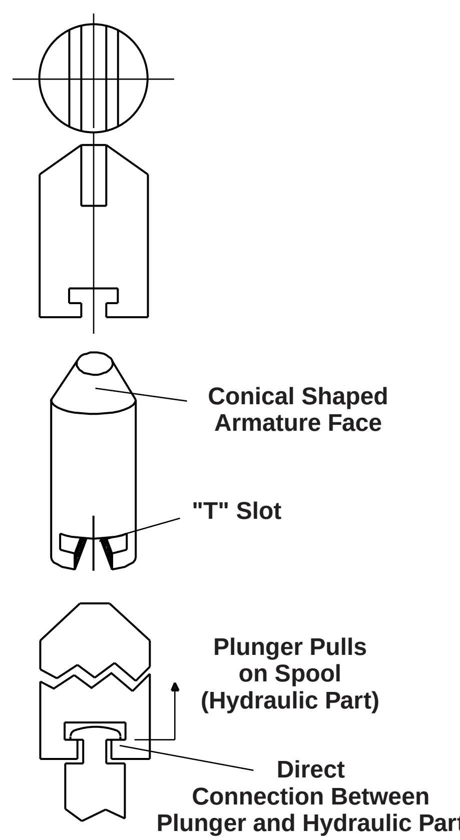
The pull style plunger is more complex than the push style. The shape of the armature is more detailed due to its conical shape and its coupling feature. The coupling feature is the “T” slot and connects the armature and the spool. This design allows for some misalignment of the parts (spool and armature).

The reasons for selecting a push style or pull style armature will be discussed in the following chapter.

Push Style Armature



Pull Style Armature

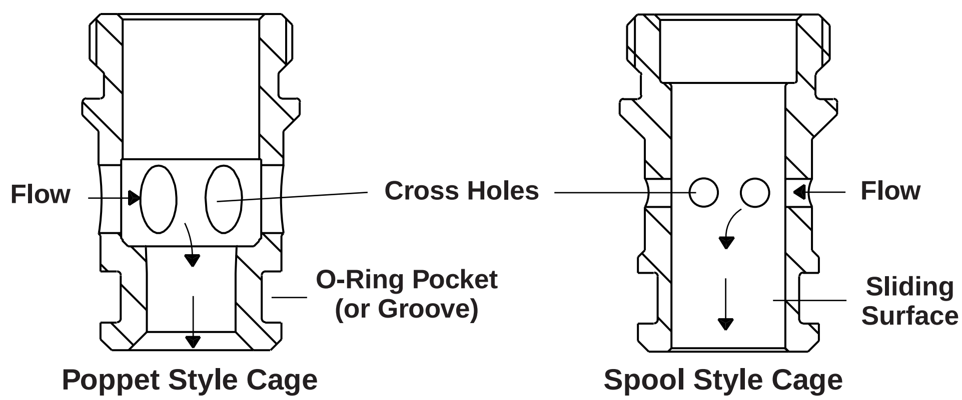


Cage

The cage serves the following functions.

- Acts as a guide for the spool or cage.
- Provides a pocket (or groove) for the o-rings.
- Provides a flow passage.
- In conjunction with the seat (in the poppet style), provides a positive seal against the flow of oil.

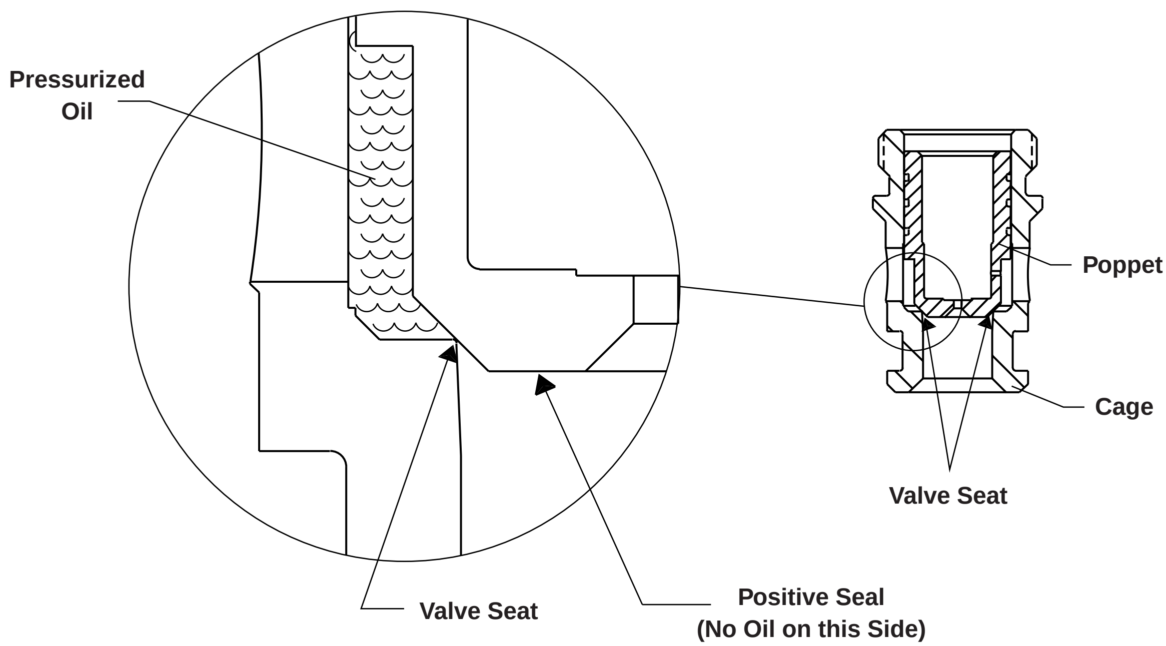
Both the spool style cage and the poppet style cage can be seen in the following diagram.



The spool style cage is made from SAE 12L14 steel because it is easy to machine, which keeps the cost low. The *L* in the number 12L14 designates lead. Lead is an additive which acts as a lubricant for machining. After the part is machined it is hardened in a heat treating process. This is done to provide a hard guiding surface for the spool as it slides during operation. If the cage was not hardened, the surface would wear due to the sliding action of the spool and contamination in the oil.

The poppet style cage is made from SAE 1215 steel. This steel (unlike the 12L14), does not have additives to make it easier to machine. The additives are not used because they melt or dissolve during heat treating. If this occurs, small voids are left on the seat which would compromise the quality of the positive seal of the seat. While these voids are acceptable on the spool style valve, they are not acceptable on the poppet. As noted, the poppet style cage is also heat treated. Again, the hardening process is done to protect the cage from the sliding action of the poppet. It is also done to protect the seat from becoming damaged when the poppet comes in contact with it. This helps to keep the positive seal, which the seat provides, intact.

In the poppet style valve, the poppet rests on a cage seat. The function of the cage seat is to work with the poppet to provide a positive seal against the flow of oil.
A positive seal can be defined as one which allows no fluid to pass.
A diagram of the valve seat can be seen below.



One machining process performed on the cage is known as *honing*. Honing is the finishing process done on the inside surface of the cage. This process removes material and polishes the surface. The smooth polished surface minimizes wear of the spool or poppet and allows them to move easily with little opposing friction.

Spring

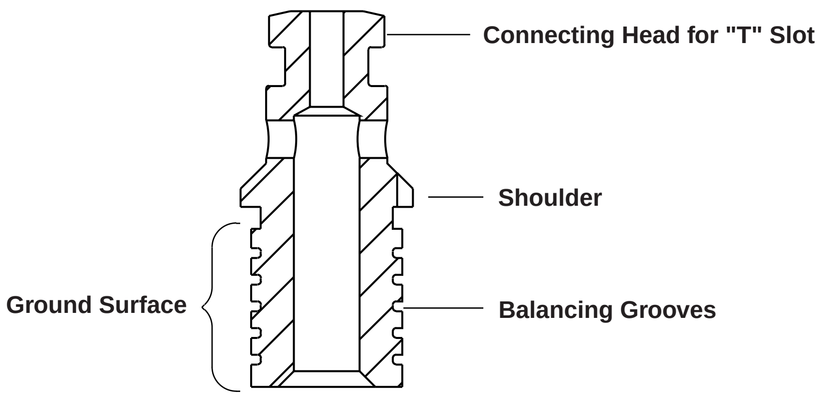
The spring is used in both types of valves and is used solely to return the valve to the neutral or de-energized position. The material typically used in HydraForce solenoid valves is known as *music wire.* Music wire has the highest strength for the least amount of money. It comes in various thicknesses, depending on the application and how strong the spring needs to be. This material is also suitable for the majority of applications.

Occasionally another type of wire, chrome silicon is used in place of music wire. Because it is more costly, it is only used in applications where the spring will be subjected to temperatures above 150^{o} F. If the spring is subjected to continuous high temperature for the majority of the application (70% of greater), it begins to relax over time. When it relaxes, the force decreases and the spring may not be stiff enough to operate the valve. The use of the chrome silicon wire prevents this from occurring.

In general, springs are designed to be compressed and relaxed at least a million times. This usually exceeds the life of most applications.

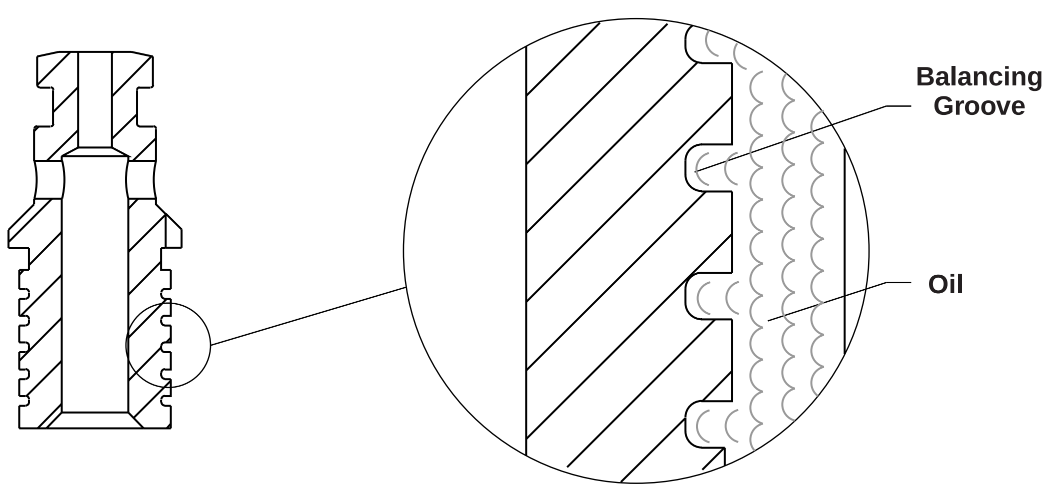
Spool

The spool is the sliding element inside the cage which blocks or allows fluid to pass. It is made from a low carbon steel and is hardened. In addition, the sliding surface is ground as the final machining process in order to minimize wear and reduce friction. A diagram of the spool can be seen below.



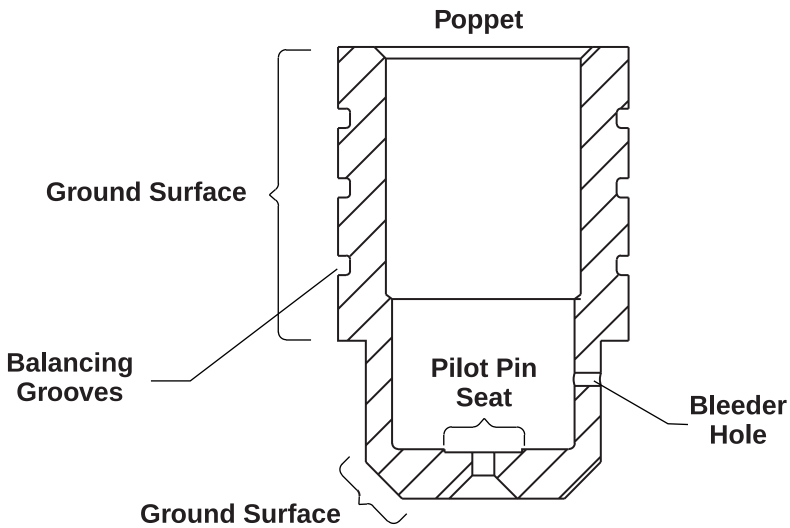
In the SV08-24, the spool blocks the cage cross holes when the coil is not energized (no power applied). When power is applied to the solenoid, the plunger pulls the spool, uncovering the cross holes, and allowing the flow to pass through.

The basic features of the spool are the balancing grooves, shoulder, and the connecting head for the plunger “T” slot. The connecting head provides a link between the spool and the plunger. The shoulder provides a stop to the movement of the plunger and the spool when the coil is de-energized and the spring returns them to the neutral position. The function of the balancing grooves is to help center the spool inside the cage. During use, oil gets between the cage and the spool. The balancing grooves provide a pocket for the oil, allowing the oil pressure to be equally distributed around the outside of the spool. When the spool is centered by the pockets of oil, it can slide easily, minimizing friction and wear.



Poppet

The poppet is located inside the cage, and slides up and down to block or allow fluid to pass through the valve. In the SV08-21, the poppet blocks the flow of oil across the seat when the coil is energized (power applied). When the power is turned off (coil is de-energized), the poppet lifts to allow the oil to flow.
A diagram of the poppet is shown below.



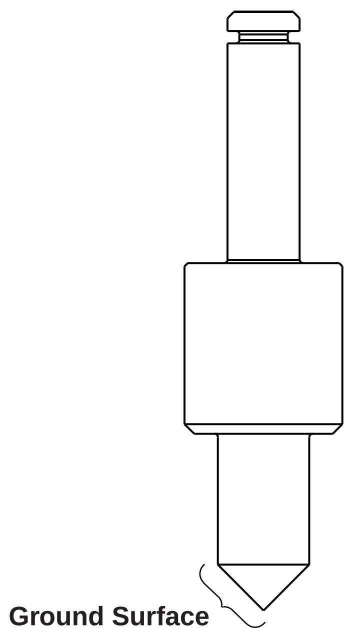
The poppet is made from the same steel as the poppet cage. As with the poppet cage, this is used because there are no additives present in this steel. A smooth surface, free of voids, is needed on the poppet. Additives have the potential of melting during the heat treating process, causing voids to form on the surface. The poppet is hardened to make it resistant to wear while sliding, and provides strength where it comes in contact with the seat.

The poppet is ground on two surfaces. To minimize wear, the outside diameter (the portion which slides against the cage), is ground to a very smooth, shiny finish. The other surface which is ground is the one which comes in contact with the seat. Grinding of this surface is done to ensure that it is perfectly round. This allows a tight fit between the poppet and the seat, to create the positive seal.

The pilot pin seat in the poppet acts the same way the seat in the cage does. A positive seal is formed between the poppet pilot seat and the pilot pin. The balancing grooves provide a pocket for the oil, which helps center the poppet in the same way the spool is centered. Finally, the bleeder hole provides a passage for the oil. This passage allows oil into the poppet and around the pole piece and plunger.

Pilot Pin

The pilot pin acts as a mini poppet without the balancing grooves, seat and bleeder hole. Its function, just as the poppet, is to block and allow fluid to pass. It is made of the same material as the poppet, is hardened, and is ground on the portion which comes in contact with the seat. These processes are done for the same reasons as the poppet.



Summary

In this chapter the following concepts were presented:

- The two basic types of valves and their components.
- What the tube subassembly consists of and how it is constructed.
- The difference between poppet and spool type cages.
- The differences between the push and pull style armatures.
- What a “T” slot is and what it is used for.
- The function of the spring in the solenoid valve.
- What balancing grooves are and what they are used for.
- Why parts are hardened and ground.
- What a poppet and a spool are.
- The reason poppets and spools are ground.
- What spring materials are used
- The number of times a spring can be compressed.

Review Questions

Use the following review questions as a measure of your understanding of the chapter material. Answers are provided in the appendix.

1. What is the proof pressure of an SF08 tube subassembly? ________________________

2. Why is there a spring in a solenoid valve? ________________________

3. What is the function of the poppet and cage seat? ________________________

4. Why is the cage heat treated? ________________________

5. Why is the spool ground? ________________________

6. What is brazing? What type of brazing compound (filler) does HydraForce use? ____________/___________

7. What is the proof pressure of an SV08 tube subassembly? ________________________

8. What do the balancing grooves do? ________________________

9. What material is the plug in the push style tube made from? Why? ____________/___________

10. What is the “T” slot? Why is it used? ________________________

11. Why are the poppet and the poppet cage made from steel with no lead? ________________________

12. What material are HydraForce springs typically made of? ________________________

Chapter 8: Valve Design

Objectives

The objectives for this chapter are as follows:

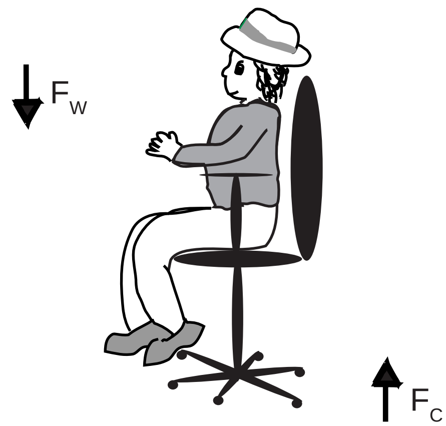
- Introduce the concept of summation of forces, needed in valve design
- Learn what the actuator force, the spring force, the Bernoulli (flow) force, and the two friction forces are.
- Discuss the two types of friction forces, mechanical and viscous.
- Determine how each of these forces affect the spool and poppet valves.
- Obtain an understanding of how the forces must be taken into account in valve design.
- Learn how the actuator force is measured and calculated using FEA.
- Discover the difference between the free length and the compressed length of the spring.
- Walk through the steps of the poppet and spool valve in operation.

Introduction

In this chapter, the concept of the summation of the forces which act on the valves, is presented. Each of the forces and how if affects both the poppet and spool valves are discussed. In addition, the reader is given an understanding of some of the factors which need to be considered in designing the valve.

Summation of Forces

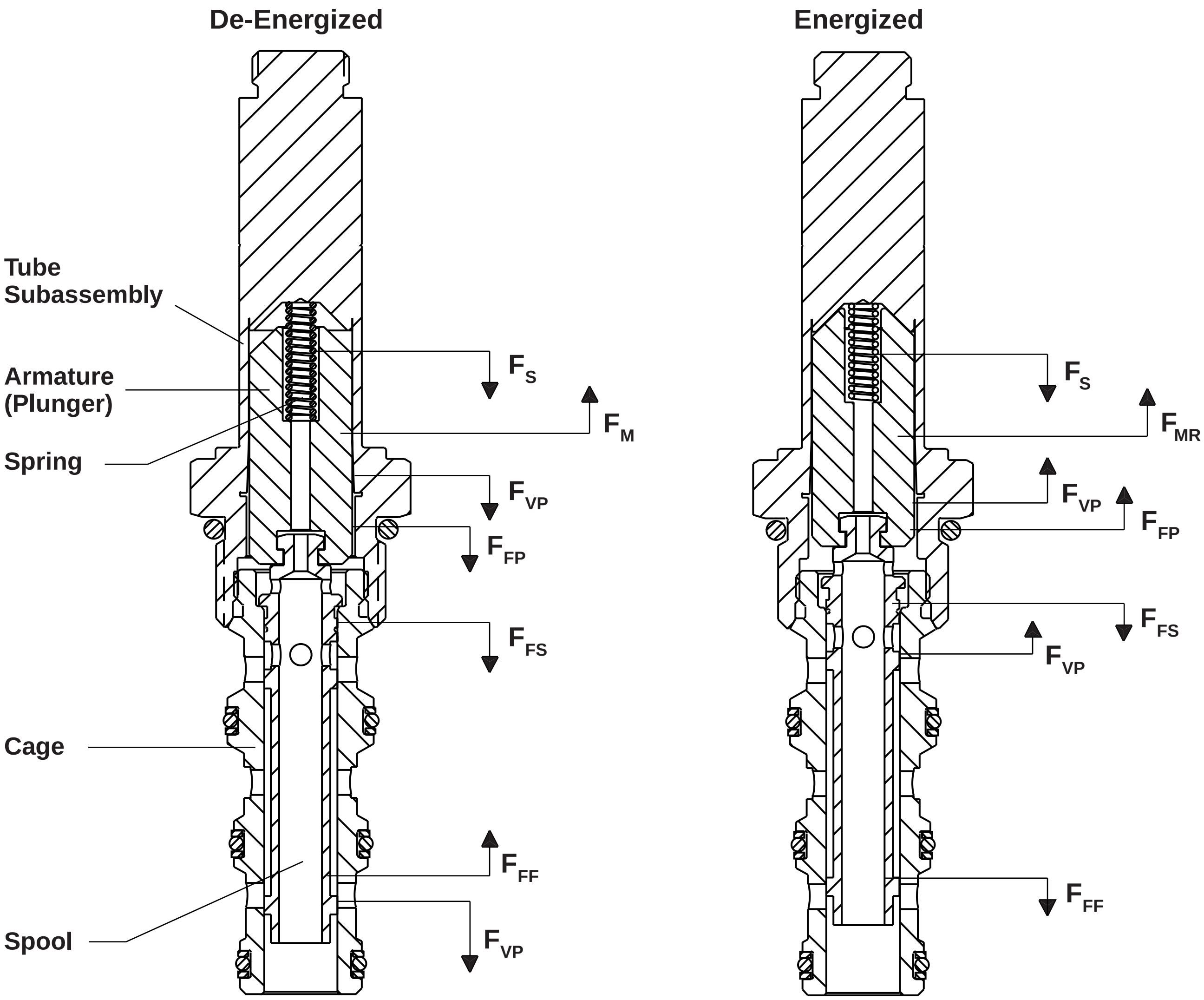
Valve design is based on the summation of forces acting on the valve. An example of the summation of forces, is the force you exert on the chair you are sitting on due to your weight. The chair exerts an equal and opposite force on you. If it didn't, you would fall through the chair.



The summation of forces shows that $F_w + F_C = 0$. Since F_w points down, it is considered negative. Therefore, the summation of forces for the man on the chair is $-F_w + F_C = 0$. To show that the system is balanced (the chair supports the man), the equation can be written $F_w = F_C$. (Note, the arrow represents the direction the force is acting).

Spool Valve Design

Unfortunately, in valve design, defining an exact quantity, (like your weight) for all the forces involved is nearly impossible, because many of the forces are immeasurable. Some of the forces that must be considered are, the actuator force, spring force, flow force and friction force. The location of the forces, in reference to the parts of a valve are shown in the following diagram. The symbol representing each force as well as a brief definition is given. These forces are discussed in detail in the sections which follow.

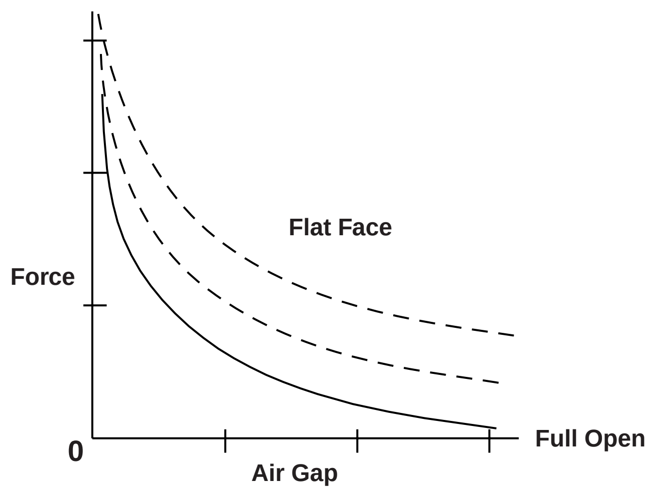


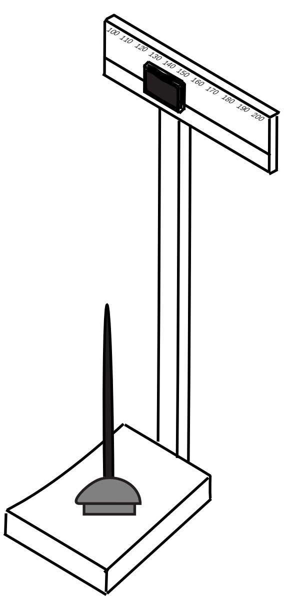
F_S = spring force
F_M = magnetic actuator force
F_{MR} = residual magnetic force
F_{FP} = friction force acting on the surface between the tube subassembly and the plunger
F_{VP} = friction (or viscous) force due to the oil between the plunger and guide tube
F_{FF} = flow force or Bernoulli force
F_{FS} = friction force related to the spool
F_{VS} = friction (or viscous) force due to the oil between the spool and the cage

Actuator Force

The actuator force is the first of the forces to consider. Either the flat face or the conical face actuator is selected over the linear proportional actuator, for two reasons. The cost for the flat face and the conical is lower than the proportional. In addition, the magnetic force versus the stroke characteristic for these two armatures is desirable for solenoid valves. This point will become more apparent as we discuss the interaction of all the forces later in this chapter.

In previous chapters, we learned that the magnetic force for the flat face and conical face actuator changes as the air gap changes. We also learned that the magnetic force was dependant on the current flowing through the coil. Recall the typical graph of the flat face armature shown below.





The force versus the air gap can be measured by connecting a force measuring device known as a load cell (similar devices are used in bathroom scales) to the plunger. The plunger is moved from zero air gap to a distance or air gap which exceeds the required stroke. The stroke, or air gap of the 08 size valve is typically 0.065 in. and 0.095 in for the 10 size. As the plunger is moved, the force is graphed against the distance traveled.

HydraForce uses another method of determining the magnetic force of an actuator. A computer program named MAXWELL uses Finite Element Analysis (FEA). It can solve complex mathematical equations to find the force by breaking the components (coil, frame, plunger etc.) into tiny pieces. The program calculates the magnetic force through the tiny pieces of each part, as well as the air surrounding it. It then reassembles the pieces to determine the force of the entire actuator.

Spring Force

Another factor to consider is the spring force. The spring force, like the magnetic force, is not fixed. It varies due to the amount it is compressed and is defined by the following relation:

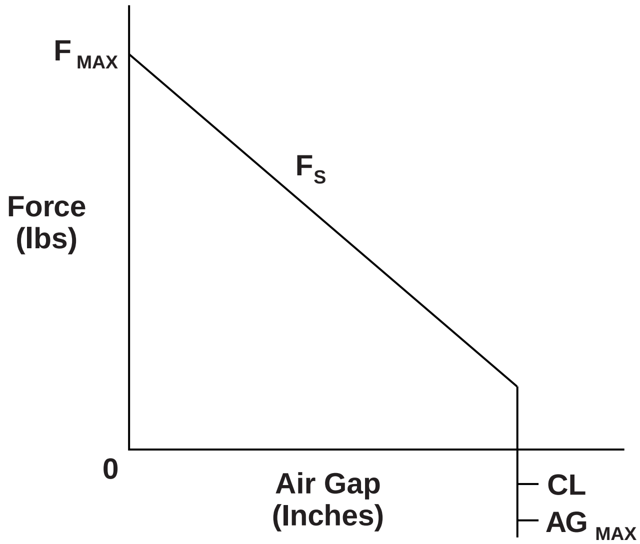
$$F = K\ (FL - X)$$

where: F = force measured in lbs
K = spring rate measured in lbs/inch
FL = free length of spring measured in inches
X = compressed length of spring measured in inches

Note that the spring rate is a physical constant of the spring. It describes the amount the force can change with a change in compression (distance). The free length of the spring is the length of the spring when uncompressed.

This equation can be extended to valve design in the following manner. The spring is installed in the valve with some initial compression at the maximum air gap. This is done to balance the flow force and because it is impractical to have a spring which begins at zero compression. Since the plunger cannot be made perfectly every time (exactly the same length), it is better to initially compress the spring slightly so the force is more predictable. In addition, in order for the spring to return the valve back from the energized position, it needs a “high” force when the valve is energized. To accomplish this, the spring must be installed with some force, or it has to have a high rate (large change in force for a small deflection). Springs with high rates tend to take up more space because the wire has to be stiffer (therefore thicker) to make the spring stiffer. If the wire is too thin, the spring might break.

When the coil is energized (power applied), the plunger begins to move, compressing the spring and therefore increasing the spring force. The following graph represents this relationship.



The graph above describes the spring force in a valve.
The variables are defined as:

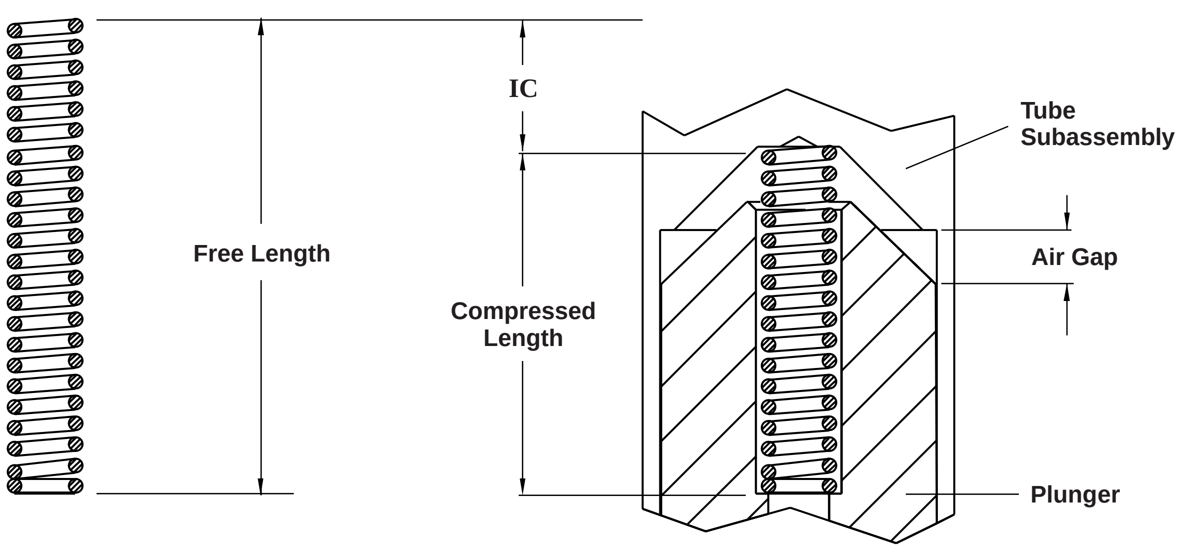
$F_S = K\,(IC + (AG_{MAX} - AG_{CUR}))$

IC = This is equal to the free length minus the initial compressed length (see diagram below)

AG_{MAX} = Maximum air gap or the maximum distance between the armature and the pole piece.

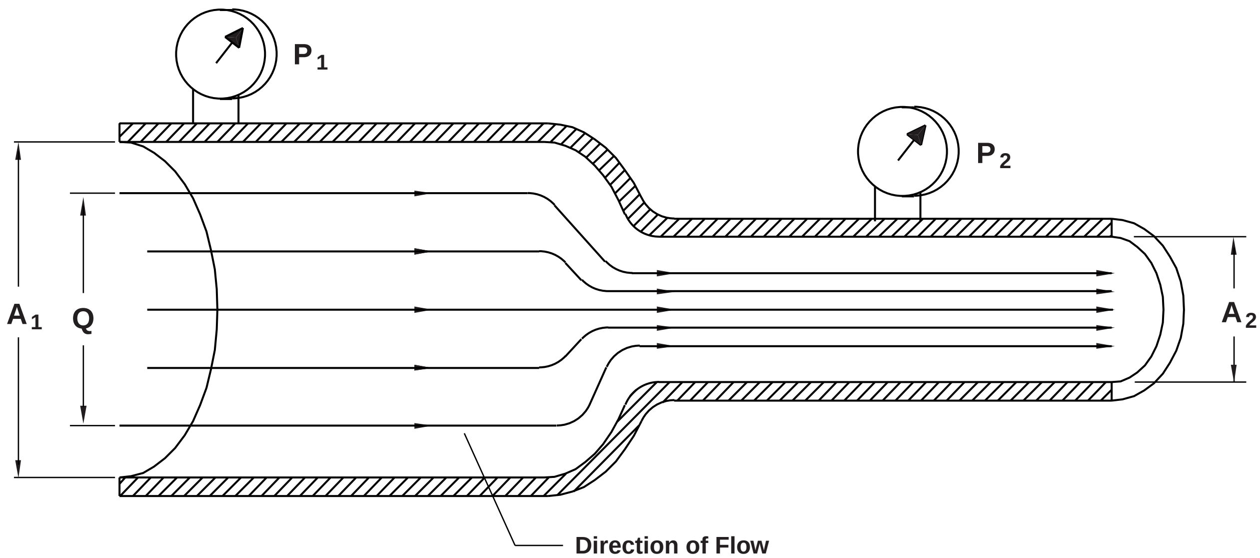
AG_{CUR} = Air gap or distance that the plunger is currently at, relative to the pole piece.

The following diagram shows a spring at free length and one installed in a valve.



Bernoulli (flow) Force

The Bernoulli Force is a force which acts on the spool. It is caused by the acceleration of the oil as it flows from a larger passage through a smaller one.
To clarify this concept, let's first take a look at fluid flowing through a pipe in the diagram below. The diagram shows the inside diameter of the pipe is reduced along the length of it. Assume that the flow or quantity of oil moving through the pipe is fixed.

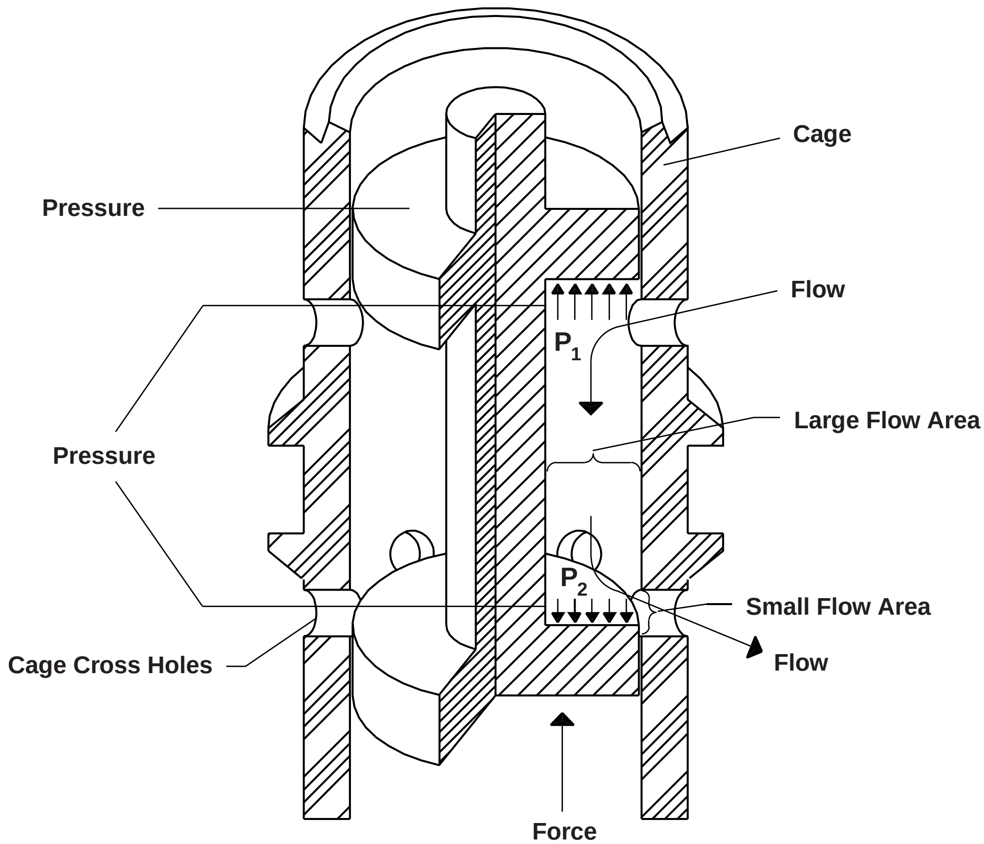


A_1 = initial tube diameter
A_2 = reduced tube diameter
Q = amount of flow
P_1 = pressure measured in the A_1 portion of the tube
P_2 = pressure measured in the A_2 portion of the tube

As stated, the flow rate for the oil running through the pipe is fixed. The same amount of fluid passes through A_1 as it does through A_2. Therefore, in order to fit through the smaller area, it must speed up (accelerate). To do this, energy must be expended. The loss of energy can be measured by the decrease in pressure between P_1 and P_2. In this example, P_1 is greater than P_2. The difference between the two pressures measured in the tube is known as the *pressure drop*.

Similar to the flow through a tube, acceleration of fluid and decreased pressure occurs as the fluid passes through the valve. The following diagram shows a typical cross section of a spool valve. We are specifically looking at the flow of oil as it goes into the cage, past the spool and back out.

In this example, as with the pipe, when the fluid goes from a larger area through a



smaller one, there is a drop in pressure. The difference in pressure is shown by the small arrows (P_2) acting on the spool. The larger arrows (P_1) indicate a higher pressure. Since pressure is force divided by area (measured in lbs / in^2 or psi), or force is equal to pressure multiplied by area, it can be shown that the flow force is pushing up on the valve.

As noted in the diagram, $P_1 > P_2$ and in general pressure = force / area, orforce = pressure x area.

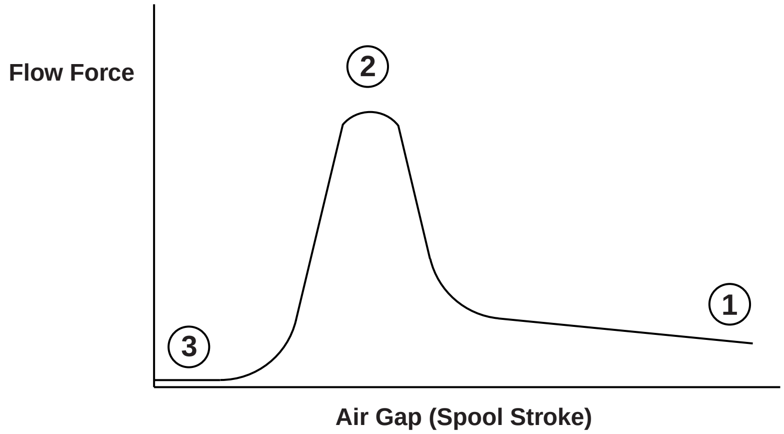
Since the area of the spool exposed to the pressure is equal on both sides of the spool, then the force due to the pressure P_1 is greater than the force due to P_2. This concept can be further shown below.

$P_1 > P_2$ then:

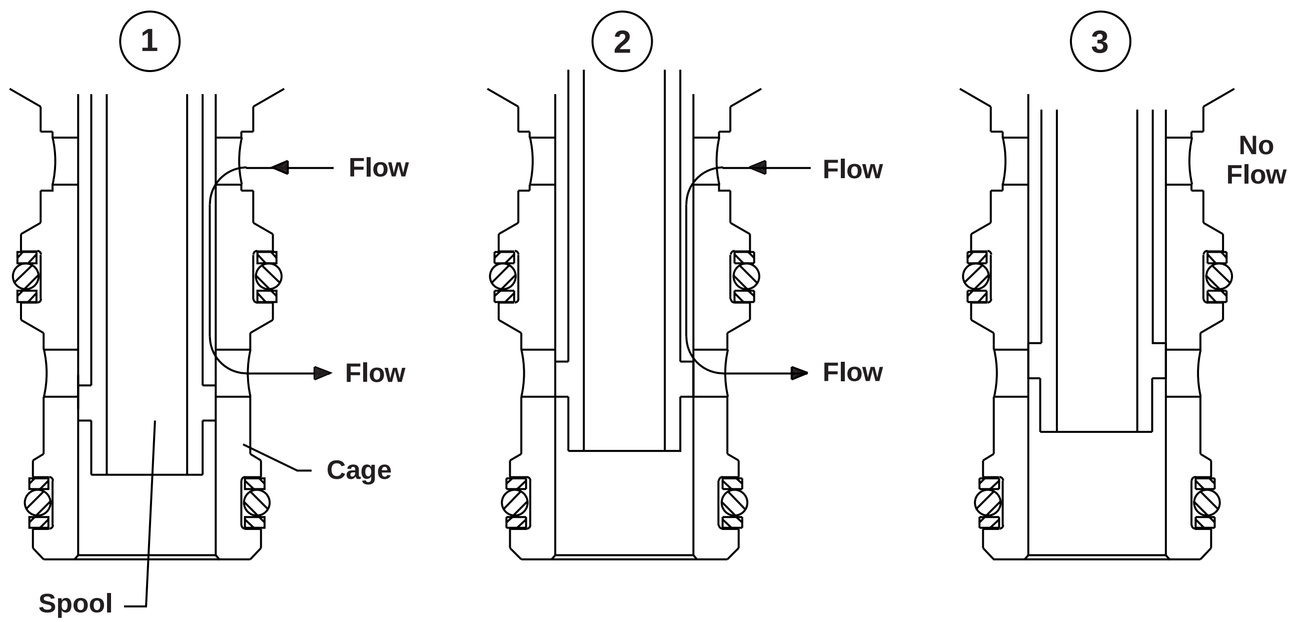
$F_1 = P_1 \times A > F_2 = P_2 \times A$

Therefore, there is a force acting to close off the flow through the cross holes. As these holes close and the force pushes on the spool, the force increases because the difference in pressure increases. This increase in force continues until the limit of the system delivering the oil (the pump) reaches its pressure relief setting. When the force begins to decrease, it continues to push on the spool until it is closed. The following graph represents the typical trend of the flow force vs. the stroke of the spool (the stroke is the same as the plunger air gap).

The following diagram shows the flow through the spool in various stages.



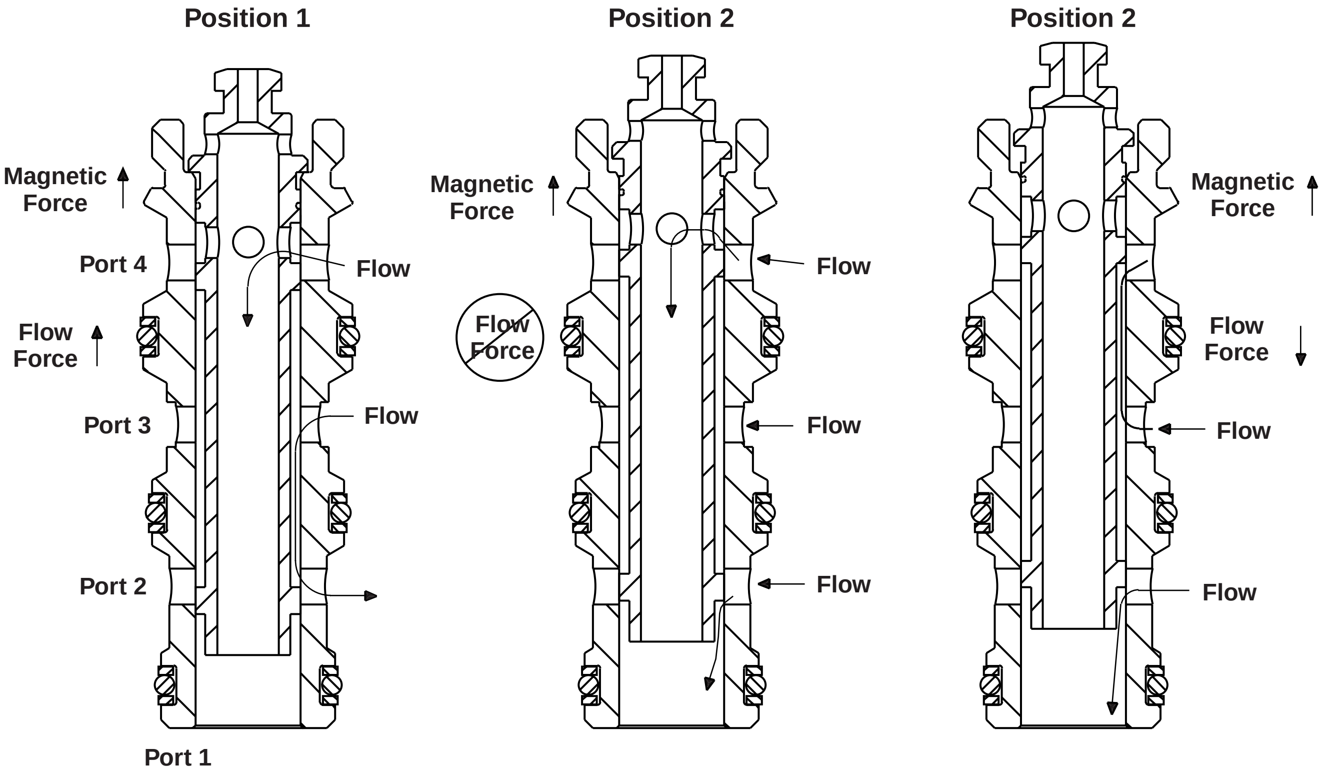
When the spool is in position 1, the plunger is at the full open air gap position. At



position 2, the coil has been energized and the spool begins to move. As previously stated, when the spool begins to close off the holes, the force builds. The force continues to increase until the system pressure is reached. Point 3 represents the flow force when the plunger and spool are fully shifted. In this case, there is no flow and therefore no flow force.

Flow Forces acting on SV10-40

As shown in the force diagram of the SV10-40 at the beginning of the chapter, the flow force can act in either direction. This is due to the fact that the oil switches flow paths when the coil is energized or de-energized. The diagrams shown below indicate how the flow goes through the valve during different positions of the stroke.



Position 1 (the de-energized position) shows flow going from port 3 to port 2 and from port 4 to port 1. (The port and its number are simply a designation for the passage.) When flow is going in these directions, the flow force tends to act in the same direction as the magnetic force. In position 3 (the energized position), flow goes from port 3 to port 4 and from port 2 to port 1. When the flow travels through the valve in this direction, the flow force is acting in the same direction as the spring force. Position 2 shows the spool in the transition position. This stage is neither fully de-energized nor energized. In this stage, the flow is traveling in all directions and therefore no flow force is acting on the valve. Note that when the spool allows fluid to pass through other ports in the transition position, it is referred to as an *open* in transition spool or a *negative lap spool*. When the spool does not allow fluid to pass in the transition state it is referred to as a *closed* in transition spool, or *positive lap*.

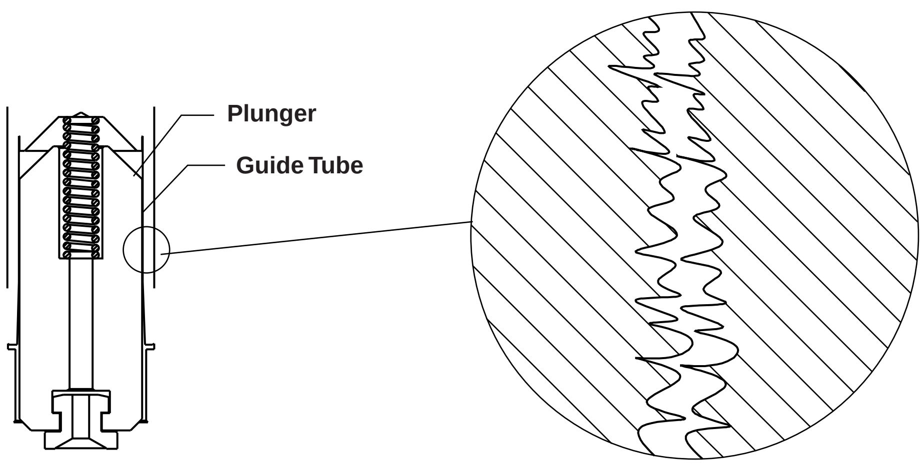
Friction Forces

Two types of friction force exists, as shown in the diagram. The mechanical friction force is due to the surface of the parts rubbing against one another. The viscous force is due to the parts moving through the oil. The following section describes each force in more detail.

Mechanical Friction

Most people have experienced friction by rubbing two objects together, such as a brick across sandpaper. Friction force, or resistance to movement is created by this rough surface and is opposite to the movement of the plunger. This force is small compared to the spring force, armature force or flow force, and is difficult to measure.

The following diagram is an enlarged view of the plunger in contact with the guide tube. The magnified view shows extreme jagged peaks and valleys on the surface. This surface roughness (peaks and valleys) is measured in micro inches (μ in.) which is equivalent to 0.000001 inches or 1 in. / 1000000. The surface finish of the plunger is typically 125 μ in. (0.000125 in.) or less. The surface finish of the guide tube is less than 46 μ in. The cage and spool have polished surfaces with a surface finish of less than 10 μ in.

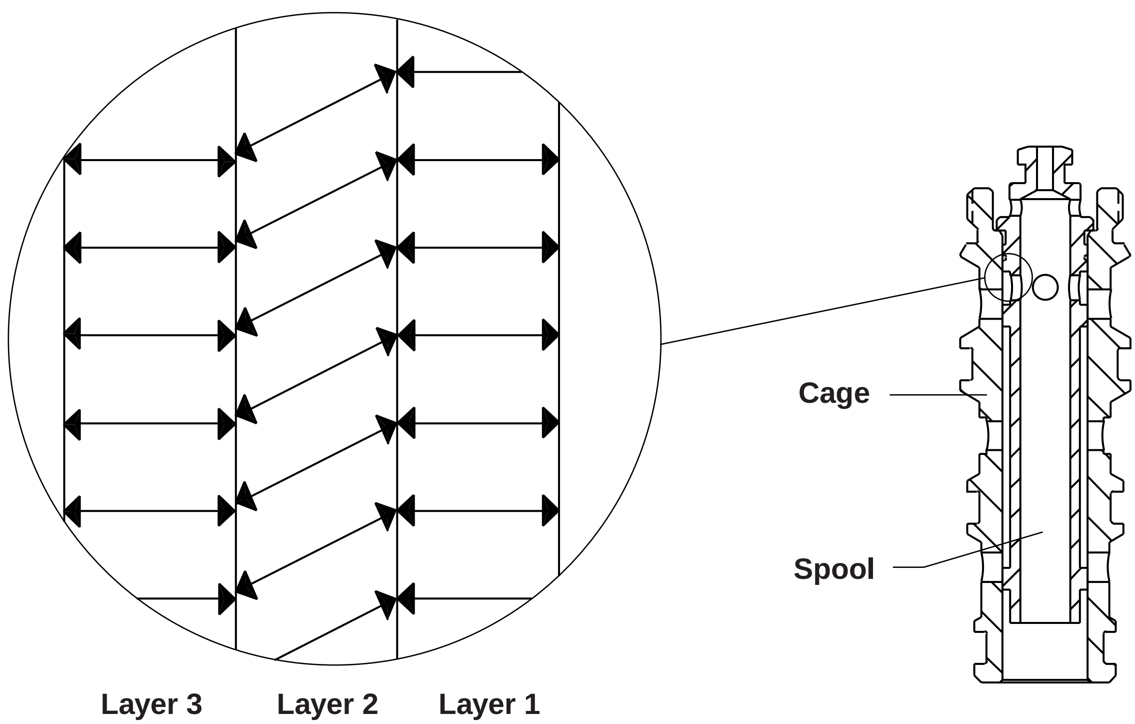


As a practical example, the size of these peaks and valleys can be compared to a sheet of paper. One sheet of paper is typically 0.005 inches thick. This measures fifty times greater than the highest peak on the plunger surface. It would seem that since the peaks and valleys are so small that they are not significant. However, all forces must be taken into account. The magnetic force developed by some of the solenoid valves is only a few pounds. Therefore, the combination of the spring force, flow force and the friction force may be too great to be overcome by the magnetic force.

Viscous Force

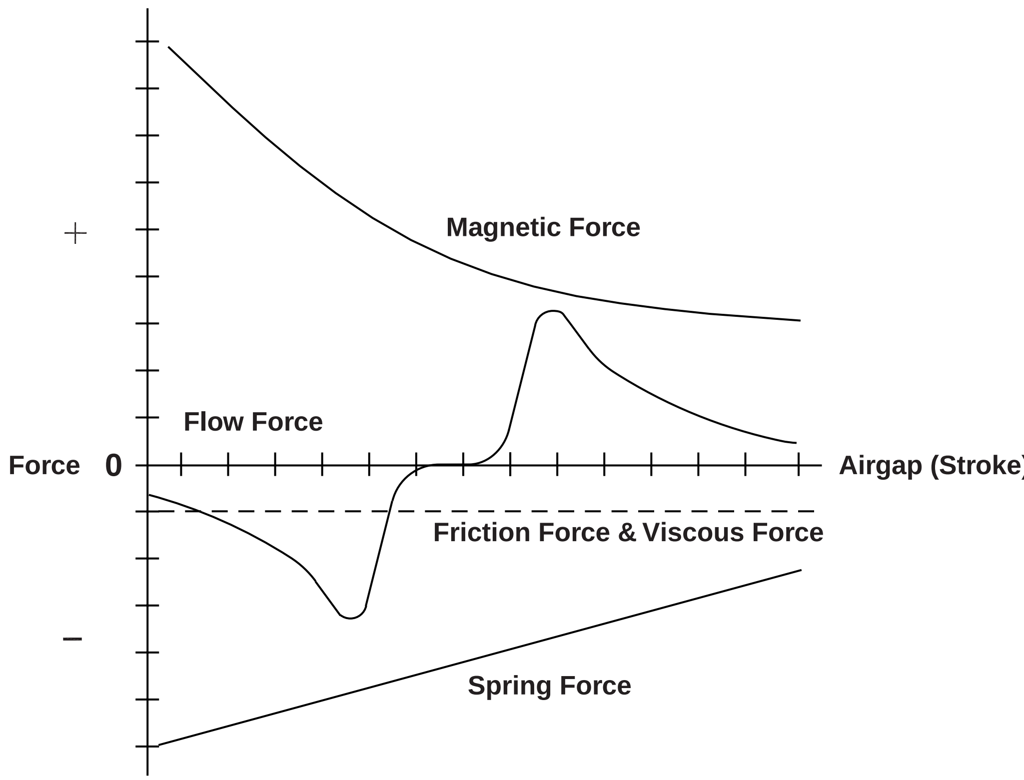
The second type of friction force, the viscous force, can be described by use of an example. When drying dishes, have you ever noticed that when pulling two very smooth plates apart they stick together slightly? This sticking together is a viscous force. The force specifically at work between the two plates and the water is an adhesive force. Adhesive forces exist between two unlike substances such as a plate and water or a spool and oil. Another type of viscous force is the cohesive force. This is the force which pulls water together to form a drop. These two forces work together opposing the movement of the spool and plunger.

The following diagram represents the spool moving through oil. The enlarged view shows three layers of oil and the surfaces of the spool and cage. The first and third layers represent the oil which adheres to the surface of the valve. The second layer represents the oil which coheres or joins the other two layers together. This layer will be stretched as the parts begin to move. Eventually, the magnetic force overcomes the strength of the cohesive force, and the bonds between the molecules in layer two break. The bonds immediately reattach to the next adjacent molecule and are again broken by the magnetic force. This continues throughout the movement of the parts.



Summary of Forces

The following graph summarizes the forces and shows how they interact. Notice that the spring is drawn on the negative side of the axis. This shows that the force acts opposite the magnetic force as shown in the flow force diagram at the beginning of the chapter.



The graph shows that the magnetic force is greater than the spring force and friction force. It also shows that the spring force is greater than the flow force and the friction force.

$$F_M > F_S + F_{VP} + F_{FP} + F_{VS} + F_{FS}$$

and

$$F_S > F_{FF} + F_{VS} + F_{FS} + F_{VP} + F_{FP}$$

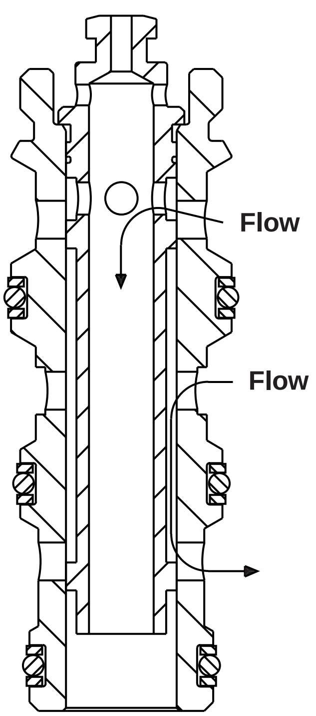
These factors indicate which parameters affect the performance of the valve. The factors can be adjusted to vary the performance for certain applications. For example, let's take a look at the performance specifications for an SV10-31 valve.

Maximum operating flow: 6 gpm
Maximum operating pressure: 3000 psi
Maximum leakage: 10 in^3 / min
Allowable voltage range: $\pm$ 15% nominal (nominal voltage is the ideal voltage which a system is designed to)

To extend the performance of this valve for a particular application the forces need to be adjusted. For example, assume a higher operating flow is required.
If the flow is increased, the pressure drop increases and the flow force increases. When this occurs, the spring force must increase so that it is still greater than the flow and friction force combined. If the spring force is increased, the magnetic force also must be increased. As we learned in previous chapters, if more magnetic force is required, more current is needed. When more current is needed, the voltage range must be limited to ensure that the coil can still draw sufficient current at the lower operating voltage. It can be clearly seen that there are many factors affecting performance. Trade-offs exist when choosing which performance factors to increase.

Spool Valve Operation

Now that we've described how the forces exerted on the valve affect it, let's discuss how the valve actually operates. Assume that the fluid is passing through the valve as shown in the following diagram.



When the coil is energized, the plunger is attracted to the pole piece (or plug in, the pull style armature). The armature pulls on the spool. As the two parts move, the magnetic force has to overcome the friction forces and the spring force. Initially, the flow force assists the magnetic force because it is acting in the same direction. As shown in the flow force section, this force switches directions as the spool passes through transition. When the flow is rerouted, the flow force acts against the magnetic force. During the final third of travel, the plunger must overcome the spring force, friction forces and flow forces combined. When the armature hits the plug, the valve is in the energized position, or *pull in* has occurred. The term pull in is from the action of the armature pulling the spool into position.

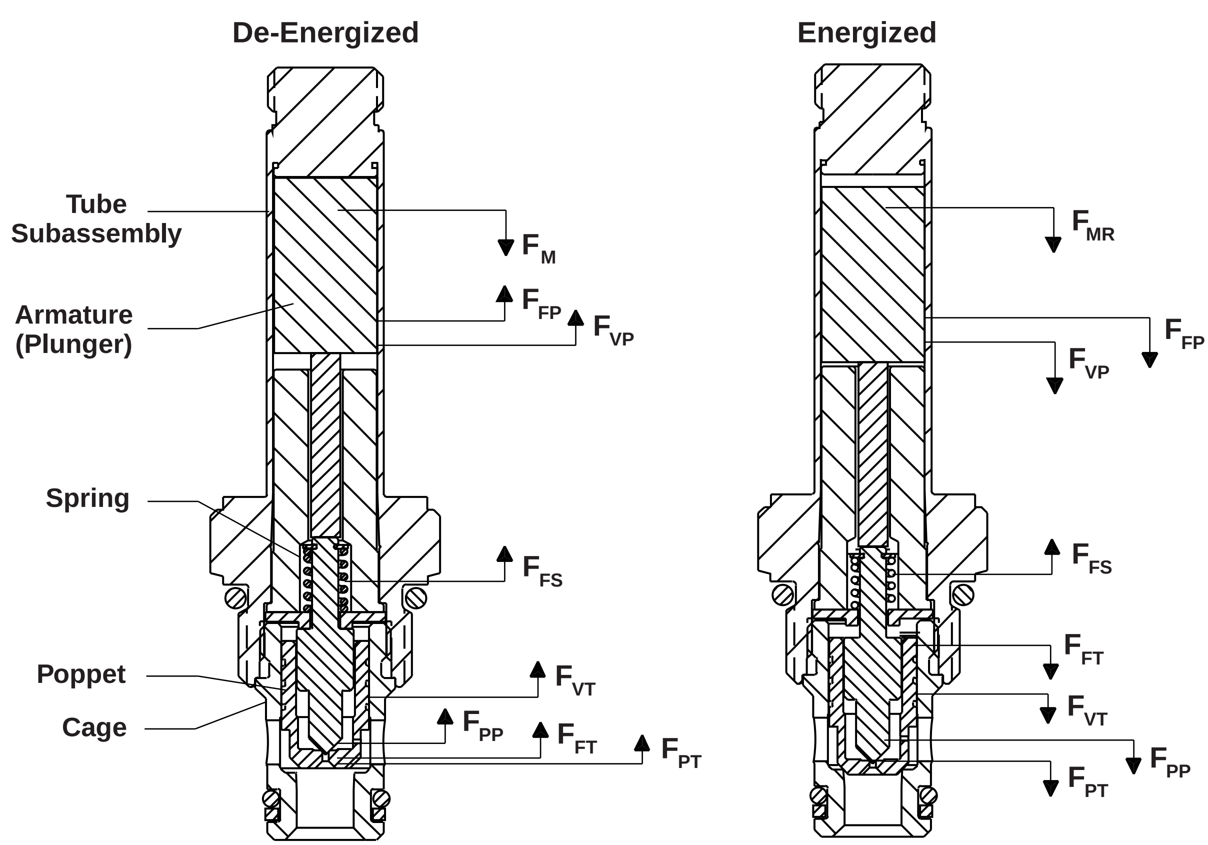
When the power to the coil is turned off, the spring pushes against the armature. The spring force must overcome the residual magnetic force. It must also overcome both mechanical and viscous friction forces. Recall that these forces oppose the movement of the parts regardless of the direction of travel. During the first one third of the spool travel, the flow assists the spring. When the flow switches directions, the spring must overcome flow force as well as the others. Once the spool shoulder hits against the cage, the spool and armature are considered to be in the de-energized position. The action of these parts returning to this position is known as *drop out*.

Poppet Valve

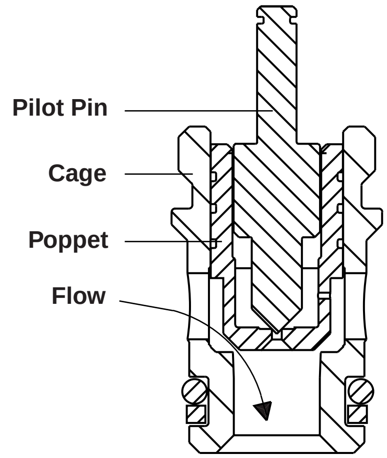
The following diagram shows an SV08-21 normally open, pilot operated, poppet valve. As in the spool valve shown at the beginning of the chapter, there are various forces acting on the parts.

F_S = spring force
F_M = magnetic actuator force
F_{MR} = residual magnetic force
F_{FP} = friction force acting on the surface between the tube subassembly and the plunger
F_{VP} = friction (or viscous) force due to the oil between the plunger and guide tube
F_{VT} = viscous force acting on the poppet
F_{FT} = mechanical friction force acting on the poppet
F_{PP} = pressure force acting on the pilot pin
F_{PT} = pressure force acting on the poppet

The friction force, spring force and magnetic force are basically the same as those discussed with the spool valve, with the exception of the pressure force acting on the pilot pin.

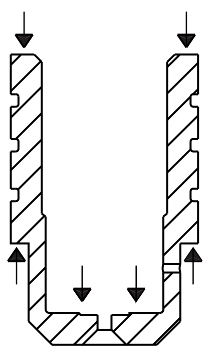


Pressure Force Acting on a Poppet



In the diagram of the SV08-21 shown to the right, the valve is shown in the de-energized state. The poppet is opened, which allows flow to pass from one port to another. Assume that the oil is flowing through the valve, as shown in the diagram.

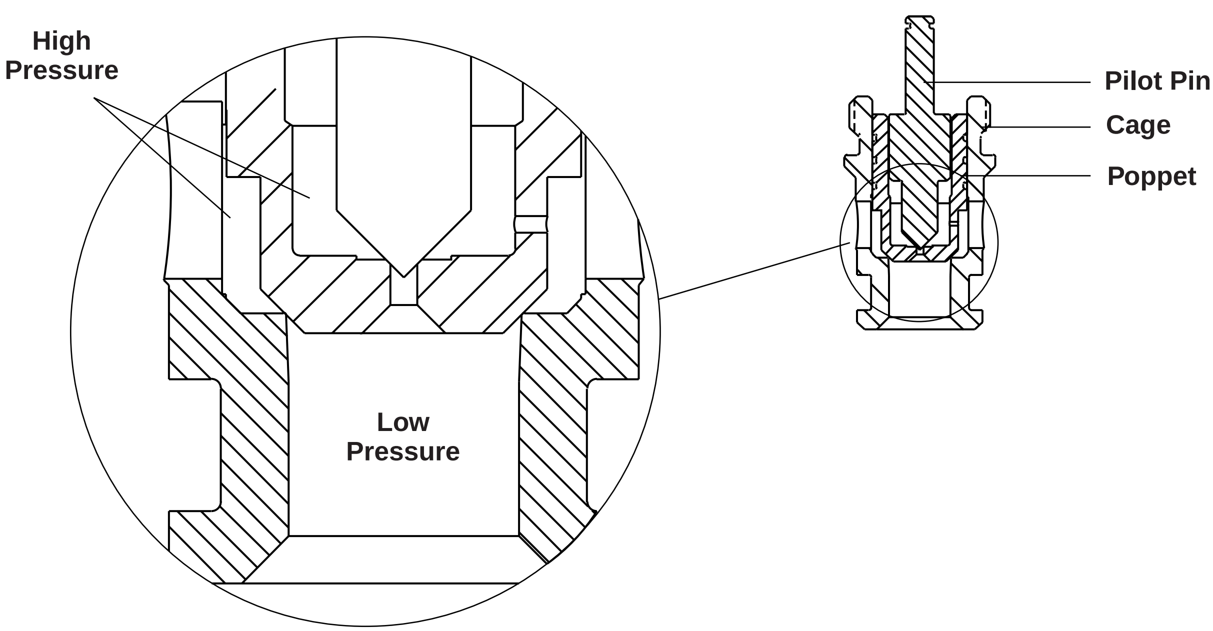
Similar to the flow through tubing, there is a pressure drop as oil flows past the poppet and cage seat. This pressure pushes up on the poppet, holding it in place.



When the valve is energized, the oil flows through the bleeder hole and pressurizes all the surfaces of the poppet. This is shown in the diagram to the left.

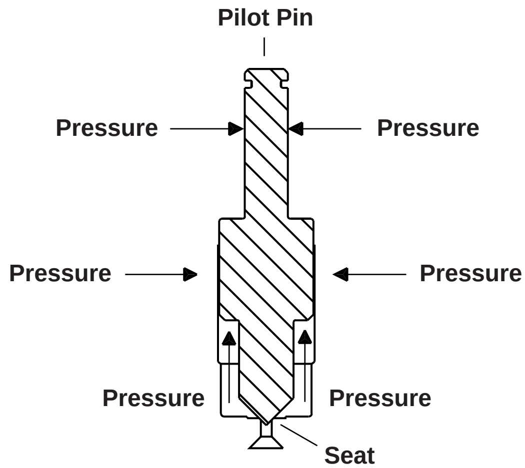
This pressure force acting on the poppet assists the valve when the coil is energized.

Although there is pressure acting on all parts of the valve, the pressure which acts on the pilot pin directly affects the ability of the valve to open. The following diagram shows the areas of pressure while the pin is sitting on the seat and the coil is energized.



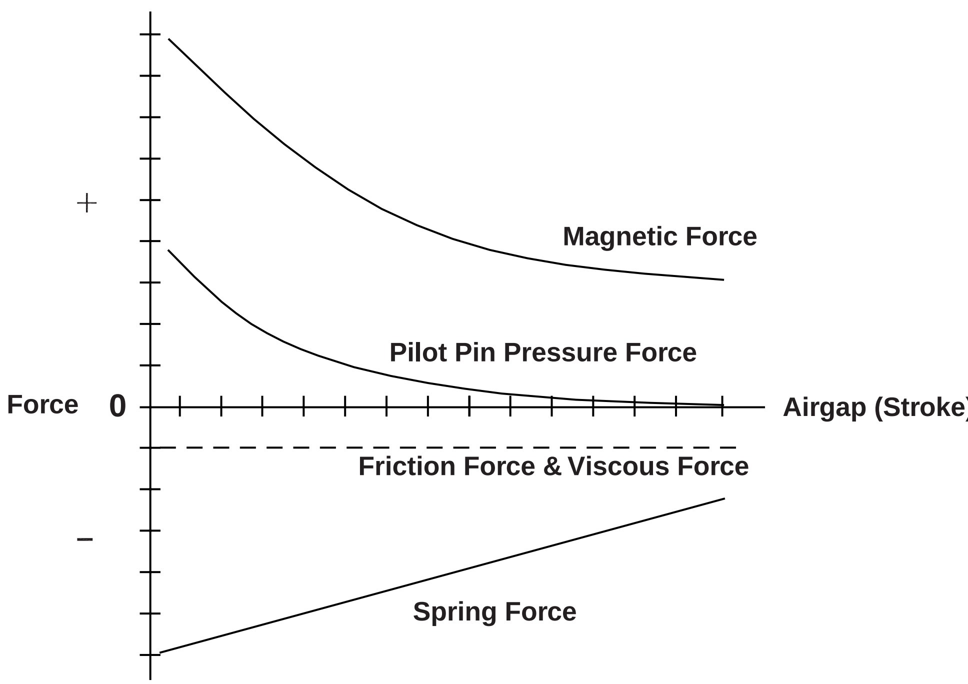
As the diagram below illustrates, there is high pressure around the pilot pin, except for the small area which sits on the seat and is exposed to low pressure. This small area exposed to low pressure creates a force imbalance which is equal to:

$$F_{PP} = \text{high pressure x seat area}$$



The following graph shows the forces acting on the poppet valve when it moves from the de-energized to the energized position. The equations show the balance of forces:

$$F_M > F_{FS} + F_{FP} + F_{VP} + F_{VT} + F_{FT} + F_{PP}$$



$$F_S > F_{FMR} + F_{FP} + F_{VP} + F_{VT} + F_{FT} + F_{PP}$$

As in the spool valve, the forces shown on the previous graph are balanced, to obtain the best performance of the valve. Again, trade-offs exist between the available magnetic force due to the temperature and voltage range, and the other forces acting on the valve. The factor which most often influences the poppet valve performance is the pressure force acting on the pilot pin. The friction forces remain basically unchanged, even when flow or pressure changes.
However, if pressure increases the force (F_{pp}), the spring must compensate. When the spring force is increased, the magnetic force must also increase.

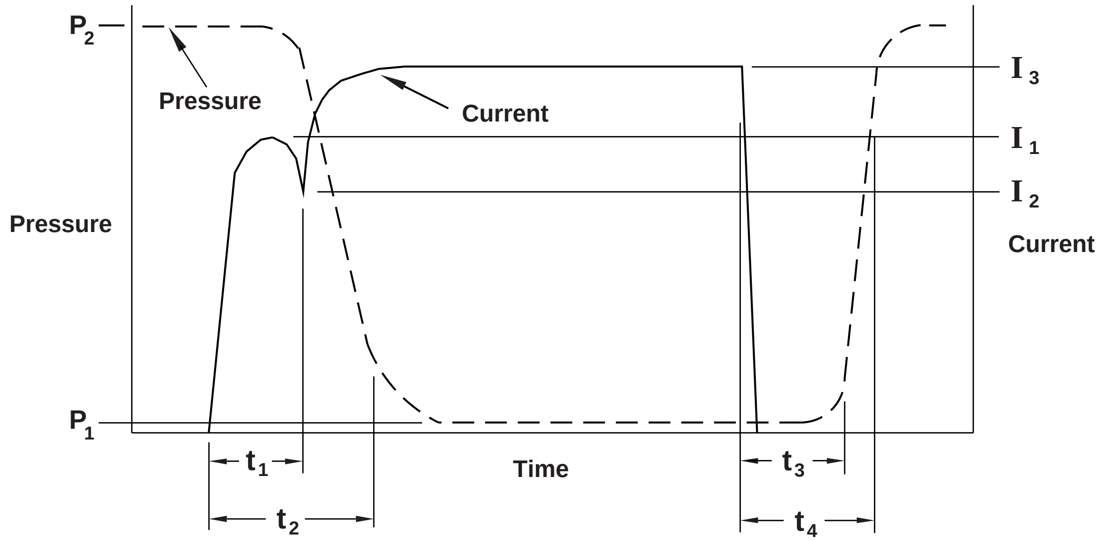
Pilot Operated Poppet Valve Operation

We have discussed the features of the poppet valve as well as the forces exerted on it. We will now take a look at how this valve works. As described in previous chapters, the coil is energized, which causes the plunger to be attracted to the pole piece. The plunger pushes on the push pin, which in turn pushes on the pilot pin. The parts begin to move, compressing the spring and pushing down on the poppet. When the poppet finally reaches the seat, the parts stop moving. At this point the valve is considered to be in its energized state.
Another way of stating this is that *pull-in* has occurred. The forces which the armature force must overcome during pull-in are, the spring force, mechanical and viscous friction forces and the pressure force acting on the poppet. When the valve is in the energized position, fluid gets behind the poppet and around the pilot pin creating the pressure force on the pilot pin.

When the coil is de-energized (power turned off), the term *drop-out* is used to describe it. In order for the valve to drop out or return to its initial state, the spring must overcome the residual magnetism between the plunger and the pole piece. The spring force must also be larger than the pressure force acting on the pilot pin, as well as the friction forces. Once the spring overcomes these forces, the oil behind the poppet and in the tube drains through the seat, relieving the pressure force acting on the poppet. Fluid drains faster than it fills because the bleeder hole is smaller than the seat. The spring continues to push on the push pin until it is back in its original de-energized position.

Valve Response Time

Response time is a measurement of how quickly a valve shifts fully from the de-energized state to the energized state or from the energized state back to the de-energized state. Simply put, it is the time it takes the valve to turn on or off. Response time is typically measured in units of milliseconds. A millisecond, ms for short, is 0.001 second or 1 second / 1000. The device typically used to measure response time is an oscilloscope. This device is able to measure fast changes in voltage from sources such as electronic pressure sensors or the current applied to a solenoid coil. The following graph is a typical example of a response time test recorded on an oscilloscope.



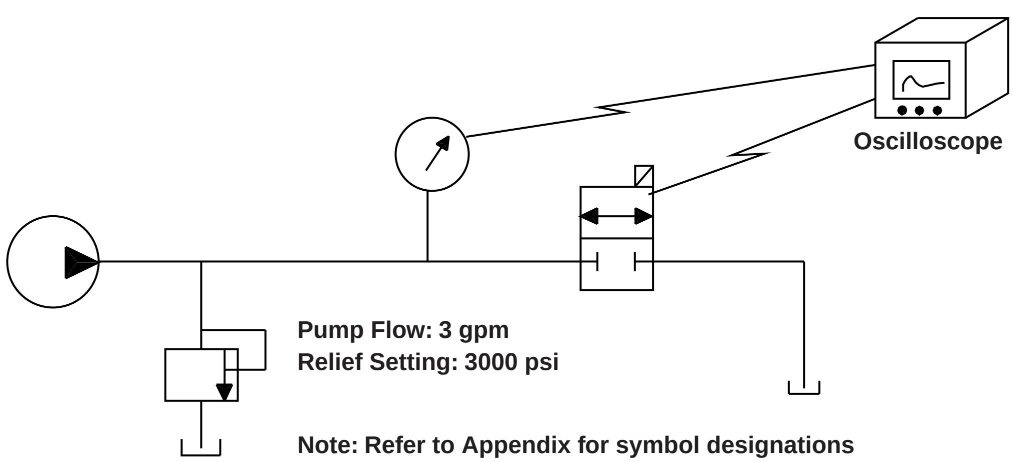
The solid curve on the graph shown above is a typical trace or graph recorded when current is applied to a coil as well as when the current is turned off on an SV08-24. The dashed curve on the graph above shows how the pressure changes as the spool opens and closes. The points defined on the graph are as follows:

- P_1 = steady state pressure when spool is opened (coil energized)
- P_2 = steady state pressure when spool is closed (coil de-energized)
- I_1 = current level where the plunger begins to move
- I_2 = current level when the plunger has stopped moving
- I_3 = steady state system current

Time elapsed from when current is:

- t_1 = first applied to when plunger stops moving
- t_2 = first applied to when pressure reaches 10% of P_2
- t_3 = turned off to when the pressure is 20-30psi above P_1
- t_4 = turned off to when the pressure reaches 90% of P_2

The illustration which follows, shows a typical schematic for testing the valve response time. (Refer to the appendix for further clarification on the symbol designations).

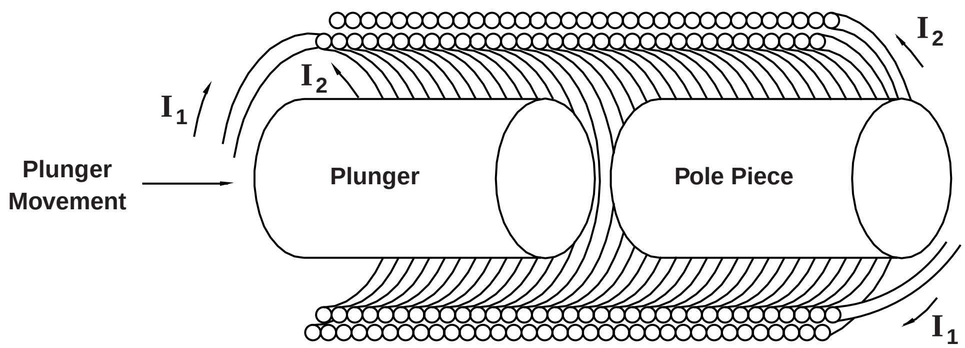


Pressure Defined

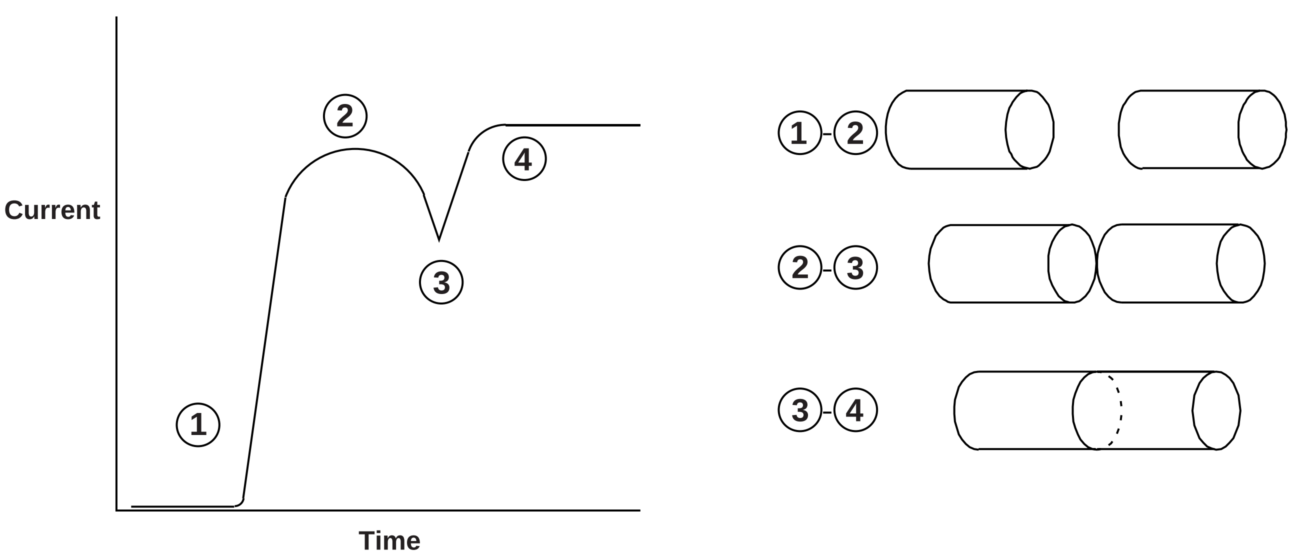
When no current is applied, the SV08-24 is normally closed and the pressure seen at the pressure gage or transducer is 3000 psi. (P_2) When the coil is energized, the spool opens and the pressure falls. The pressure measured at the transducer is the pressure drop due to the oil flowing through the valve. (P_1)

Current Defined

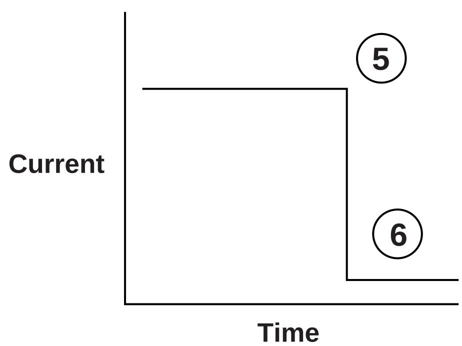
In chapter three we discussed how current flowing through the solenoid coil induces a magnetic field. To expand on this concept, as a magnetic part moves though a coil of wire, it induces a current. In the case of a coil which has current flowing through it, the induced current flows in the opposite direction of the current which is applied to the coil. Recall the diagram of the pole piece and plunger inside a solenoid coil.



Shown below is the pull in portion of the current response graph.



From points one to two, the current in the solenoid is building. The time required for this to occur is based on the inductance of the coil. The inductance basically describes the amount of time required for the current to flow through the solenoid coil. This time is based on the number of turns and the resistance of the coil. When the current reaches point two, the magnetic force is strong enough to overcome all the other forces previously discussed. The plunger begins to move at this point. The time between points two and three shows a decrease in the current because the plunger movement forces current backwards or against the direction of the applied current. At point three, the current begins to build because the plunger has stopped moving. The current continues to build as if the plunger were never there. The current reaches a steady or constant level at point four based, on the system voltage and resistance of the coil. (Recall Ohm's law I = V/R.)



The drop out end of the trace begins at point five. At this point the current goes from ON to OFF at point six. This occurs when the switch connecting the solenoid and power supply is opened.

Time Described

The times defined in the valve response graph are based on a combination of the current and pressure traces. The times described by t_1 and t_3 and are times which HydraForce uses to determine the response of their solenoid valves. Those described by t_2 and t_4 represent the times currently proposed by the NFPA (National Fluid Power Society) to describe the response time of a valve. There are pros and cons to using each of these times which are described in the following section.

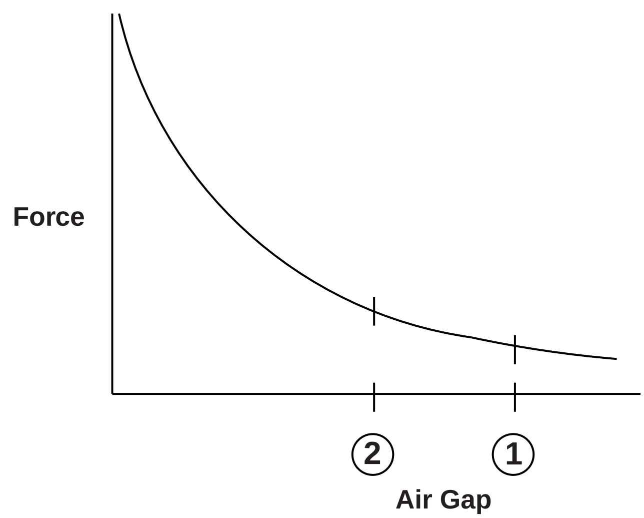
t_1 = This time is the most exact of all four times because it relates directly to the movement of the plunger. This is described in the previous section, on the description of the current.

t_2 and t_4 = These times are not always as good as t_1 and t_3. The shape of the pressure graph is not only determined by how quickly the valve opens, but also by how the rest of the system is connected. For example, if the system is stiff because the connections are made with hard tubing, the response time recorded may be faster. If the system is soft because the connections are made with hoses, the time recorded may be longer. Another reason for this may be that other valves (such as relief valves) must react during the test.

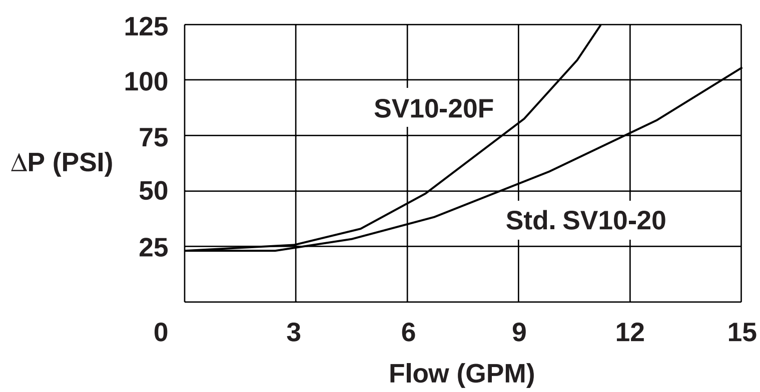
t_3 = This time is less dependant on the rest of the system (as t_2 and t_4 are). Testing shows that regardless of the compliance (stiffness) of the system the initial rise in pressure takes the same amount of time. The downside of using this time is that the spool may be only be partially shifted and the pressure may still begin to rise. This means that the spool and plunger may still be moving after this time

Parameters Affecting Response Time

All the forces described in the previous sections affect the response time. For example, to decrease the pull-in response of an SV10-20, normally open pilot operated poppet valve, the air gap could be decreased. By reducing the air gap, the initial magnetic force when the current is turned on, is higher. A graph of the force versus the varying air gap is shown below. Point one represents the air gap of the standard valve. Point two is the air gap of the valve with the faster opening time.



The following graph shows that the pressure drop through the valve increases when the air gap is decreased.



Another way to decrease the time to actuate the valve is to increase the magneto-motive force (NI). NI can be increased by changing the winding used in the coil or by increasing the system voltage. This is typically accomplished by changing the winding. Both methods are known as *hot shotting* the coil. As the name implies, this process causes the coil to heat up due to the increase in voltage or decrease in resistance, which in turn draws more current or power. This method of decreasing the ON response time should only be used in applications where the coil is not on for long periods of time. If the coil gets too hot, the resistance increases and the current draw decreases. Therefore, there will be no increase in force.

As stated, one way to increase NI is to decrease the resistance. To accomplish this on a standard HydraForce product, the coil can simply be changed. For example, if the nominal system voltage is 12V, a 12 V coil would be used. To hot shot the valve (coil), the coil could be replaced with a 10V coil. The 10V coil has a room temperature resistance of 4.8**Ω** and has 880 turns on the winding. The resistance of the 12V coil is 7.2**Ω** and has 1054 turns. The following comparison shows the NI of the 10V and the 12V coils when the available voltage is 12 V:

10V coil	I = V/R
	I = 12V / 4.8**Ω**
	I = 2.5 Amp
	NI = 880 X 2.5 amp = 2200 NI
12V coil	I = V/R
	I = 12V / 7.2**Ω**
	I = 1.667 Amp
	NI = 1054 X 1.667 amp = 1760 NI

By changing the coil, a 25% increase in force is obtained. Before hot shotting a coil, HydraForce should be contacted to determine if the application is suitable for this method of decreasing the ON response.

Decreasing the OFF response can be accomplished by increasing the spring force. This increase needs to be weighed against the flow and pressure to which the valve is subjected, as well as the available NI. Again, the NI is affected by the number of turns, system voltage, coil resistance, time that the coil is energized and ambient temperature.

HydraForce makes several valves which have response times lower than the standard product. These are denoted by a *F* in the model code. For example, a fast acting SV10-20 is model coded as an SV10-20F. This valve has both a smaller air gap (to decrease the on time) and a spring with higher force (to decrease off time). The response time of each is given in the following table.

Voltage Applied	Response Time SV10-20 Pull-in (ms)	SV10-20F Pull-in (ms)
10.2	58	28
12.0	40	24
13.2	31	22
Dropout (ms)	32	17

(Note: A millisecond is 0.001 seconds or 1 second / 1000)

The graph above shows the affect of changing the air gap and the voltage (NI). As previously discussed, decreasing the airgap increases the force. The same is true if you increase the voltage. When the current is higher the voltage or current increases as well as the NI or magnetic force.

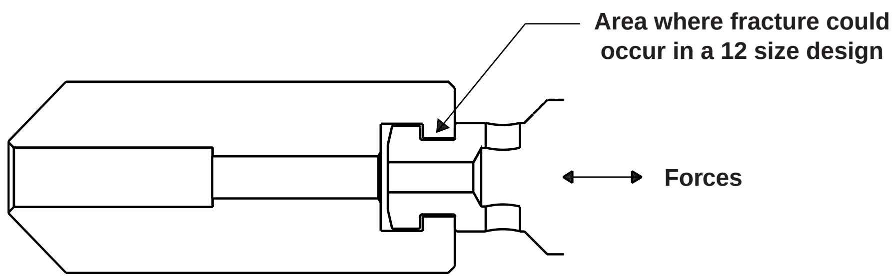
Conical Vs. Flat Face

The reasons for choosing either the conical or flat face over the other are based on the summation of forces. The main question is, how the other forces affect the valve. In the normally open pilot operated poppet valve, the forces opposing the pull in action are small, with the exception of the spring force. This force is large because it must overcome the pressure force acting on the pilot pin. For this reason, the flat face armature is used. Refer to chapter four for further comparison of the Force vs. Air gap characteristic.

The conical plunger is selected in the spool valve because it has a higher force than the flat face at the larger air gap. This higher force is required to overcome the flow forces acting on the valve.

Push vs. Pull

The choice between a push or pull style armature is based on the hydraulic function and strength of the valve. In 08 and 10 size spool valves the armature type is a pull style. This style allows for a variety of spool functions. However, a push style armature such as that used in the 12 size spool valves could also be used. The 12 size uses the push style because it is more robust than the “t” for this size valve. The flow force in the 12 size valves can be as high as 20 lbs compared to 8 lbs in the 10 size valves. Simply increasing the thickness of the parts would not be sufficient. The diagram below shows the area that would be weak in the 12 size if it used a “t” slot.



Pull-In

Pull-in occurs when the armature has traveled fully through the air gap from the de-energized to the energized position. HydraForce has established values which are used in production, to ensure that the products will consistently pull in lower than a certain threshold current. The values tested in production for pull in are approximately 69% of the room temperature nominal current draw. The reason this pull in value is so high is to ensure the valve will actuate at 85% of nominal voltage, when used continuously in an ambient of 78^{O} F (25^{O} C). Additional continuous duty voltages required are discussed in Chapter 10. For a 12 V coil, these values are:

08, 80, 98 size: 840 mA

10, 12 (poppet valves), 16, 38, 58 size: 1140 mA

12 size (spool valves): 1850 mA

These values are for standard products. Customer specific products may be tested at other values.

Drop-Out

Drop out current is the amount of current that can still be applied to the coil when the valve shifts back to the neutral or de-energized position. HydraForce has established that valves must drop out above a current level equal to 5% of the nominal room temperature current draw. The values used in production are based on the 12V coil, and are as follows:

08, 80, 98 size: 60 mA

10, 12 (poppet valves), 16, 38, 58 size: 80 mA

12 size (spool valves): 130 mA

These values are for standard products. Customer specific products may be tested at other values.

HydraForce designs in the ability for the valves to continuously dropout over the life of the product. This is accomplished in two ways, one of which is to use strong springs. The second way is for the armature and pole piece surfaces to never come into full contact. In the push style, a small gap remains between these parts even when the coil is energized. In the pull style, the conical plug and plunger have slightly different angles. Therefore, when the coil is energized and these parts come in contact, only an edge comes into contact, not the entire surface. Both of these designs eliminate the possibility of a concept known as *latching*. Latching occurs when the residual magnetic force is greater than the spring force.

Summary

In this chapter the following concepts were presented:

- The term summation of forces.
- What the actuator force, spring force, flow force and friction forces are.
- The two types of friction forces were discussed, mechanical and viscous.
- How the various forces affect the poppet and spool valves.
- How to measure and calculate the forces.
- What the compressed and free lengths of the spring are.
- The operation of the spool and poppet valve.
- How the response time is measured.
- Parameters affecting valve performance and response time, such as:
  - amp turns, available voltage, spring force, pressure, flow
- The meaning of open and closed in transition.
- What pull in and drop out are.
- When a push or pull style armature is used.

Review Questions

Use the following review questions as a measure of your understanding of the chapter material. Answers are provided in the appendix.

1. List two ways to measure the actuator force. ___________/___________

2. True or False. The spring force is a fixed force. ______________________

3. True or False. The free length of the spring is its length when installed in the de-energized valve. ______________________

4. Does the spring force increase or decrease when the coil is energized? ______________________

5. What causes the Bernoulli force to occur? ______________________

6. When fluid passes from a larger area to a smaller area is there a rise or drop in pressure? ______________________

7. What do the port numbers on the valve designate? ______________________

8. What term is used when the spool allows fluid to pass through to other ports in the transition position? ______________________

9. What term is used when the spool does *not* allow fluid to pass through to other ports in the transition position? ______________________

10. Name the two types of friction forces discussed in the chapter. ___________/___________

11. What type of force pulls water together to form a drop? ______________________

12. Which area of the pilot pin is exposed to low pressure? ______________________

13. What term describes the de-energized coil? ______________________

14. What are the forces acting on the spool valve. ______________________

15. What is pull-in? ______________________

16. What is the surface finish of the cage? Of the spool? ______________________

18. Describe how the poppet valve pulls in. ______________________

19. What is the pressure force acting on the pilot pin? ______________________

Notes

Chapter 9:
Types of HydraForce Solenoid Valves

Objectives

The objectives for this chapter are as follows:

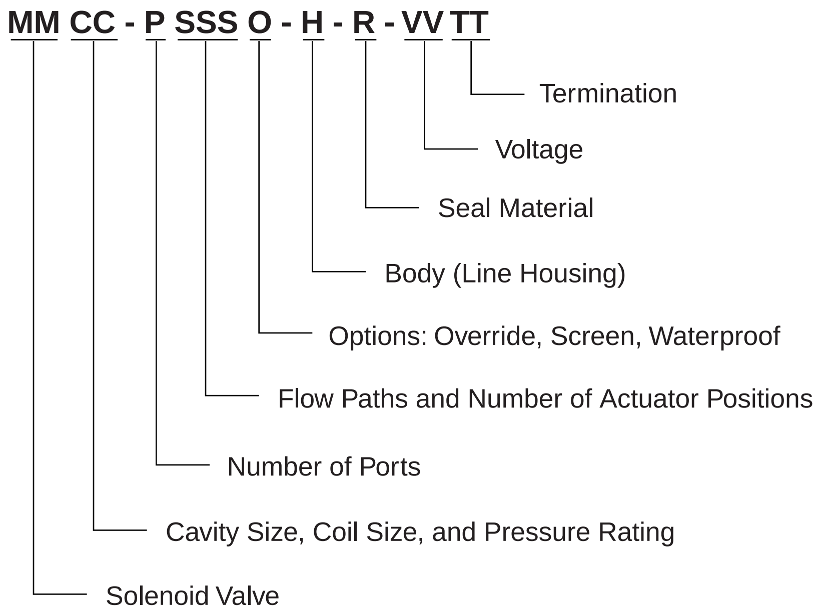
- Become familiar with the model coding system used by HydraForce.
- Recognize what each portion of the model code designates as well as the options available.
- Review a brief description each type of Solenoid valve as well as the corresponding hydraulic symbol.
- Learn what a reverse flow check valve is and which valves use it.
- Become familiar with the manual override option, how it works and the types available for the various valves.
- Learn what the screen, waterproofing, body, seal and termination options are and why they are available.

Introduction

In this chapter, we will learn about the standard solenoid valves available from HydraForce. This will be done by discussing the model coding system used to describe each valve. Following this, the valve symbol for each type of valve will be shown as well as a cross section of the corresponding valve.

Model Coding

HydraForce uses a model coding method which is specific to its product line. Each part of the model number represents an aspect of the valve which differentiates it from other solenoid valves. The following section breaks down the model number and describes the information which can be obtained from each portion of the number.



MM

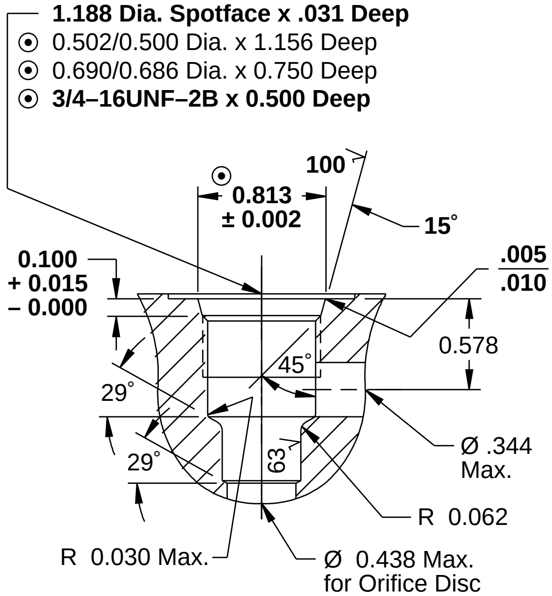
As shown in the chart above, MM indicates the type of valve. The designation for a solenoid valve is SV. Other designations exist for the various types of valves. For example, PD would indicate a pilot operated directional valve and RV would indicate a relief valve.

CC

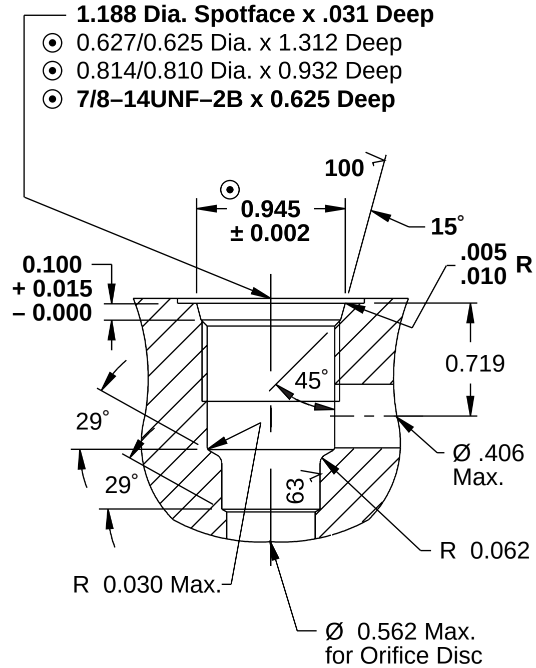
This portion of the model number indicates the size of the cavity, the coil size and the pressure rating of the valve.

HydraForce cavities are considered to be common industry cavities. The designations shown in the model code are based on the SAE (Society of Automotive Engineers) port sizes. For example, this means that the thread and top o-ring of an 08 size cavity is the same as one used in an SAE 08 port. An example of the cavities used on the 2-way cartridges is shown on the following pages. The dimensions in bold are the same as those used in an SAE port.

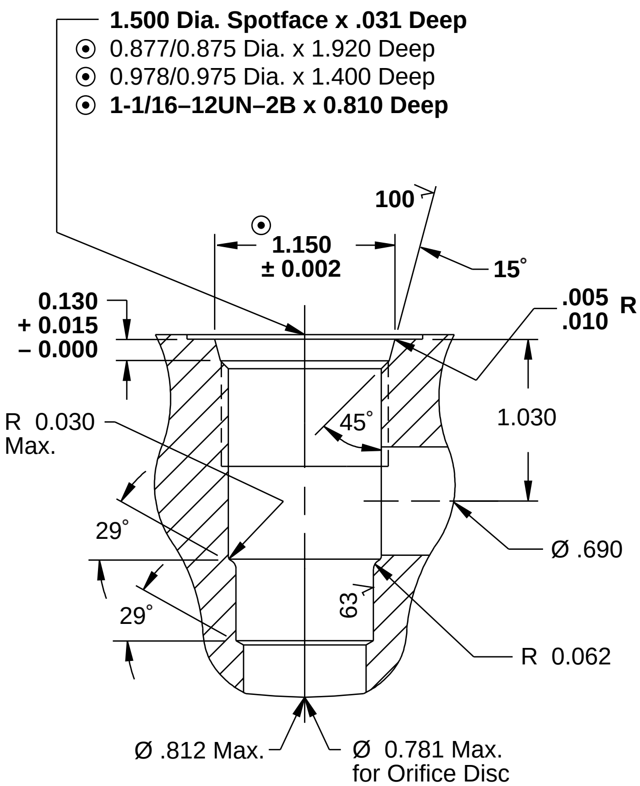
Size 8, 2-Way



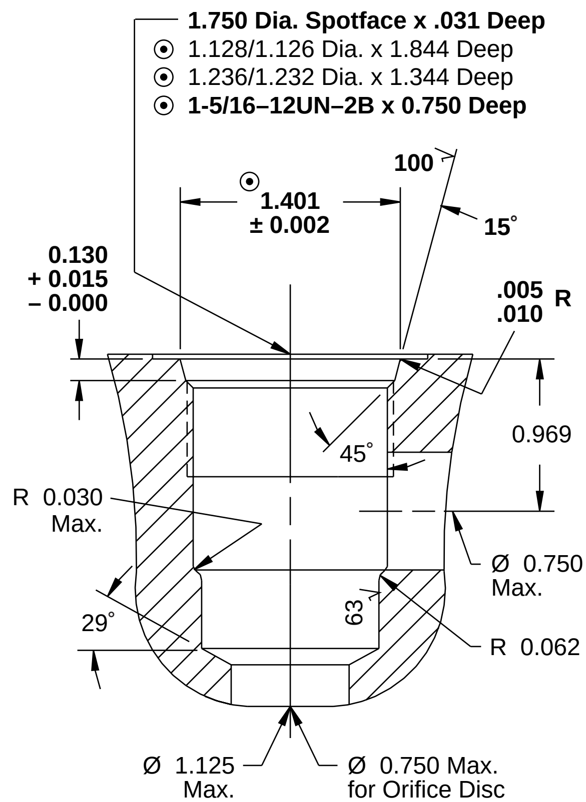
Size 10, 2-Way



Size 12, 2-Way



Size 16, 2-Way



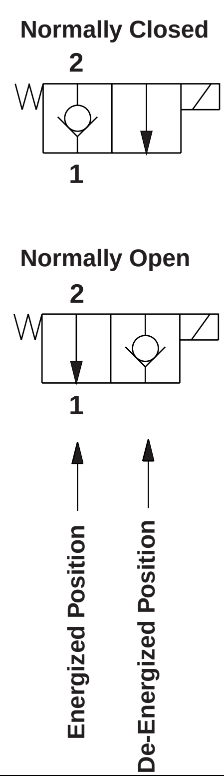
The cavity sizes as well as the coil size and pressure ratings available are listed in the following table:

Model Code	**Cavity Size**	**Coil Size**	**Pressure Rating**
08	08	08	3000 psi
98	Special (Typically Metric)	08	Determined by Application
80	10	08	Determined by Application
82	12	08	Determined by Application
68	08	60	3000 psi
10	10	10	3000 psi
38	08	10	3000 psi
58	08	10	5000 psi
12	12	10	3500 psi
16	16	10	3000 psi

P SS

The P in this portion of the model code indicates the number of ports present on the valve. Ther are either two, three or four ports available. The first and second S indicate the flow paths as well as the number of positions in the actuator. If the third S is left blank, this indicates a two-position actuator, otherwise a three-position actuator is indicated (except in the case of the SV12-40R which is a two-way actuator). The discussion has been focused on the two -position actuator throughout this manual. The three-position actuator will be presented in the following sections.

Before continuing with the model coding designations, let’s take a moment to define what normally open and normally closed actually means.



Normally Closed

The term normally closed is used on valves which control flow between two ports. As shown in the symbol, the flow from port two to one is blocked in the neutral or de-energized state. The flow is blocked when no power is applied to the solenoid. Hence the name normally closed.

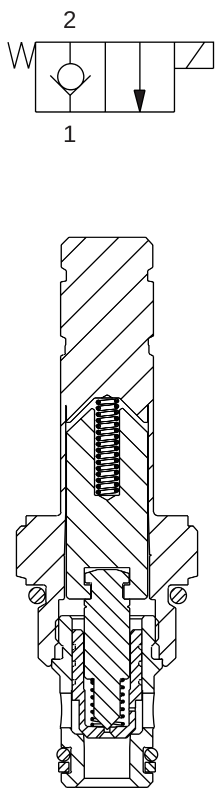
Normally Opened

The term normally opened is used to describe valves which control the flow between two ports. As shown in the symbol, flow or oil passes between ports two and one, in the neutral or de-energized position. Oil flows between the two ports when no power is applied to the solenoid. Hence the name normally opened.

The following diagrams, and those on the next several pages, are cross sectional views of some of the standard valves available from HydraForce. The views include the corresponding hydraulic symbol.

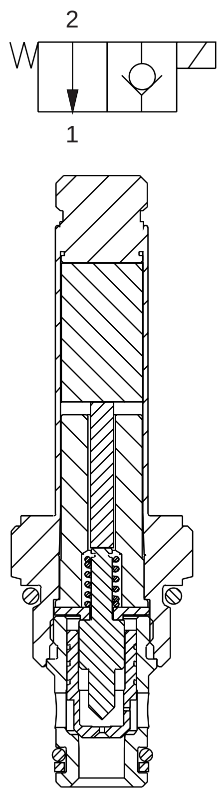
2-Way 2 Port

0
Normally Closed



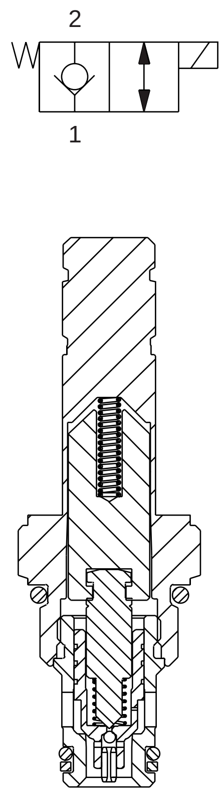
SV08-20

1
Normally Open



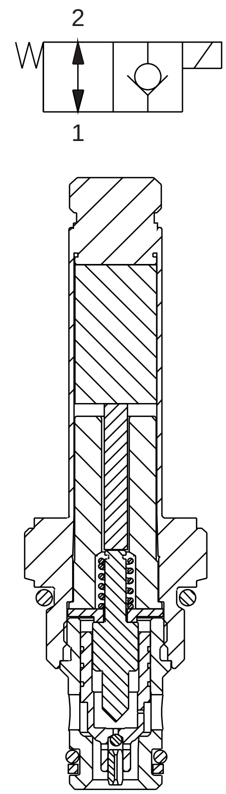
SV08-21

2
Normally Closed



SV08-22

3
Normally Open



SV08-23

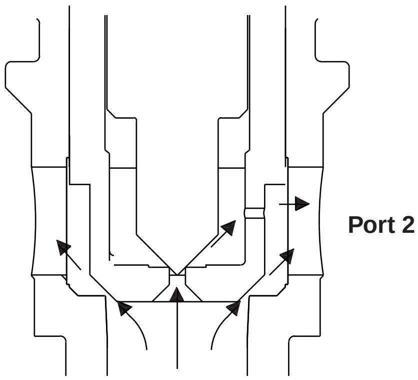
The SV08-20 is a two position pull style valve. The armature has two working positions; de-energized, and energized. The hydraulic portion consists of a normally closed, pilot operated poppet valve. This means that the pilot pin controls the opening and closing of the poppet.

The 21 type valve shown above, is a normally open, pilot operated poppet valve using a two position push style actuator. When de-energized, oil flows between ports 2 and 1. When energized, the pilot pin pushes down on the poppet, closing off the flow of oil.

The 22 type is a normally closed pilot operated poppet valve using a two position pull style actuator. This valve allows unrestricted flow from port 1 to port 2 when the valve is de-energized. This is the main difference between the SV08-20 and SV08-22. (See the following page for further explanation.)

The valve shown above is a 2-way normally open, pilot operated poppet valve. When the coil is not powered, oil can flow from 2 to 1 or from 1 to 2. When energized, the poppet blocks the oil from flowing from port 2 to 1. The actuator used is a two position, push style.

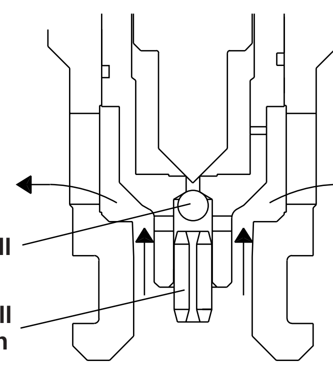
Reverse Flow Check Valve Function



The illustration to the right is a cage, poppet and pilot pin from the SV08-20. The oil is shown trying to flow from port 1 to port 2. As shown, the oil also flows into the area around the pilot pin. Since the bleeder side hole of the poppet is smaller than the pilot pin seat, oil fills behind the poppet and pilot pin. Eventually, these two parts move closer to the cage seat, until the flow is restricted to approximately the flow passing through the bleeder hole.

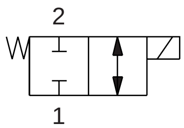
The diagram below shows the cage, poppet and pilot pin from the SV08-22 along with two additional parts which make up the *check valve*. A check valve is a valve which allows flow in one direction. Two parts which make up a portion of this valve are the ball and roll pin. (A roll pin is a piece of flat metal rolled into a cylindrical shape or a pin.) The check valve shown below is known as a free reverse check valve when inside a solenoid valve. It is given this name because it allows oil to flow freely in the opposite direction as indicated in the symbol shown with the SV08-22 valve.

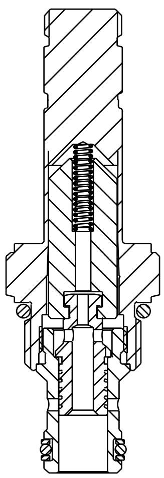
In this valve, when oil goes from port one to two, it also pushes on the ball. The ball blocks the oil from getting around the pilot pin. Oil does not fill this area, it instead pushes on the poppet until it has fully opened. In other words, the flow is not restricted by the poppet.



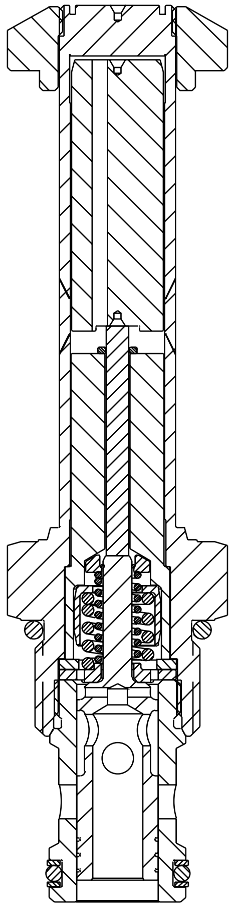
2 Way (2 Port) 2 Positionn

4
Normally Closed



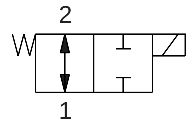


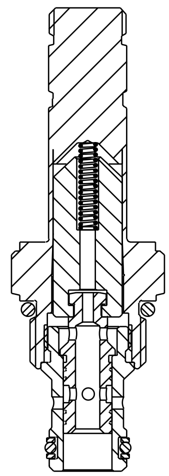
SV08-24



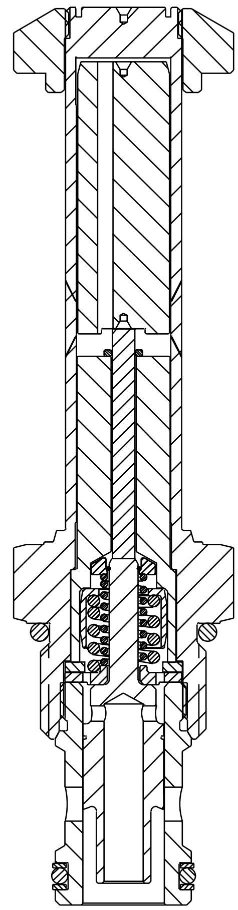
SV12-24

5
Normally Open





SV08-25



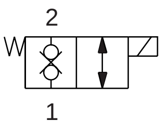
SV12-25

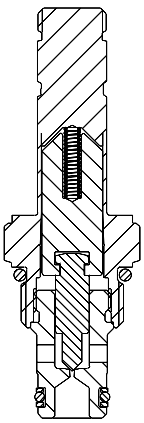
The 24 type is a normally closed, direct acting spool valve. When de-energized, flow is blocked. In the energized position, oil can flow from ports 2 to 1 or 1 to 2. The actuator used by HydraForce in this valve has two positions and can be either a push or a pull style. Both the 08 and the 10 size are pull style and the 12 size is a push style.

The 25 type is a 2-way, normally closed, direct acting spool valve. In the neutral position, oil can flow from port 2 to 1 or 1 to 2. When energized, oil is blocked from flowing. The actuator is a two position type. It is a pull style in the 08 and 10 size and a push style in the 12 size.

2 Way (2 Port) 2 Position

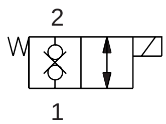
6
Normally Closed

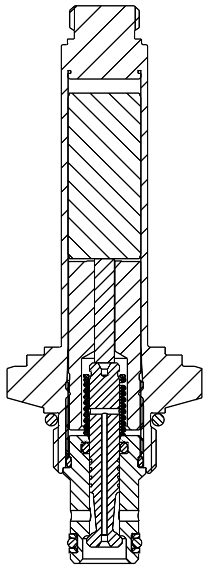




SV08-26

8
Normally Closed

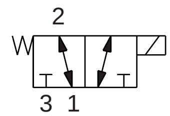


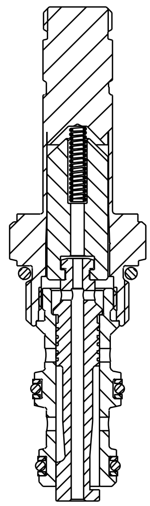


SV38-28

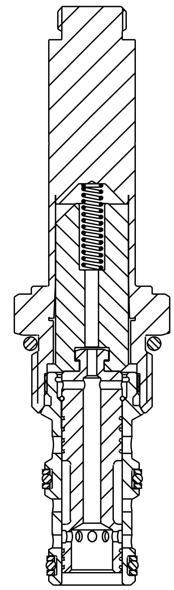
3 Way (3 Port) 2 Position

0, 4





SV08-30



SV10-34

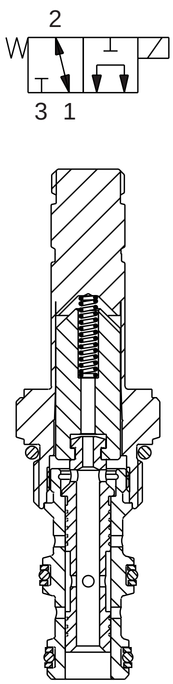
The 26 type is a 2-way, normally closed, direct acting poppet valve. The actuator is a two position pull type. Notice that this valve is made from the pilot section of the 20 style valve. This means that the hydraulic parts are made up of the pilot pin and the pilot pin seat, which is in the cage. There is no poppet in this valve. This valve is called a double blocking valve because either port can be used as used as the inlet and still block flow.

The SV38-28 is a normally closed, direct acting poppet valve. It blocks oil from passing between ports 2 to 1 or from ports 1 to 2 when de-energized. When energized oil flows between the two ports. The actuator in this valve is a two position push style. This valve is called a double blocking valve because either port can be used as used as the inlet and still block flow.

This valve is a direct acting, spool valve. In the de-energized or neutral position, flow can pass from port 2 to 1. When energized, oil can flow from port 3 to 2 or 2 to 3 and is blocked from flowing from port 1. The 34 style spool can allow bidirectional flow from ports 2 to 1 or 1 to 2. The 30 style spool generally only allows flow from 2 to 1. The 30 style (only available in the 08 size) is unique because it extends out of the bottom of the cage. In the 34 style (available in the 10 and 12 size), the spool stays within the length of the cage. The actuators are 2 position types and are pull style in the 08 and 10 size, and push style in the 12 size. The 08 and 10 size valves are both closed in transition and the 12 size is open.

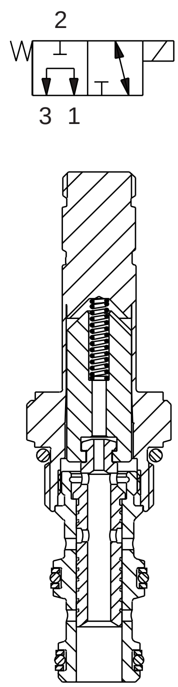
3-Way (3 Port) 2 Position

1



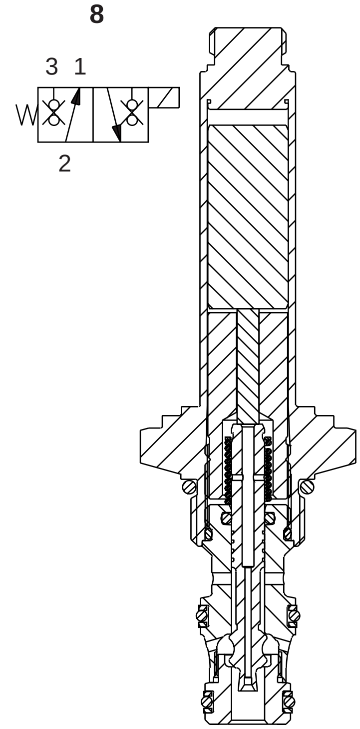
SV08-31

3



SV08-33

8



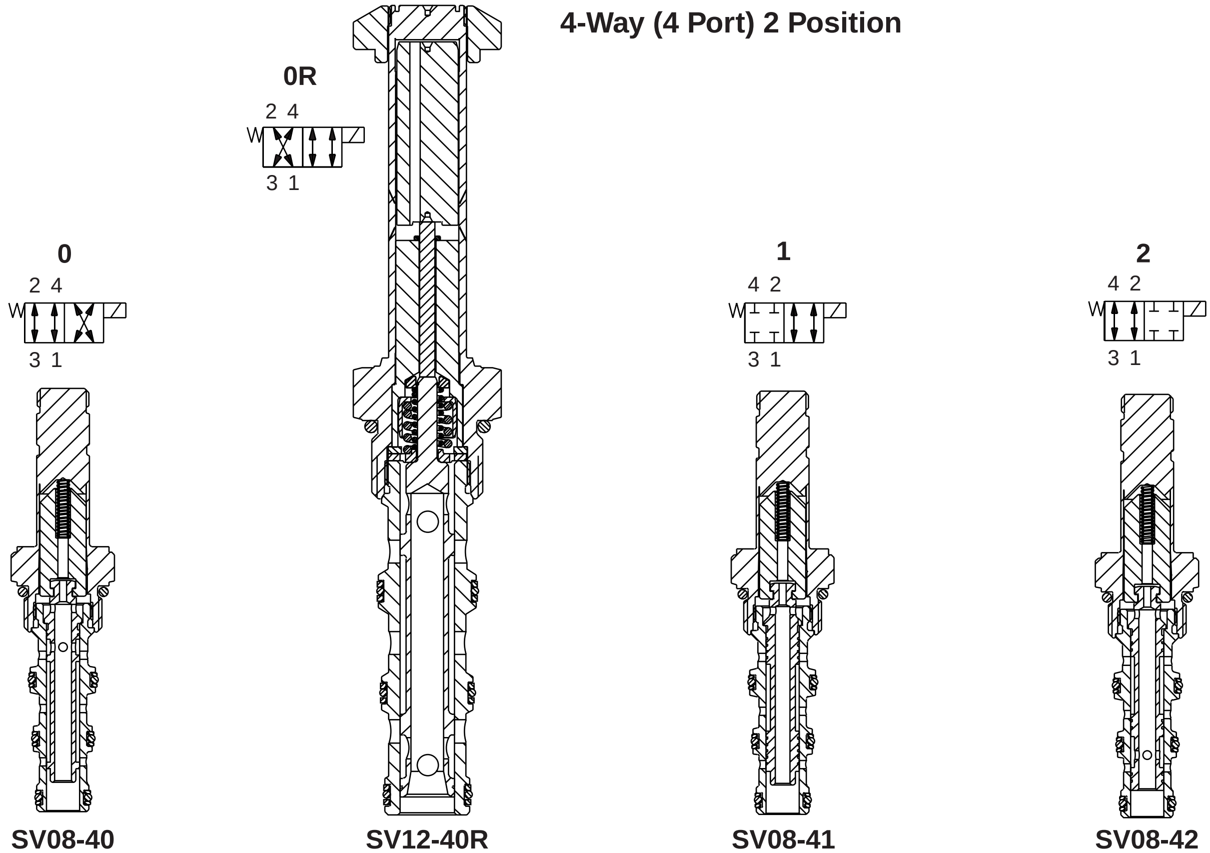
SV38-38

The 31 type valve is a direct acting, spool type. It allows flow from ports 2 to 1 or 1 to 2. It also blocks oil at port 3 in the de-energized position. In the energized position, oil can flow from port 1 to 3 or 3 to 1 and is blocked at port 2. The actuator has 2 positions and is either a push or pull type. The 08 and 10 size use a pull style actuator and the 12 size uses a push style actuator. In addition, the 08 and 10 size valves are both closed in transition and the 12 size is open.

The 33 type valve is a 2 position direct acting, spool valve. In the de-energized position, oil can flow between ports 3 to 1 or 1 to 3 and is blocked at port 2. When the spool is in the energized position, oil can flow from ports 1 to 2 or 2 to 1 and is blocked at port 3. The actuator has 2 positions and is either a push or pull type. The 08 and 10 size use a pull style actuator and the 12 size uses a push style actuator. In addition, the 08 and 10 size valves are both closed in transition and the 12 size is open.

The SV38-38 valve is a 2 position direct acting, poppet valve. In the de-energized position, the poppet is seated, blocking flow at port 3 and allowing flow from 1 to 2 or 2 to 1. When energized, the poppet sits on a second seat, blocking oil at port 1 and allowing it to flow from 2 to 3 or 3 to 2. The actuator is a 2 position, push style. This valve is only available as an SV38-38, which means that it is in an 08 size cavity, a 10 size coil and is only rated to 3000 psi. This valve is open in transition.

4-Way (4 Port) 2 Position



The 40 type valve is a 2 position, direct acting, spool type. In the de-energized position, it allows oil to flow from ports 3 to 2 and 4 to 1. When the spool is in the energized position, oil flows from port 3 to 4 and 2 to 1. The actuator has 2 positions and is a pull style. This spool type is open in transition.

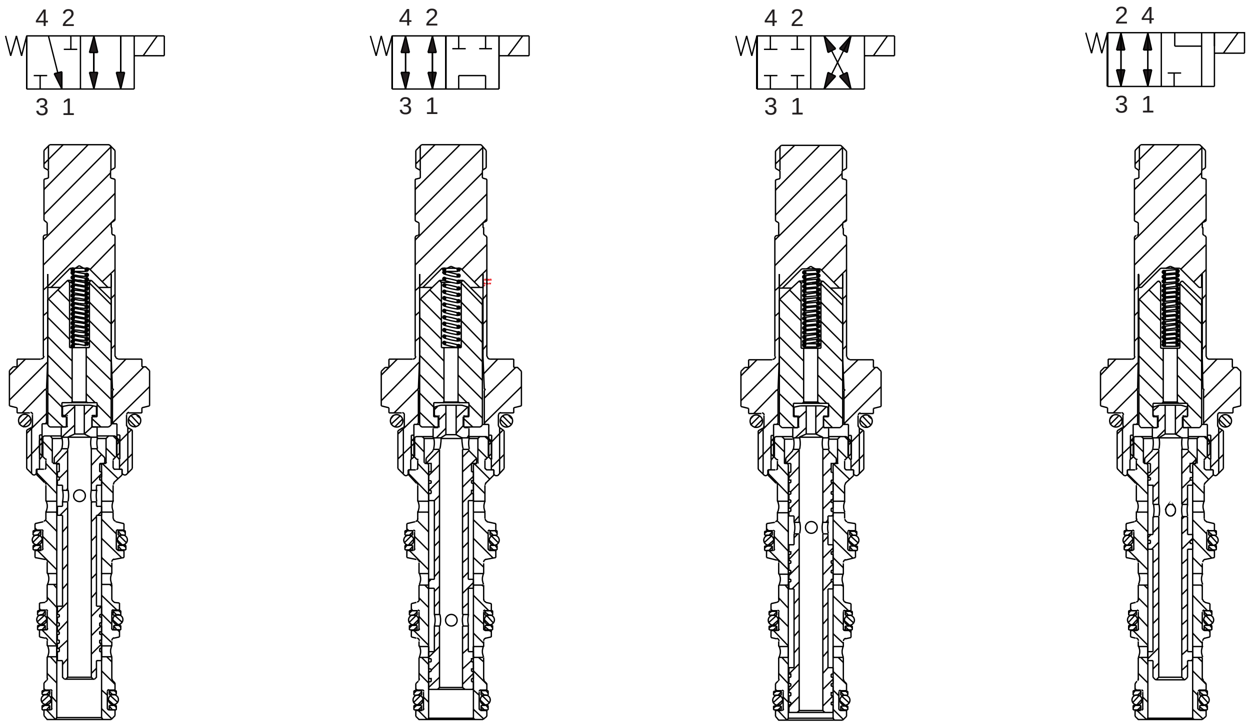
The 40R is a 2 position direct acting, spool valve. The model code indicates that the flow paths are the same as the 40 spool, but the logic is reversed, as indicated by the R. In the de-energized position, flow passes from port 3 to 4 and 2 to 1. When energized, oil passes from 3 to 2 and 4 to 1. The actuator is a 2 position push style. This valve is only available in a 12 size and is open in transition.

The 41 type valve is a 2 position, direct acting, spool valve. In the de-energized position, oil is blocked from flowing through any of the ports. When shifted, the spool allows oil to flow from ports 3 to 4 and 2 to 1. The actuator is a two position pull or push type. The 08 and 10 size are pull types and the 12 is a push type. This valve is closed in transition.

The symbol and valve above represent a 2 position / 4 way direct acting spool valve. In the de-energized position, ports 3 and 4 are connected. When the coil is energized, the spool shifts, blocking the flow of oil through any of the ports. The actuator is a 2 position type. It is a pull style in the 08 and 10 size valves and a push style in the 12 size. This valve is closed in transition.

4-Way (4 Port) 2 Position

3 **4** **5** **6**



SV08-43 **SV08-44** **SV08-45** **SV08-46**

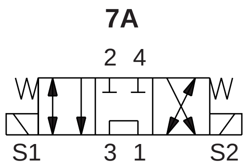
This valve is a direct acting spool type. In the de-energized or neutral position, port 4 is connected to port 1 and oil is blocked at both ports 2 and 3. When in the energized position, port 3 is connected to 4 and 2 is connected to 1. The actuator is a 2 position pull type. The actuator is a 2 position pull type in both the 08 and 10 size. This valve is open in transition.

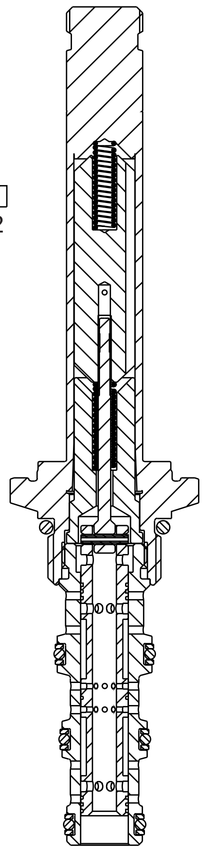
This is a direct acting 4 way spool type valve. When the valve is energized, ports 3 and 1 are connected and oil is blocked at ports 2 and 4. When the valve is de-energized, ports 3 and 2 are connected as well as ports 4 and 1. The actuator is a 2 position pull type in both the 08 and 10 size. This valve is open in transition.

This valve is a direct acting 2 position / 4 way spool valve. In the de-energized position, all ports are blocked. When energized, oil can flow between ports 3 to 2 and 4 to 1. The actuator is a 2 position pull type. This valve is only available as an 08 size, and is closed in transition.

The 46 valve is a 2 position / 4 way direct acting spool type. In the de-energized position, oil is allowed to flow from ports 3 to 4 and 2 to 1. When the coil is energized, the spool connects ports 4 and 2 to 1 and blocks oil at port 3. The actuator is a 2 position pull type. This valve is only available in an 08 size, and is open in transition.

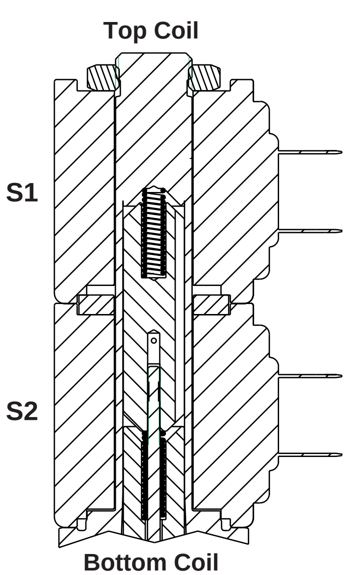
4-Way (4 Port) 3 Position

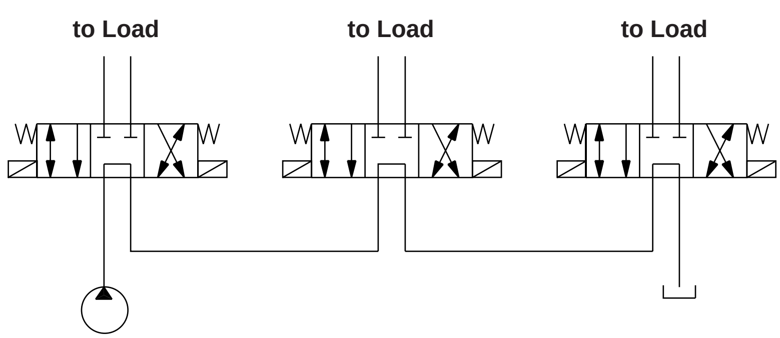




SV08-47A

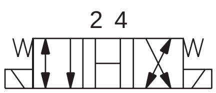
The 47A shown to the left is a 3 position / direct acting spool valve. The spool type is known as a tandem center spool. This means that several valves can be connected in tandem (or one following the other as shown in the schematic below). This valve is available in the 08 and 10 size cavities. The actuator has 3 positions, 2 energized and 1 neutral. In the neutral position, flow occurs between ports 3 and 1 and oil is blocked at ports 2 and 4. When the top coil (referred to as solenoid 1 or S1) is energized, ports 3 and 2 are connected as well as 4 and 1. When S2 (the bottom coil) is energized, oil can flow between ports 3 to 4 and 2 to 1. This spool type valve is open in transition.

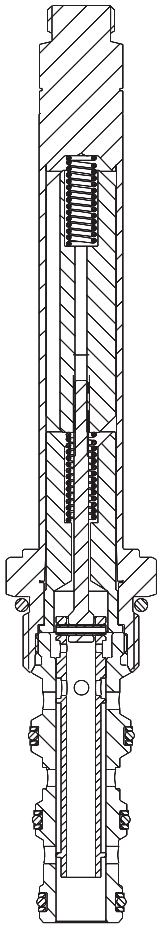




4-Way (4 Port) 3 Position

7B

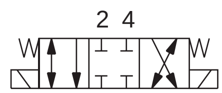


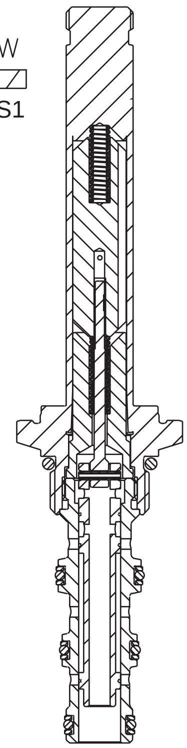


SV10-47B

The 47B is a 3 position / 4 way direct acting spool valve. The valve is termed the open center spool valve because in the neutral (or central) position all ports are connected. When the top coil is energized, port 3 is connected to port 4 and port 2 is connected to port 1. Energizing S2 (bottom coil) allows oil to flow between ports 3 to 2 and 4 to 1. This valve is only available in a 10 size. The actuator is a 3 position type. When S1 is energized, the actuator acts as a pull style. When S2 is energized, the actuator acts as a push style. This valve is open in transition.

7C



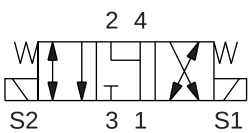


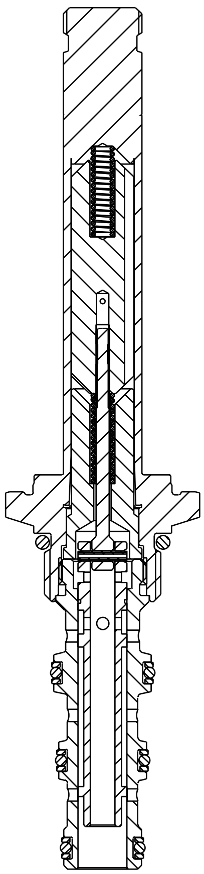
SV08-47C

The 47C is a 3 position / 4 way direct acting spool valve. When both coils are de-energized, the armature and spool are in the neutral (central) position. All ports are blocked in this position. For this reason, this spool type is called a closed center spool. When in the center position, oil is closed off and no flow passes through any of the 4 ports. If S1 is energized, oil can flow from ports 3 to 4 and from 2 to 1. When power is applied to S2, port 3 is connected to 2 and port 4 is connected to 1. The actuator is a 3 position type. Energizing S1 pulls the armature and energizing S2 causes the armature to push down on the spool. This valve is available in the 08 and 10 size cavities. This valve is closed in transition.

4-Way (4 Port) 3 Position

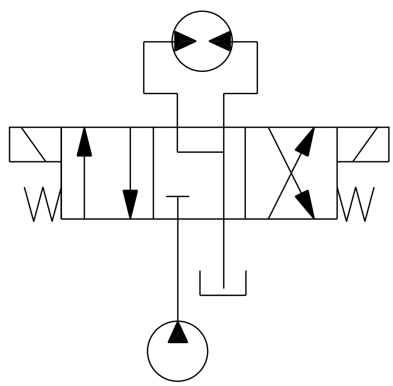
7D





SV08-47D

The 47D is a 3 position / 4 way direct acting spool valve, and is open in transition. In the neutral position, ports 2 and 4 are connected to port 1. When energizing S1, oil flows from port 3 to 4 and from port 2 to 1. When S2 is energized, port 3 is connected to 2 and 4 is connected to 1. This type of spool is known as a motor spool. It is often used to control the direction of rotation of a hydraulic motor. The diagram below shows a simple circuit of this application.



With the spool in the center position, the motor can spin freely in either direction. When S1 is energized, the oil flows into the motor, causing it to rotate in a given direction. If S2 is energized, the motor spins in the opposite direction.

The actuator is a 3 position type with 2 energized positions acting opposite each other (a push & pull). The neutral position is between the 2 energized positions. This valve is available in both an 08 and 10 size cavity.

Options

MM CC - P SSS O - H - R - VV TT

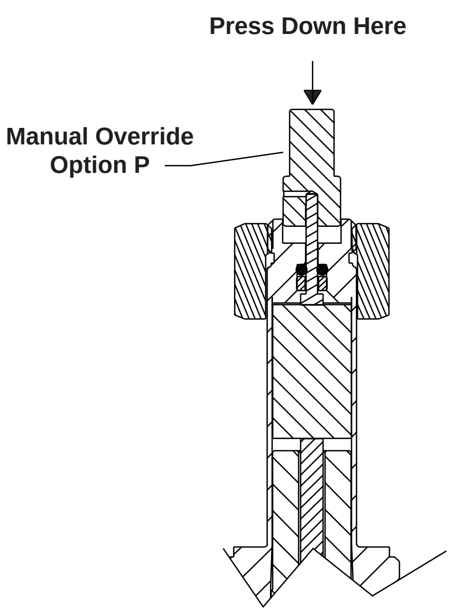
Options: Override
Screen
Waterproof

Manual Override

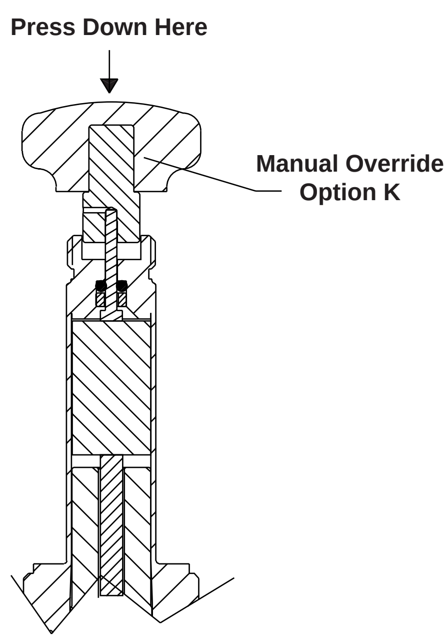
Manual override is used occasionally, when the power fails. This feature allows the user to manually actuate the valve and allow the object which the valve controls, to be moved. As stated, this is used only occasionally or in emergency situations.

There are five types of override which include; *P*, *K*, *M*, *J*, and *Y*. The *P* style override is used on the 21, 23, 28 and 38 size valves. To operate this override, the override button is pressed down. See the following illustration. The *K* style is similar to the *P* style, but has a plastic knob added to the top which makes the override button easier to push down.

The following illustration shows both the *P* and *K* style overrides.



SV08-21P



SV08-21K

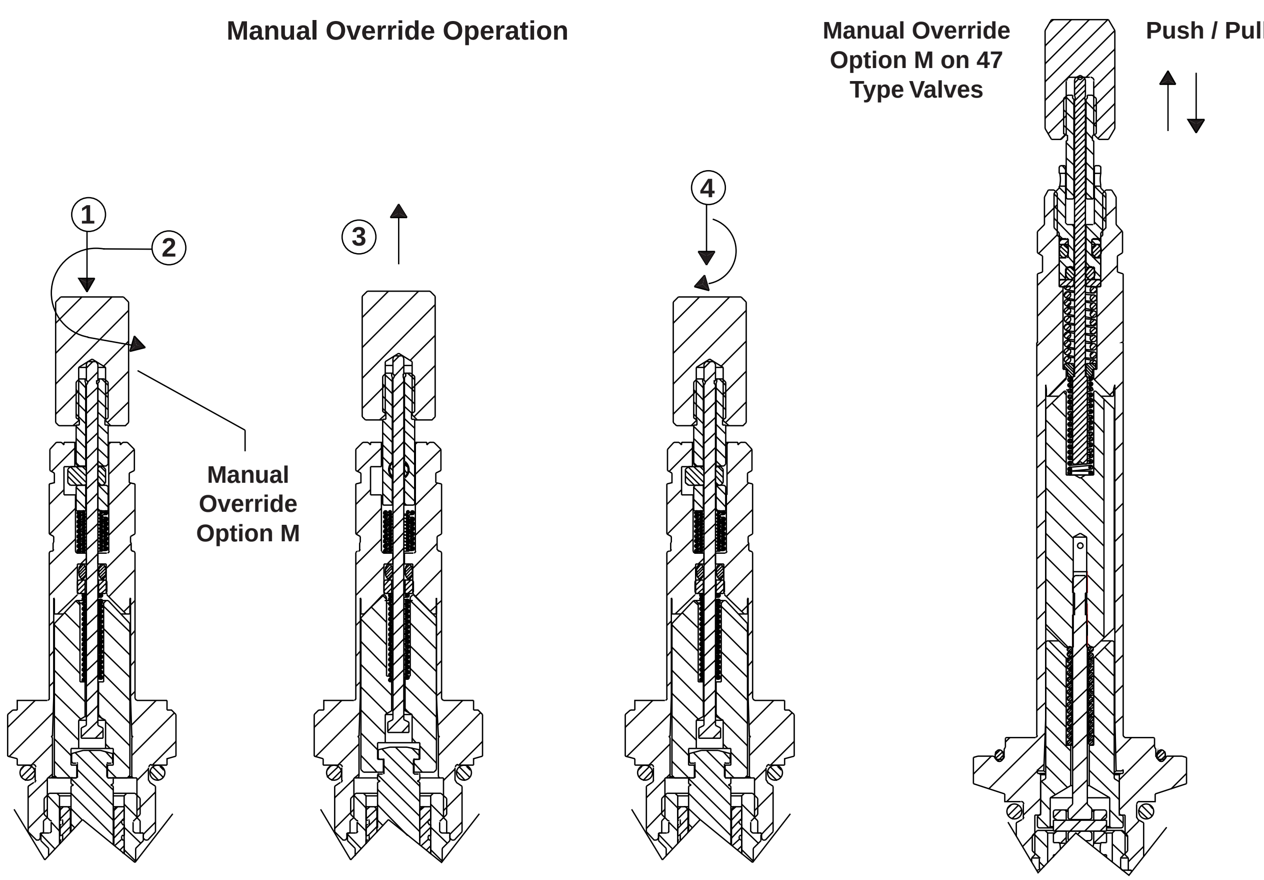
The *M* style manual override is available for valves with a two position pull type actuator, as well as valves with a three position push/pull type actuator. The following valves are included in these types:

20	30	40	45
22	31	41	46
24	33	42	47A,B,C,D
25	34	43	
26			

The following steps describe the use of the *M* style override with the 2 position pull type actuator (see diagram below):

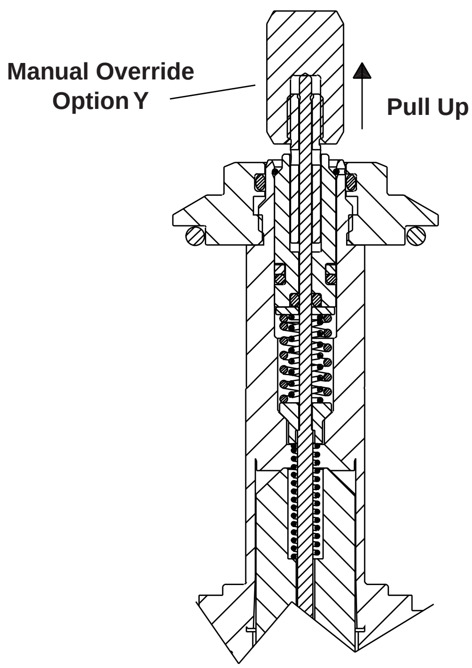
1. Push down on the button to move it from the detent lock position.
2. While holding down the button, rotate it clockwise 90^0 until it can't be turned any further.
3. Release the button and a spring will push it out. This spring also pulls up the plunger to move the spool or pilot pin into the energized position.
4. To disengage the override (move it back to the de-energized position), push down on the button until it stops, rotate counter clockwise until it stops. Release the button and it will pop back into the detent position.

As stated, the *M* style override also works with the 3 position push / pull actuators. With this style valve, the override works by simply pushing or pulling on it. Pushing on it moves the spool and plunger into the S2 energized position. Pulling on it moves it into the S1 energized position. To move the armature and spool back to the de-energized position, simply release the button and springs will move these parts to this position. (Note: to pull up on the button requires 10 to 13 lbs of force.)

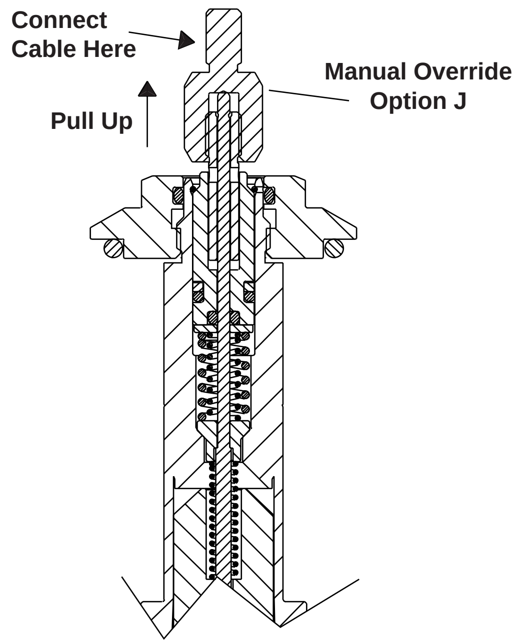


The *Y* style override is available on any of the 10 size, 2 position, pull style actuated valves listed for the *M* style override. To actuate this override, the small red button is pulled up. When the button is released, springs inside the valve return it to the de-energized position.

The *J* style is similar to the *Y* style, but uses a screw in place of the button. This screw can be used for connecting cables to the valve. In this manner, the override can be actuated remotely (at the other end of the cables). The diagram below shows a cross section of both a *J* style and a *Y* style override. (Note: Both the *J* and *Y* overrides require 10-13 lbs of force to pull up on the button.)



SV10-34Y



SV10-34J

Screens

A screen is another option for the valve. It is used to protect the valve from large contaminants floating through the system. These are not intended to replace the system filter, but merely add additional filtering for the valve. This option is designated by an S in the model code and is only available for the 08 and 10 size valves.

The standard screen available stops particles which are 0.006 in size. These screens can be used on spool or poppet valves and can be used on any port, with the exception of port 1. Since port 1 is connected to the tank, oil flows out rather than in, carrying any contamination away from the valve.

Waterproof

An additional option available is the waterproof option, and is designated in the model code with a *W*. This option available for HydraForce Solenoid valves, allows the coils to meet the IP67 weather rating. This rating means that the coil and cartridge can be immersed in 1 meter of water for 30 minutes with no water penetration. During this test, the coil and water remain at a constant temperature. The *W* option typically includes a special nut and two to three o-rings. Some 08 and 10 size cartridges require a different hex size to hold the o-ring in place.

MM CC - P SSS O - H - R - VV TT

H — Body (Line Housing)

Body (Line Housing)

The body or line housing is the part which the valve screws into. This part connects the solenoid valve to the rest of the system. The bodies can be made of plated steel or anodized aluminum. Both of these processes protect the bodies from oxidizing. Applications up to 3000 psi typically only require an aluminum body. If the application is operating above this pressure, steel is recommended. Also, if the system is expected to see a high number of cycles or pressure spikes above 3500 psi, steel is recommended. (Note: a pressure spike is a momentary peak in pressure. This is usually only a concern when the application is above the pressure rating of the valve, body or system.)

Seals

MM CC - P SSS O - H - R - VV TT

R — Seal Material

The type of seal on the outside of the cartridge valve is known as an o-ring. The material used in this seal is dependant on the application. There are four materials offered as options; N, V, P & E.

The N option designates a seal made from a material known as Buna N. This seal is used in general applications up to 3500 psi and can be used (is compatible) with a wide variety of fluids. The temperature range it can be used in is -40^0 to 120^0 C. This is the standard material used for HydraForce valves.

The V option is a seal made from a fluorocarbon material named Viton$_{TM}$. This seal is also used in general applications and is compatible with more fluids than the Buna N. Like Buna N, this seal is used in applications where the pressure is lower than 3500 psi. The major difference between this material and Buna N is the temperature range the material can withstand. Viton is rated for -30^0 to 205^0 C (-20^0 to 400^0 F). It is recommended that Viton is used when the oil temperature is expected to be above 100^0 C continuously or 120^0 C intermittently.

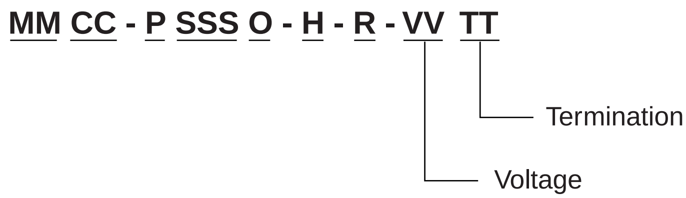
P designates a seal made from Polyurethane, which is a more durable material than Viton or Buna N. It is typically used in applications where the pressure is at or above 3500 psi. This material can work between -50^0 to 100^0 C.

E designates a seal made from a material known as EPDM (ethylene propylene di monomer). This material is specifically for brake fluid and similar fluids made from phosphate esters. It can be used in applications which have a temperature range of -55^0 to 135^0 C and pressures up to 3500 psi.

Each of the seals discussed is available in two different grades. The grade refers to the hardness of the material which is known as the *durometer* of the material. The two grades available are 70 durometer and 90 durometer.

Seals with a 70 durometer hardness are used in applications up to 3500 psi. For higher pressures 90 durometer material should be used. HydraForce standard o-rings are 70 durometer Buna N, Viton or EPDM. For applications above 3500 psi the standard is a 90 durometer polyurethane. If the application requires a 90 durometer seal other than the polyurethane, it can be ordered in a special cartridge.

Coil Voltages and Terminations



Each coil is available with different windings which enables the coil to be used in various applications. The coil is stamped with the rated nominal voltage and the appropriate winding for that voltage is housed within the coil. Several terminations are available for various application. These are listed in chapter 5.

Summary

In this chapter the following concepts were presented:

- The model coding structure.
- Options available when ordering a valve and how these options are designated in the model coding structure.
- Normally open and normally closed valves and symbols for each.
- A symbol, cross section and brief description was given of the standard HydraForce valves.
- Explanation of the reverse flow check valve.
- Detailed explanation of the override options, how the work and which overrides are used on the various valves.
- Detailed explanation of the seal types and the materials used in each option.

Review Questions

Use the following review questions as a measure of your understanding of the chapter material. Answers are provided in the appendix.

1. Describe the type of actuator used in the SV08-47A ______________________

2. What does the SV portion of the model code designate? ______________________

3. True or False. In a normally opened valve, oil flows between the two ports when no power is applied to the solenoid. ______________________

4. Which side of the hydraulic symbol designates the energized position, left or right? ______________________

5. A check valve allows flow in how many directions? ______________________

6. Why is the SV08-47D known as the motor spool? ______________________

7. How many types of manual override does HydraForce offer? ______________________

8. What is the screen option used for? ______________________

9. What is the standard seal type HydraForce uses? ______________________

10. What is the term used when referring to the hardness of the seal? ______________________

Chapter 10:
Installation Considerations / Troubleshooting

Objectives

The objectives for this chapter are as follows:

• Understand the proper method of installing the coil.

• Walk through the steps of the cartridge valve installation, including the seal lubrication and consequences of not lubricating properly.

• Discuss how the tube could be stretched and the consequences of it.

• Become familiar with potential cartridge failures, possible causes and suggested actions.

• Review the concept of back EMF and determine how it affects the circuit and the coil.

• Learn about three surge suppressors to reduce the effects of back EMF; diode, varistor and zener diode.

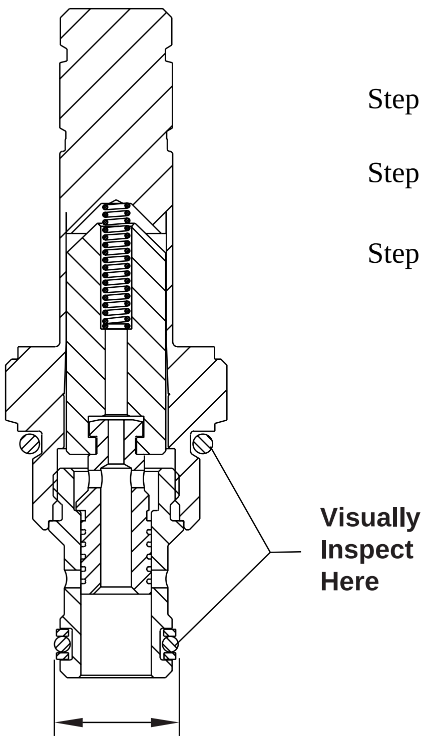
Introduction

When installed and applied within the guidelines of the catalog, the HydraForce solenoids will work reliably for a minimum of one million cycles. However, as good as the product is, problems may still arise for various reasons. In this chapter we will look at installation considerations that will help prevent failure such as correct tightening of the cartridge and coil. Also, the proper method to protect the customers' electrical system with a surge suppression device is described. After looking at preventative measures we will explore some troubleshooting techniques to help determine why the valve might fail to operate as expected.

Cartridge Valve Installation

The following section describes the method in which the cartridge valve should be installed. A list of steps as well corresponding diagrams are provided to ensure that the valve is installed properly.

Steps 1 & 2



Back Up Rings should fit in the same space as the O-Rings

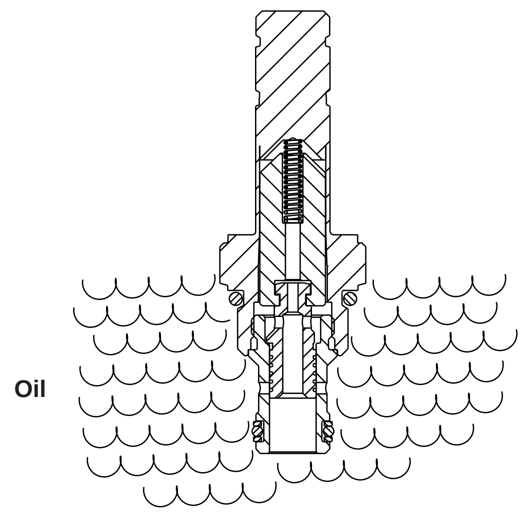
Step 1. Remove cartridge from packing.

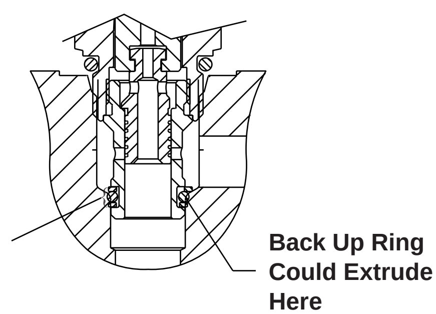
Step 2. Inspect o-rings to ensure there is no damage such as cuts or nicks.

Step 3. Check if all back up rings fit tightly within the o-ring groove. They should not stick out further than the o-rings. If they are sticking out further than the o-ring, they must be squeezed back into the groove.

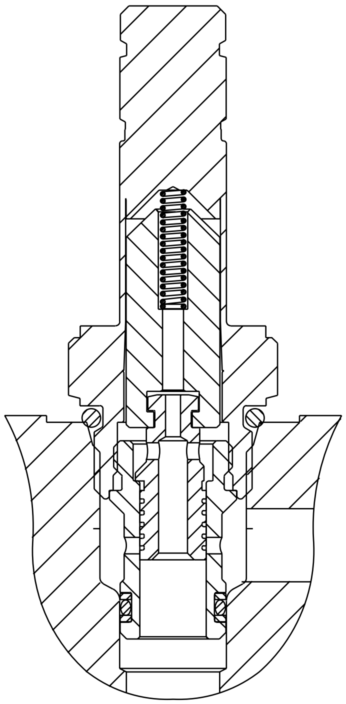
Step 4. Immerse the hydraulic portion of the cartridge in oil to lubricate the seals. It is important to install the cartridge (valve) into the cavities correctly. Before beginning, the o-ring and back up rings should be lubricated with a small amount of oil. The same oil which is used in the application should be used, and the outer surface of the seals should be lubricated. This allows the seals to slide into the cavity easily. Dry seals could cause the back up ring to spin out of the cage groove which could cause damage to or cut the seal. The diagram to the right demonstrates this procedure as well as shows the location of the grooves.

Step 4



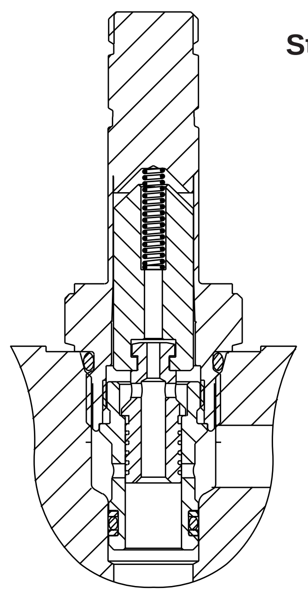


Step 5

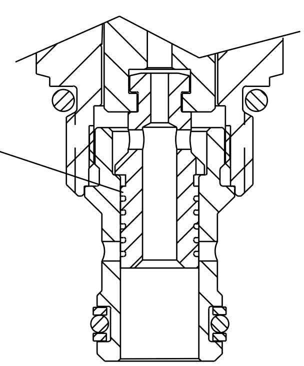


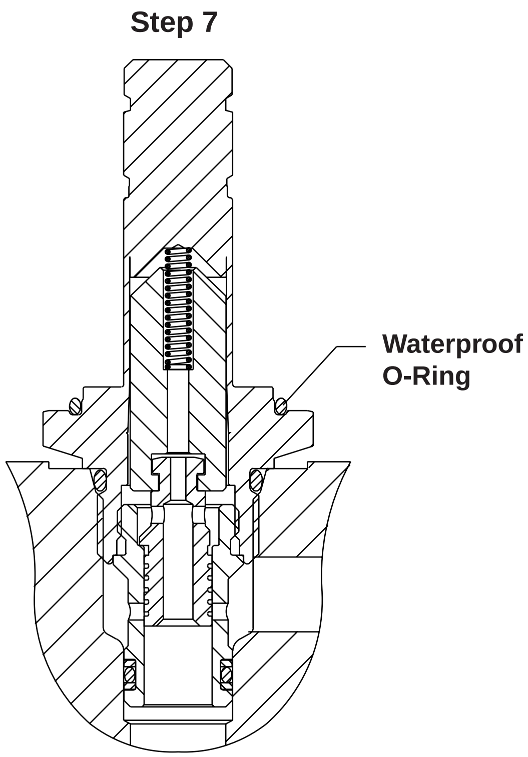
Step 5. Insert the cartridge into the cavity and tighten by hand in a clockwise manner. You should be able to screw it in with little resistance up to the o-ring, below the adapter.

Step 6



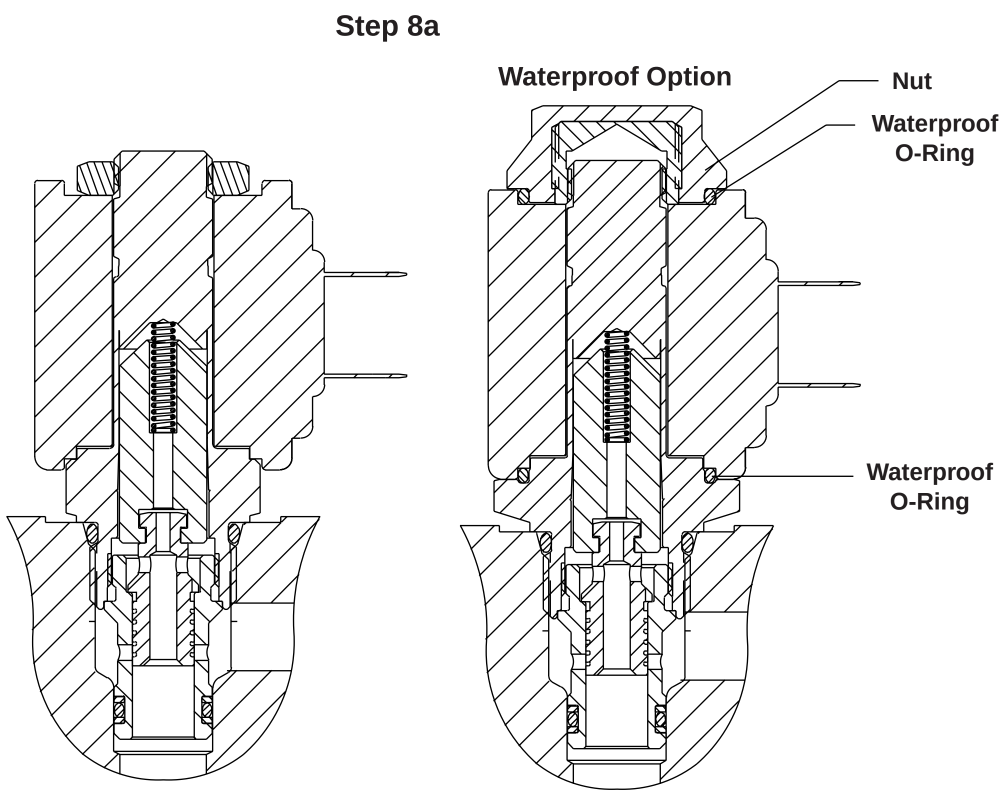
Step 6. Continue to screw in the cartridge with a torque wrench and tighten to the torque specified in the catalog. It is important to use the specified torque for each valve to ensure optimal performance of the cartridge. If the valve is tightened above the specified torque value, this may cause the spool or poppet to stick. This occurs because overtightening the cartridge can deform or collapse the inside of the cage. The diagram to the right shows an example of this. Refer to the catalog for the torque values.



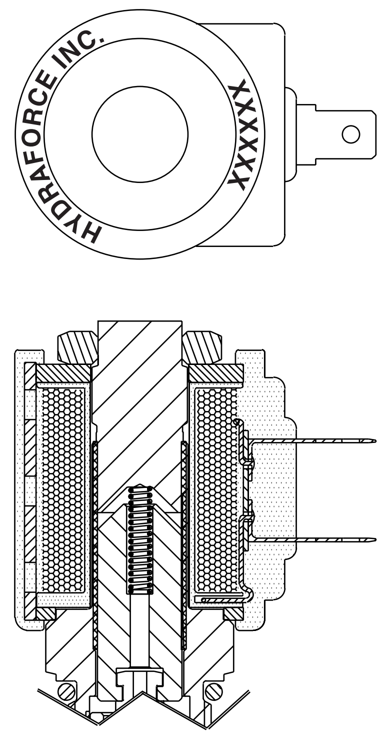


Step 7. Install the waterproof o-ring on the cartridge hex if one is required.

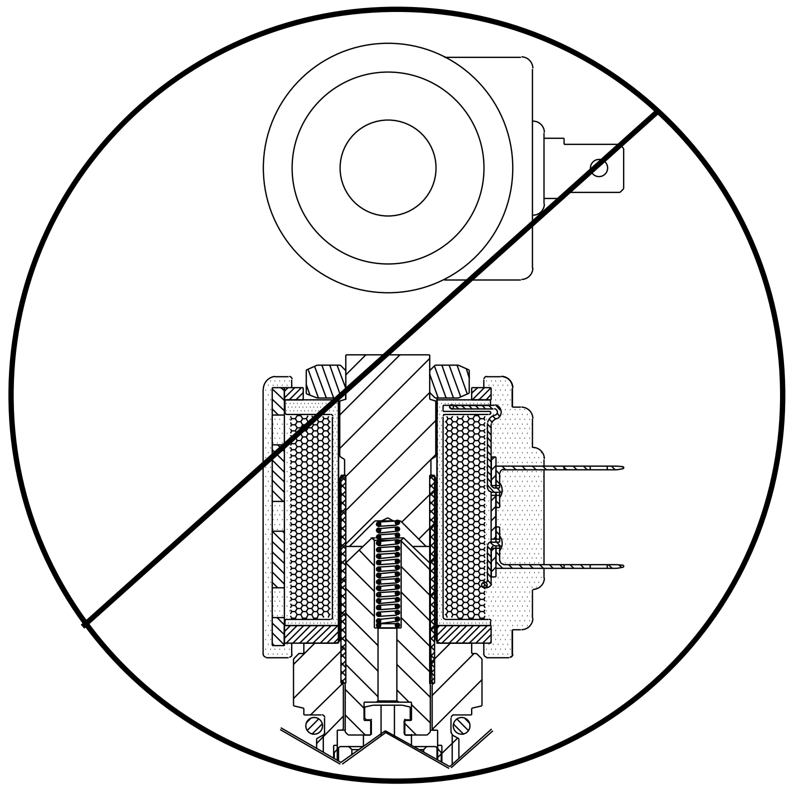
Step 8a. If the valve uses a single coil, install the other waterproof o-ring (if required) and the coil. Install the coil nut and tighten to the torque specified in the catalog.



It is important to install the 08 and 10 size coils correctly to ensure they operate as they were designed to. If the coil is installed upside down, the magnetic flux path is weak and cannot shift the spool or poppet. The diagram below shows an 08 size coil installed correctly and one installed incorrectly. To ensure the coil is right side up, verify that the HydraForce imprint is facing up.



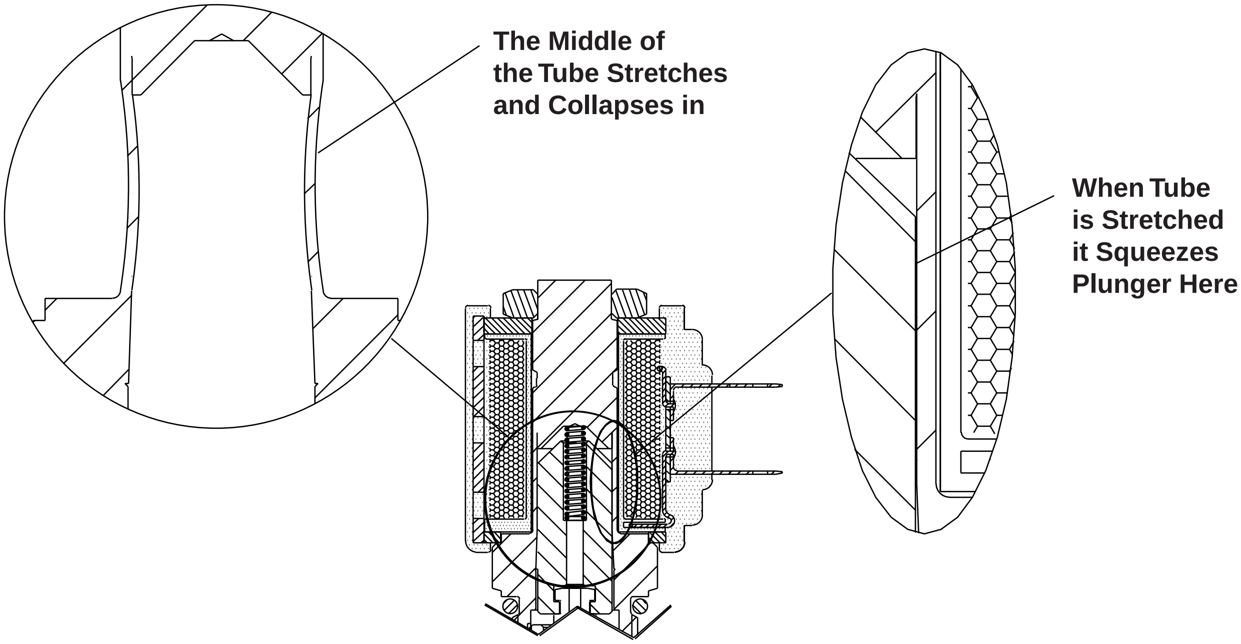
Correct Coil Installation (Lettering Facing Nut Hex)



Incorrect Coil Installation

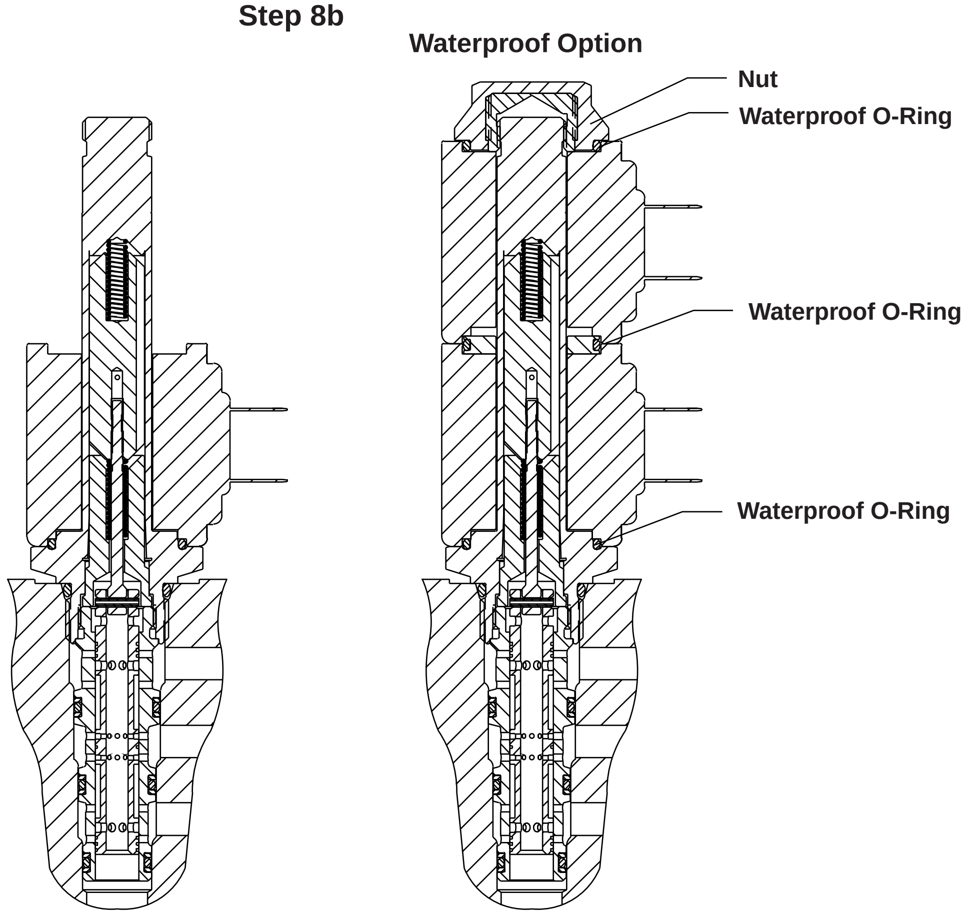
The installation torque specified for the coil nuts is also important. For example, if the nut is tightened above the specification on the 08, 60, 68, 80 size 2 position actuators, the stainless steel tube could stretch. The stretching causes the inside of the tube around the plunger to collapse, which could cause the plunger to get stuck in the energized or de-energized position. This can be seen in the diagram on the following page.

The installation torque is also important on the cartridges which use o-rings for the waterproof option. If the nut is not tightened to the specification, the o-rings will not be sufficiently compressed. This will allow water to leak past the o-ring and potentially cause the winding to fail.



Step 8b

Step 8b. If the valve requires two coils, install them separately. Install the first coil, the washer and the waterproof o-ring (if required). Then install the second coil, and waterproof o-ring (if required).



Troubleshooting

The following section describes several possible valve failures as well as suggested actions to determine if the problem can be easily solved or if further action is necessary.

Potential Failure #1

If the hydraulic system fails to operate as expected, and the valve is suspected as the cause of failure, the following two actions should be done first to determine if the valve is causing the problem.

Possible Cause

There are several possible causes which are listed on the following pages.

Suggested Action

a. Remove the cartridge from the cavity and push on the spool or poppet to see if it moves easily.

b. Hold the valve outside of the cavity. Energize and de-energize the coil to see if the spool or poppet moves. Listen to hear the plunger hitting the pole piece. On the SVXX-20 and 22 type valves, there is a spring pushing down on the poppet even when the coil is energized, therefore, you may not see the poppet move. To determine if the plunger has moved, push on the poppet. It should be easier to move the poppet when it is energized than when it is de-energized.

If you can see the poppet or spool moving, hear the plunger hitting the pole piece and are able to move the spool or poppet with little effort, the cartridge is most likely not the problem. However, if you still suspect the cartridge, move onto further troubleshooting techniques. If you are unable to do any of the above, contact HydraForce for help.

Potential Failure #2

High internal leakage between ports above catalog specification.

Possible Cause

a. Extruded O-ring
b. Contamination causes spool or poppet to stick
c. Fluid viscosity

Suggested Action

a. Remove the cartridge from the cavity and inspect o-rings. If an o-ring is extruded, it can be replaced with a seal kit (consult the catalog for the seal kit). Also, measure the system pressure. If the pressure exceeds the one specified for the o-ring material you are using, contact HydraForce for the correct seal.

b. Remove the cartridge from the cavity and inspect the outside of the cartridge for metal chips and pieces of rubber. If contamination is found, it is recommended that the failed cartridge is sent back to HydraForce. While the external contamination can be cleaned off, internal contamination may still exist.

c. If the fluid viscosity is less than 32 cst, the leakage may be higher than what the catalog specifies.

Potential Failure #3

Cartridge fails to pull in (change from neutral to secondary position).

Possible Cause

a. Contamination causes spool or poppet to stick
b. Cartridge installation torque is too high
c. Cavity diameters are not concentric or in line with one another
d. Stretched tube restricts movement of plunger
e. System flow and / or pressure above valve rating

Suggested Action

a. Refer to potential failure 2b.

b. (See potential failure #1) After verifying that the spool or poppet shifts, reinstall it into the cavity and tighten to the torque specified in the catalog.

c. (See potential failure #1) After verifying that the spool or poppet shifts, remove all o-rings from the cartridge. Screw the cartridge into the cavity by hand until the adaptor hits the body or manifold. If it feels like the valve is binding or rubbing against the cavity, the cavity diameters may not be concentric. If it is determined that the cavities are not concentric, contact HydraForce for further action.

d. (See potential failure #1) There are two ways to tell if the tube is NOT stretched. The first indication is if the spool or poppet move easily when pushed on. The second is if the current required to shift the valve is less than 70% of the nominal voltage divided by the nominal resistance. (This failure only occurs on the 2 position, 08,60, 68 and 80 cartridges). If the spool or poppet does not move easily or the current to shift the valve is higher than 70%, the tube may be stretched. If you determine that the tube may be stretched, return it to HydraForce for review.

e. After performing the steps in action 1a, determine if the valve is being used beyond its pressure and flow rating. First, measure the pressure. Second, if possible, determine the system flow. This can typically be done by multiplying the pump displacement, which is listed in volume per revolution, by the RPM (revolution per minute), of the motor.

Next, if the valve is controlling a hydraulic cylinder, consider if the flow or pressure is being intensified because of the cylinder. In addition, if an accumulator is part of the system, it may be contributing to the problem. The flow from an accumulator may not be regulated or controlled and could exceed the rating of the valve.

Potential Failure #4

Cartridge fails to drop out (change from secondary to neutral position).

Possible Cause

a. See potential failure #3
b. Trickle voltage

Suggested Action

a. Trickle voltage is a term associated with a low level voltage applied to the coil in the off state. This voltage exists in electrical systems that use a solid state relay to actuate. The trickle voltage is typically not a problem for HydraForce valves because the return spring force ensures that the valve will drop out at a mimimum or 5% of nominal room temperature current draw.

Trickle voltage could cause a problem if the valve were applied in a cold ambient environment. When the temperature decreases, the coil resistance decreases causing the current draw to increase.

In addition, if any of the causes noted in Potential Failure #3 exist, and trickle voltage is present, the valve may hesitate or fail to drop out at all. A valve which hesitates is one in which the switch that control it has been turned off and the valve waits several seconds before dropping out.

Suggested Action

Unfortunately no action can be taken if trickle voltage is determined to be a problem. Contact HydraForce for assistance.

Potential Failure #5

High pressure drop

Possible Cause

Contamination causes spool or poppet to stick

Suggested Action

(See potential failure #1) If the spool or poppet moves freely, compare the amount of movement to the same type of cartridge (if available). If the movement appears to be less in the suspect valve, there may be contamination in the valve. Return the valve to HydraForce for review and consult for possible solutions.

Potential Failure #6

The coil is stuck on the tube after the nut is removed.

Possible Cause

The tube may have been over pressurized above the proof pressure.

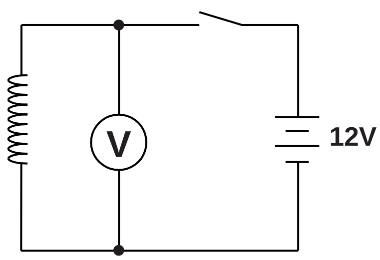
Suggested Action

Pry the coil off. Record the system pressure with a digital pressure transducer. Return the valve to HydraForce and consult for possible solutions.

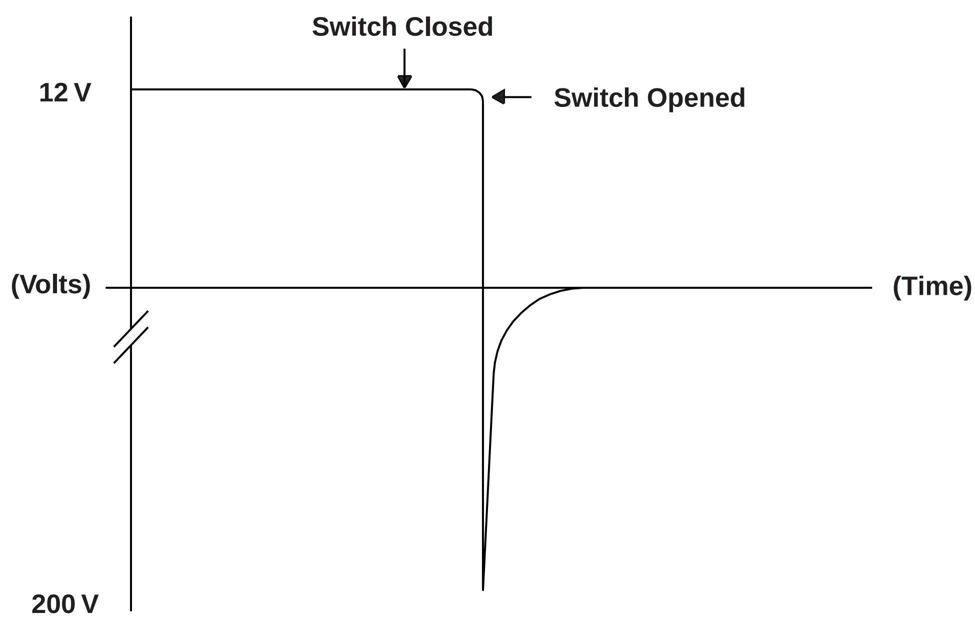
Electrical Considerations

Back EMF

As noted in chapter three, when a solenoid is powered and the power is turned off, the change in magnetic field creates an induced voltage and current. A term commonly used to describe this induced voltage is *back EMF.* It is given this name because the induced voltage or electromotive force is pushing against the externally applied power supply.



The wiring diagram shown to the left shows a coil, switch and battery. Assume that the voltmeter which is connected across the coil measures and records the following graph.

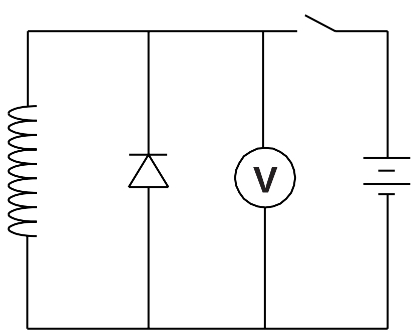


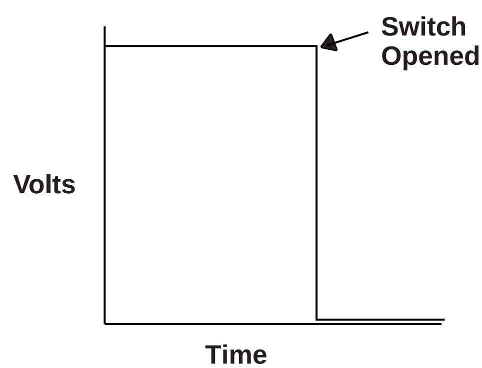
When the switch is closed, the voltage flows in the positive direction from the battery. When opened, the voltage drops to zero and becomes negative. This indicates that the induced voltage is acting in the direction opposite of the battery. The graph shows that this voltage could be as high as 200 - 400 V. However, this negative voltage exists for only a fraction of a second (10 nanoseconds or 10 seconds/ 1,000,000,000) . Therefore, for a very short time a very high voltage exists.

This induced voltage makes an arc or spark jump across the terminals of a switch when it is opened. The spark could potentially damage the switch. To keep back EMF from damaging a switch, a device known as a surge suppressor is used. A surge suppressor keeps the back EMF from jumping across the switch. Instead, it directs this voltage back into the coil. There are several electronic components which can be used as a surge suppressor. These include the diode, varistor and the zener diode and are described in the following section.

Diode

As described in chapter two, a diode is an electronic device which allows voltage and current to flow in one direction only. The diagram below shows a diode connected in parallel with the coil and a graph of the voltage measured when the switch is opened.



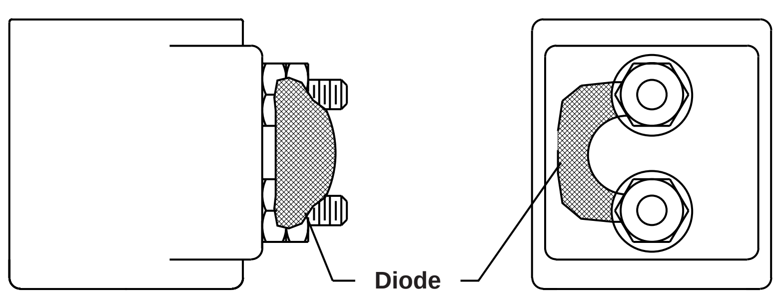


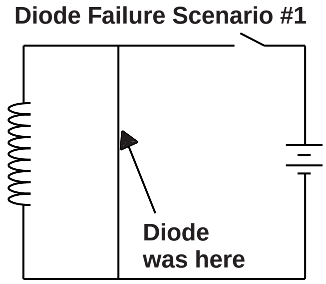
Notice that the voltage goes to zero when the switch is opened. The voltage does not become negative. Rather, it remains at zero. This indicates that the back EMF was eliminated.

The diode shown in the circuit above can either be molded into the coil as the winding is, or it can be connected across the terminals with dual bolts as shown below. The preferred method of installation is molded into the coil.

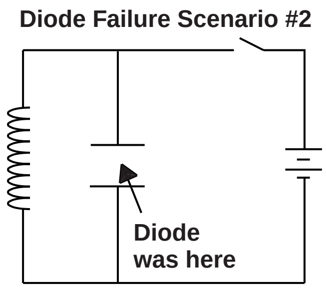
HYDRAFORCE POLICY

The preferred method of installation is molded into the coil.





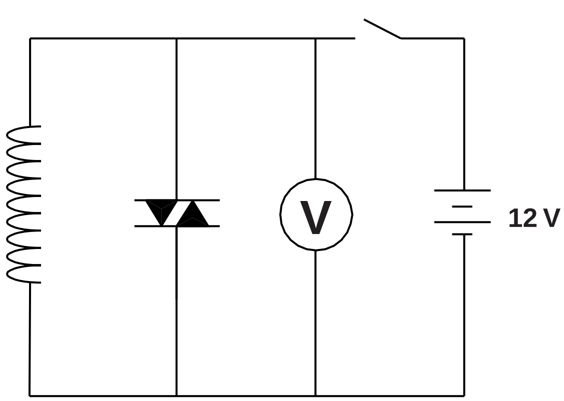
When connecting power to the coil, care must be taken to connect the positive and negative wires to the correct terminal. If the wires are not correctly connected, damage to the diode could occur. When a diode is damaged it can fail in two ways. The first failure which can occur is that it acts as a piece of wire rather than the diode, and has a much lower resistance than the coil winding. Since the resistance is so low, it draws higher current than the coil would have. This high current draw could be above the electrical rating of the electronics or switch which the diode was supposed to protect. The high current draw could cause these components to fail as well.

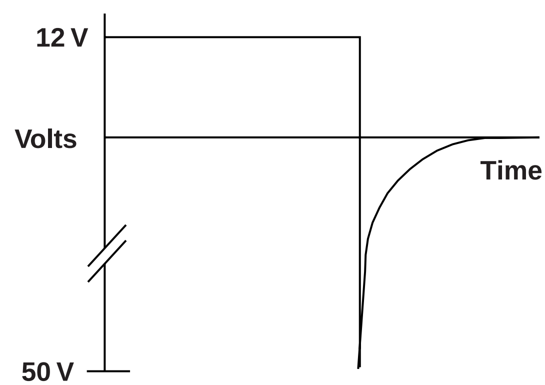


The second type of diode failure is when the diode burns out and is basically no longer part of the circuit. See the diagram to the left. When this occurs, the back EMF creates an arc across the switch, possibly causing it to fail.

Varistor

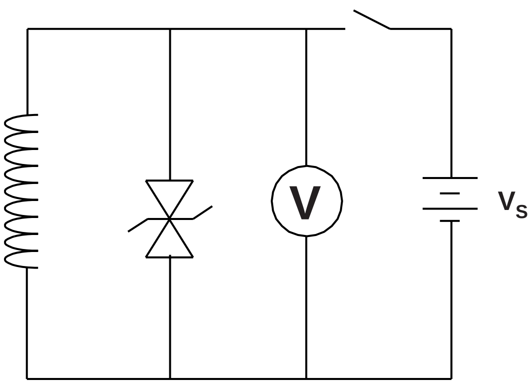
The varistor, like the diode is used to protect the switch from the back EMF. The advantage of the varistor over the diode is that it does not matter which way it is connected to the power supply. Current is blocked from flowing through a varistor until the voltage exceeds a certain level. For example (refer to the diagram below), assume the varistor is connected in parallel across the coil. The graph shows the voltage across the coil. When 12V from the battery is applied to the varistor and coil, all of the current is flowing through the coil because the coil has a much lower resistance. After the switch is opened, the voltage drops and becomes negative, indicating the plunger is moving and creating back EMF. At 50V, the voltage begins to return to zero. At the 50V point, the resistance in the varistor suddenly drops to a very low level and the current can flow through it. This limits the back EMF to a maximum voltage within the level the switch can handle. The voltage level at which this occurs is known as the clamping or limiting voltage, because the back EMF is clamped to a certain level.

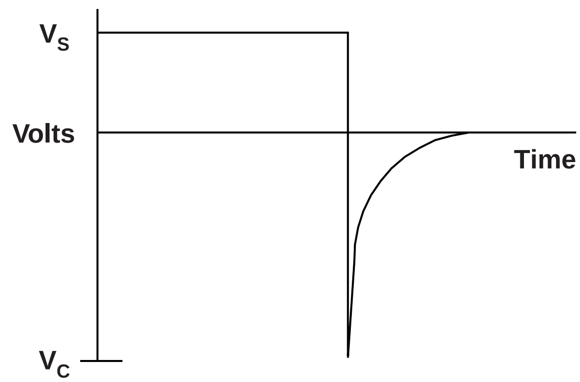




Bidirectional Zener Diode

The bidirectional zener diode is similar in function to the varistor. When the voltage potential across this diode exceeds the rated clamping or limiting voltage of the zener diode , the diode opens to allow that voltage or current to flow through it. The diagram below shows a schematic of the zener diode in parallel with the coil. The graph beside it shows what is happening with the voltage as the switch opens.





V_S is the Battery Voltage
V_C is the Clamping Voltage

V_C for a 12V or 24V system is typically no greater than 50V. This means that when the switch is opened, back EMF still occurs, but is limited to 50V. Switches can typically handle this level of voltage without damage.

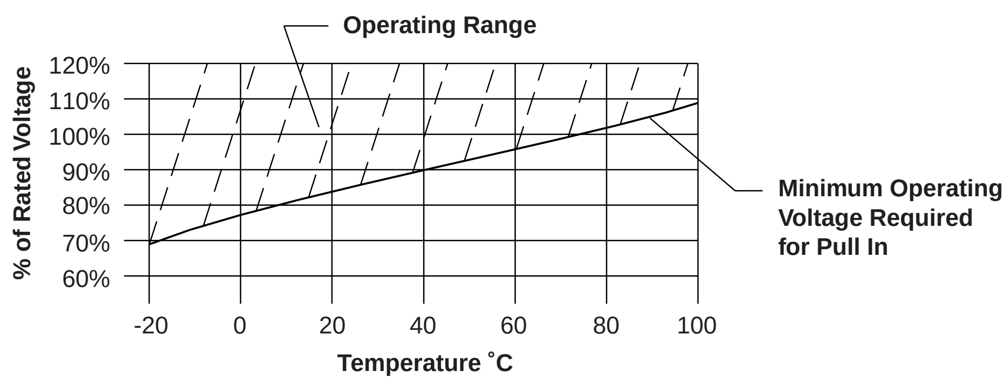
The advantage of using the bidirectional zener diode is that it does not matter how it is wired to the power source. The positive terminal of the power supply can be connected to either terminal of the coil. The disadvantage to having this ability however, is that it is more costly than the standard diode.

The bidirectional zener diode is preferred over the varistor because varistors are easily damaged during the molding process.

Temperature and Pull-in Current

In the previous chapters we mentioned that when the temperature increases, so does the resistance of the coil. This increase in temperature can be from the environment the coil is in, or from power applied to the coil. The resulting resistance determines if the coil will be able to draw sufficient current to operate the valve. Recall the pull in current required for a valve using an 08 size, 10 size or 12 size coil was 840 mAmp, 1140 mAmp or 1850 mAmp, respectively. The graph below shows the voltage required to supply this current at various ambient temperatures, when power is applied continuously. Since the y-axis is given in % of rated voltage, this graph can be applied to any voltage coil. The operating range indicates that at any voltage above the minimum operating voltage line, the coil will draw sufficient current to operate the valve.

Continuous Duty Operation at Various Voltages & Temperatures



If the valves need to be operated with a voltage level lower than the curve in a given ambient temperature, consult HydraForce. The graph shown indicates continuous duty. Many applications power or energize the coil for a short time and de-energize it for at least the same amount of time. If the duty cycle of the solenoid is intermittent, the rule of thumb for the operating voltage is ± 15% of the nominal voltage, up to an ambient of 40^0 C. If the duty cycle is considered light, the valve can be operated in 60^0 C ambient temperature with a voltage range of -10% to +15%.

HYDRAFORCE POLICY

If there is any doubt if the valve will operate in a particular environment, HydraForce should be contacted.

Grounding

HydraForce recommends connecting the ground or the negative terminal of the coil to the source. This should be done through a wire, with one end connected to the coil terminal and the other to the source. While HydraForce does offer coils which are internally grounded, this method has potential problems which are not found in the recommended method. An internally grounded coil basically has the negative terminal connected to the coil shell. Also, recall the shell is in contact with the valve, which is screwed into the manifold. The negative end of the source is connected to the manifold. The problem with this method, however, is that all of the boundaries between different materials are potential points for corrosion. The corrosion acts as an insulator. In addition, the anodized manifold is a potential insulator. Each of these factors contribute to a voltage loss in the circuit.

Cartridge Fluid Compatibility

There are times when a customer wants to use HydraForce valves with a non standard fluid. The following section briefly reviews the fluids which can and cannot be used with HydraForce valves.

The standard HydraForce cartridge valves were designed to be used with petroleum based oils and synthetic oils with lubricating additives. As mentioned in Chapter 9, other seals are available for different fluids, such a brake fluid. HydraForce should also be consulted if the viscosity seems extremely high or low.

In addition to the fluids mentioned above, HydraForce valves have been used in the following fluids:

- water glycol
- diesel fuel
- cutting fluids (used in machining operations)
- biodegradables (used in machining operations)

Consult HydraForce before applying the valves in any of these fluids.

HydraForce valves are NOT compatible with several fluids. These include:

- water
- gasoline
- kerosene
- alcohol

Fluid Resistance

In many applications, the outer surfaces of the cartridge and coil are subjected to a harsh environment. We have already discussed water intrusion. However, some customers are concerned that the product will fail if it comes in contact with various fluids. To determine if there are any concerns, HydraForce cartridges and coils have been subjected to a splash test with the following fluids.

- battery acid
- antifreeze
- screen washer fluid
- Texaco Cold Climate PSF (TL-14315)
- Pentosin
- Dexron III
- Dexron IID
- Chlorinated solvents
- Body and Underbody wax
- Diesel Fuel (BS 2869)
- Distillate
- Wiping fluid
- Brake Fluid
- Grease (lithium soap based)
- Hypoid oil
- Engine oil
- Gasoline

The coils were immersed in each chemical for 30 seconds. After the coils were removed from the chemicals, they were baked for four hours at 50^0 C. This procedure was repeated for a total of three trails.

When the test was completed, the coils still actuated the valves. The only fluid which caused any material degradation was battery acid.

EMI/RFI Issues

Electromagnetic Interference (EMI) and Radio Frequency Interference (RFI) are becoming more common as technology becomes more sophisticated. The use of electronics is a normal occurrence on a large variety of systems. These electronic systems can, and often do interfere with one another. Electronic engines, computers, relay switches, solenoids, cell phones, radios and a great deal of magnetic field producing wire, are all among the systems which can interfere with one another on mobile equipment alone. Thousands more exist in other environments. The challenge now is to determine how these systems can coexist and function as intended.

Electromagnetic Interference is a form of environmental pollution which can be generated from low-power digital circuits to high-power radio antennae. Electronic malfunctions can cause a number of problems including malfunctions in safety equipment, navigation equipment and protective equipment. Radiated emissions can be solved by shielding critical parts and using line filters. This should be done while keeping in mind the effects of harmonics, voltage fluctuations, electrostatic discharge and other factors.

The European community is taking a proactive approach to this problem. The European Commission has ruled that all electrical devices should function effectively despite the existence of electromagnetic interference. Standards and shielding techniques against the interference are being developed. These standards will include rules on the acceptable levels of electrical emissions from low and high voltage industrial equipment as well as noise emissions. However, there is considerable difficulty in creating these standards, since they must apply to such a large variety of products.

At this time, HydraForce has not specifically qualified its product against any general EMI or RFI specification. This issue needs to be addressed at this time on a customer by customer basis.

Summary

In this chapter the following concepts were presented:

- The proper method of installing a coil.
- The proper method of installing the cartridge valve into the cavity.
- The importance of lubricating the seals (or consequences of not).
- Five methods of troubleshooting the cartridge valve operation.
- Review of back EMF and why it occurs.
- Surge supersession methods to avoid damage from EMF.
- How the diode, varistor and zener diode provide surge suppression.
- What EMI is.

Review Questions

Use the following review questions as a measure of your understanding of the chapter material. Answers are provided in the appendix.

1. What term is commonly used to describe the induced voltage when power is turned on and off? ________________________

2. What type of device is used to prevent damage from EMF? ________________________

3. Name the three types of surge suppression methods described. ________________________

4. What is the advantage of the varistor over the diode? ________________________

5. Which surge suppressor is the zener diode similar to in function? ________________________

6. When installing the coil, in which direction should the lettering face? ________________________

7. What step must be taken before inserting the cartridge valve into the cavity? ________________________

8. What could happen to an 08 size cartridge if the nut is overtightened? ________________________

Notes

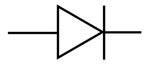
Appendix A:
Answers to Chapter Questions

Introduction

The questions at the end of each of the chapters is designed to test your understanding of the chapter. Use this appendix to verify your answers for the chapter questions.

Chapter 2 Quiz Answers

1. An ohm (Ω) is the unit of electrical resistance.

2. The symbol for a diode can be shown as:  The current is shown flowing to the right.

3. If the resistance increases and the voltage remains constant, the power does NOT increase.
(Hint - use the formula $P = V^2 / R$)

   If the resistance increase and the voltage remains constant, the current does NOT increase.
(Hint - use the formula $I = V / R$)

4. A Voltmeter is used to measure Electromagnetic force.

5. A Voltmeter or an Ammeter can be used to measure power.

6. | Beginning | Ending |
   |---|---|
   | I = 14V / 10.2Ω | I = 9 V / 10.2Ω |
   | I = 1.3725 Amps | I = .8824 Amps |

7. a) calculate the resistance of the wire. (0.2Ω/ ft.) x 30ft = 0.6Ω

   b) multiply a) by 2 for one wire between the battery and coil and another one from the coil to the battery. 2 x 0.6 = 1.2Ω

   c) add the resistance of the wire and coil by assuming they are resistors in parallel
   7.2Ω + 1.2Ω = 8.4Ω

   d) current draw of the system is
   I = V/R
   I = 12V/8.4Ω
   I = 1.43 Amp

   e) voltage drop across the coil
   V = IR
   V = (1.43 Amps) (7.2Ω)
   V = 10.3V

8. If a system can provide 10 watt, this is a measure of power.

9. a) First determine the power:
   $P = I^2 R$
   $P = (2 \text{ amps})^2 (6\Omega)$
   P = 24 watts

   b) Since 24 watts are needed and only 20 watts are available,
   there is **not** sufficient power to drive the coil.

10. $1/R_{total} = 1/4\Omega + 1/5\Omega + 1/8\Omega = 1/\ 0.575\ \Omega = 1.74\Omega$ I = V/R = 24V/ 1.74Ω = 13.8 Amp

11. A full wave bridge rectifier is used to change AC into DC.

Chapter 3 Quiz Answers

1. One reason to increase the number of turns on a solenoid is to increase the magnetic field or flux of the coil.

2. The magnetic filed lines represent the path in which the magnetic field flows.

3. Yes, the current flowing through a wire does affect the direction in which a compass points. The direction in which the compass points indicates the direction in which the magnetic force is exerted.

4. If a piece of iron was in a solenoid and the current was turned on, a steel wrench would be attracted to the iron.

5. The wrench would remain attracted to the iron due to hysteresis (residual magnetism).

6. Ferromagnetism is the ability to acquire high magnetism in relatively weak external magnetic fields.

7. Residual magnetism is magnetism that remains in the iron parts after the solenoid is turned off.

8. The magnetic field is proportional to the number of turns.

Chapter 4 Quiz Answers

1. The parts of the solenoid electromagnetic actuator include: pole piece, armature, solenoid coil winding, yoke (frame), guide tube, push pin.

2. A flat face armature is used when a lot of force at a small air gap is needed.

3. The factors which determine the shape or level of force in the Force vs Air gap curve are:
   a) shape of the pole piece and armature (ie conical or flat face)
   b) current applied
   c) amount of iron in shell
   d) coil resistance / temperature

4. Yes, increasing the shell thickness will increase the force as long as the armature is not saturated.

5. Increasing the current increases the magneto-motive force (NI)

6. a) convert from ^{0}F to ^{0}C (20-32) / 1.8 = -6.67 ^{0}C

   b) determine the resistance at -6.67 ^{0}C
   $R_F = 7.2\Omega\ (1 + 0.00393\ (6.67 - 20))$
   $R_F = 6.44\Omega$

7. The coil can draw more current at the same voltage if the resistance is lower.
   The increased current increases the NI or magneto-motive force.

8. The type of armature to be used against this force is a proportional. The reason for this is the proportional actuator applies constant force regardless of the air gap.

9. The proportional style actuator is the most expensive because there are more detailed features with tighter tolerances. The higher tolerances are required so each actuator is the same, and so that the force is constant regardless of the air gap.

10. The flat face actuator is the least expensive because there is very little detail in these parts.

11. The plunger would be attracted to the pole piece because there is no force opposing it.

Chapter 5 Quiz Answers

1. A magnet wire is insulated to keep each wire from touching the next.

2. HydraForce uses class H, 180^0 wire, with a continuous duty rating of 20,000 hours, as standard in its coils.

3. HydraForce defines continuous duty as having the coil installed in a 100^0 C ambient environment with 115% of rated voltage.

4. The components which make up the frame are the shell and washers.

5. The temperature range in which the coil can operate in is, -40^0 C - 100^0 C.

6. The start slot is used to protect the first wire during winding.

7. The type of termination used in the material handling industry is typically a dual spade.

8. The parts of the coil include: termination, shell, winding and encapsulant.

9. HydraForce uses glass filled $\text{Rynite}_{\text{TM}}$ as standard in coils.

10. The six standard sizes of HydraForce coils are: 01,08,10,12,60 & 70.

11. The voltage range standard coils operate in $\pm$15% of nominal.

12. HydraForce uses the random winding process as standard.

Chapter 6 Quiz Answers

1. The shell is external so that it does not crack the encapsulant when there are extreme temperature changes.

2. Since the dual spade termination is not waterproof, the winding is wound on a bobbin because it is less costly to wind on a bobbin.

3. The inserts are used to protect the winding during molding and provide a location for the terminal pins.

4. The advantages of molding the connector into the coil are that it is weatherproof and does not require strain relief.

5. The advantages of the waterproof coil are that there are no waterproof o-rings and no special nuts or cartridge adaptors.

6. The winding used in the waterproof coil is a bobbin-less or free standing one.

Chapter 7 Quiz Answers

1. The proof pressure of an SF08 tube subassembly is 7000 psi.
2. A spring is present in a solenoid valve to return the valve to the de-energized position.
3. The function of the poppet and cage seat is to keep oil from flowing from port 2 to 1.
4. The cage is heat treated to improve wear resistance.
5. The spool is ground to reduce friction.
6. Brazing is the joining of two parts. HydraForce uses copper for this process.
7. The proof pressure of an SV08 tube subassembly is 3500 psi.
8. The balancing grooves trap oil, which helps center the spool and reduces friction.
9. The plug in the push style tube is made from stainless steel so the plunger is not attracted to it.
10. The "T" slot is a connection between the plunger and spool or pilot pin. It allows for misalignment between the parts so that the parts are still able to move easily.
11. The poppet and poppet cage are made from steel with no lead, because the lead melts during the heat treating process, leaving small voids on the surface which allows oil to leak.
12. HydraForce springs are typically made of music wire.

Chapter 8 Quiz Answers

1. Two ways to measure the actuator force are by connecting a force measuring device (Load Cell) to the plunger or by using Finite Element Analysis.

2. The spring force is not a fixed force, rather it is a variable force.

3. The free length of the spring is the uncompressed length of the spring.

4. The spring force increases when the coil is energized.

5. The Bernoulli force is caused by an acceleration of oil as it goes from a larger passage to a smaller one.

6. When fluid passes from a larger area to a smaller area there is a drop in pressure.

7. The port numbers are a designation for passage of fluid.

8. The term used when the spool allows fluid to pass through to other ports in the transition position is open or negative lap.

9. The term used when the spool does not allow fluid to pass through to other ports in the transition is closed or positive lap.

10. Two types of friction forces discussed in the chapter are mechanical and viscous.

11. The type of force which pulls water together to form a drop is viscous.

12. The area of the pilot pin exposed to low pressure is the area which sits on the seat.

13. The term which describes the de-energized coil is drop out.

14. The forces acting on the spool valve are: actuator force, spring force, flow force and friction force.

15. Pull in occurs when the armature has travelled fully through the air gap from the de-energized to the energized position.

16. The surface finishes of the cage and spool are both less than 10μ in.

17. Pull in of the normally open poppet valve occurs when the coil is energized. The magnetic force overcomes the spring and the plunger pushes down on the push pin and pilot pin. This action closes off the pilot pin seat and then the poppet closes off the cage seat.

18. The pressure force acting on the pilot pin occurs when the pilot pin is seated, because the coil is energized. The pressure acts all around the pilot pin except where it is seated. This small area is why there is a pressure force on the pin.

Chapter 9 Quiz Answers

1. The type of actuator used in the SV08-47A is a 3 position type. It has 2 energized positions and one neutral or de-energized positions.

2. The SV in the model code designates a Solenoid Valve.

3. True. A normally opened valve does allow oil to flow between the two ports when no power is applied.

4. The left side of the hydraulic symbol designates the energized position.

5. A check valve allows flow in one direction.

6. The SV08-47D is known as the motor spool because this valve is often used to control the direction of rotation of the hydraulic motor.

7. HydraForce offers five types of manual overrides.

8. The screen option is used to protect he valve from large contaminants floating through the system.

9. The standard seal type which HydraForce uses is Buna N.

10. The term which describes the hardness of the seal is durometer.

Chapter 10 Quiz Answers

1. The term used to describe the induced voltage when power is turned on and off is back EMF.

2. A surge suppressor is used to prevent damage from back EMF.

3. The three types of surge suppressors discussed are: diode, varistor, bidirectional zener diode.

4. The advantage of the varistor over the diode is that it does not matter which way you connect the varistor to the power supply.

5. The zener diode is similar in function to the varistor.

6. When installing the coil, the lettering should face up (facing the hex nut).

7. Before the cartridge is inserted into the cavity, it should be properly lubricated to allow the seals to slide more easily, as well as preventing extrusion.

8. If the nut on the 08 size cartridge is overtightened, the spool or poppet may stick, due to the inside of the cage being deformed or collapsed.

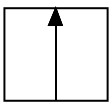
Appendix B:
Hydraulic Symbols

Introduction

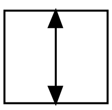
This appendix introduces the basic symbols used in hydraulic schematics. An explanation is provided on the basic building blocks used to generate the symbol for a solenoid valve. In addition to the hydraulic symbols, some general symbols frequently used in hydraulic schematics are also shown. In addition, examples are also provided to clarify the symbol generation process.

Basic Hydraulic Symbols

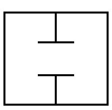
The basic symbol for a hydraulic valve is a rectangle, which represents the valve enclosure. Lines within the rectangle indicate the flow directions between the valve inlet and outlet openings. These openings are known as *ports*. Either a single rectangle or multiple rectangles are used to show the change in flow conditions. A single rectangle is used to show that only one flow path exists through the valve. Multiple rectangles indicate more flow paths, and show how the path is changed.



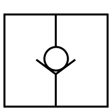
A single arrow represents oil flowing from one port. The arrow indicates which direction the oil is flowing.



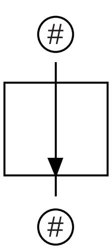
An arrow in each direction represents oil flowing to and from either port.



The “T” (tee) indicates that oil is blocked from flowing to or from that port. Two Ts indicated that the flow is blocked at both ports shown. This symbol implies that the hydraulic control element within the valve is a spool.

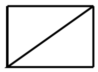


This symbol represents the check valve symbol. It indicates that the top port is blocking the flow of oil to the bottom port. It is implied that when the pressure at the bottom port exceeds the pressure at the top port, oil can flow from the bottom to the top port. It is further implied that the construction consists of a ball or poppet on a seat.

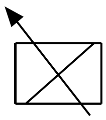


The numbers within the circles in this symbol represent the port numbers and the direction of flow. In addition, their location on the symbol indicates the neutral position of the valve. Small lines are added to the outsideof the box to further indicate the ports.

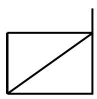
In addition to these symbols, there another set which indicate how the valve is being controlled, or how it changes position. These symbols are smaller than the first set and are shown to the right or left of the rectangle which they control. These are shown below.



This symbol indicates a solenoid coil and can be attached to either side of the symbols shown on the previous page. If the symbol contains two slash marks in opposite directions, it indicates that there are two solenoid coils acting. The armatures can be actuated in two directions.

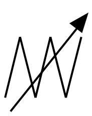


Variable power applied to the coil is represented in this symbol.

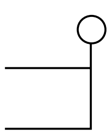


A coil with a manual override is represented in this symbol.

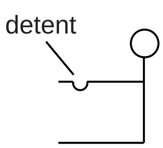
This symbol indicates a spring and can be attached to either side of the box.



This symbol indicates a spring with a variable setting.

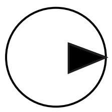


This symbol represents a manual operator.

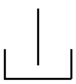


This symbol represents a manual operator with detent.

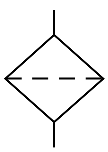
The following symbols are general symbols which are frequently used in describing hydraulic applications.



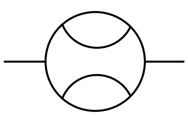
PUMP



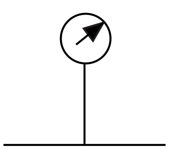
TANK (RESERVOIR)



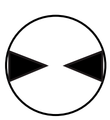
FILTER



FLOW METER



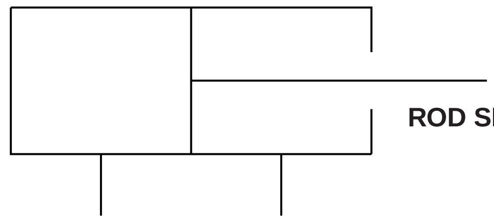
PRESSURE SENSOR



HYDRAULIC MOTOR

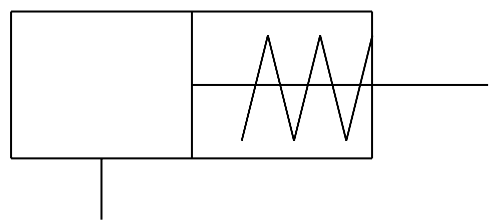
DOUBLE ACTING CYLINDER

BLIND SIDE



ROD SIDE

SPRING RETURN SINGLE ACTING CYLINDER

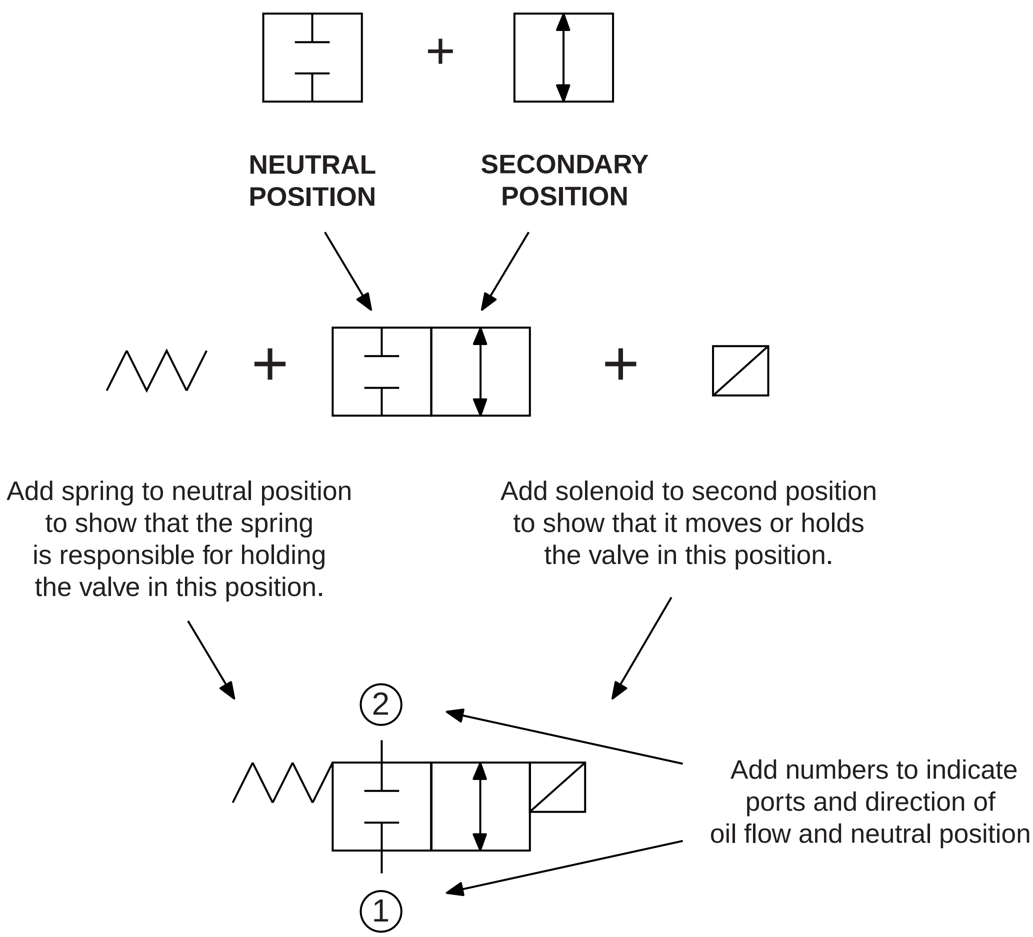


The following section walks through some examples of various symbols for solenoid directional control valves.

Create a symbol for a valve with two ports that blocks flow in the neutral position (or when no power is applied to the solenoid). In the second position, both ports are connected, allowing flow in either direction. Assume the spring holds the valve in the neutral position and the solenoid moves the valve into the secondary or energized position. Also assume that the valve is a spool type. To summarize these criteria:

- 2 ports
- neutral position, (both blocked)
- spool type
- energized position, (flow in both directions)

The symbol for these criteria is:



In this example we will create a symbol for a valve with three ports.
The symbol will include:

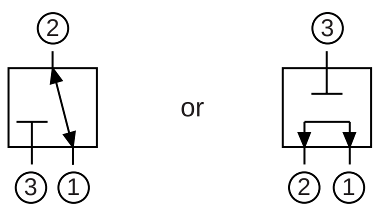
- flow paths

  neutral position: port 2 is connected to 1, flow is allowed in both directions, port 3 is blocked

  second position: port 2 and 3 are connected, flow is bidirectional, port 1 is blocked

- spool type valve
- spring holds the valve in the neutral position
- solenoid coil holds the valve in the second position

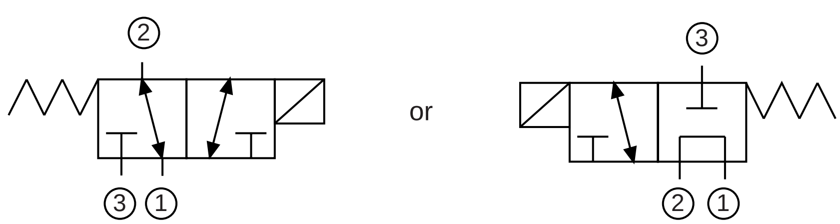
Draw Box for Neutral Position



(there can be several variations)

Draw Box for Secondary Position

Combine steps 1 and 2. Add spring next to the neutral position
and add solenoid next to secondary position.



Notice that the neutral position on the symbol shown to the right is on the right side of the symbol. By convention, because we read from right to left, the neutral position is typically on the right, but can also be shown on the left.

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