

PETER PAUL ELECTRONICS

# Solenoid Valves 101

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## Whitepaper

By Engineering Department at Peter Paul

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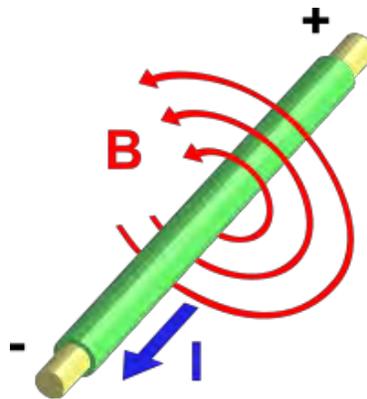
## Definitions

**Valve** is a device that regulates the flow of a fluid (gases, fluidized solids, slurries, or liquids) by opening, closing, or partially obstructing various passageways.

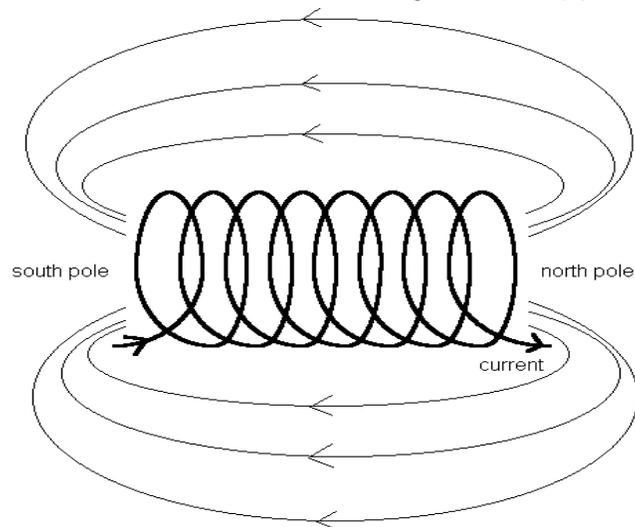
**Solenoid** is a three-dimensional coil. In physics, the term **solenoid** refers to a loop of wire, often wrapped around a metallic core, which produces a magnetic field when an electric current is passed through it. Solenoids are important because they can create controlled magnetic fields and can be used as electromagnets. The term *solenoid* refers specifically to a magnet designed to produce a uniform magnetic field in a volume of space.

Current ( $I$ ) through a wire produces a magnetic field ( $B$ ) around the wire.

- The field is oriented according to the “right hand rule”.



When wound in the form of a coil, the magnetic field ( $B$ ) is as follows:



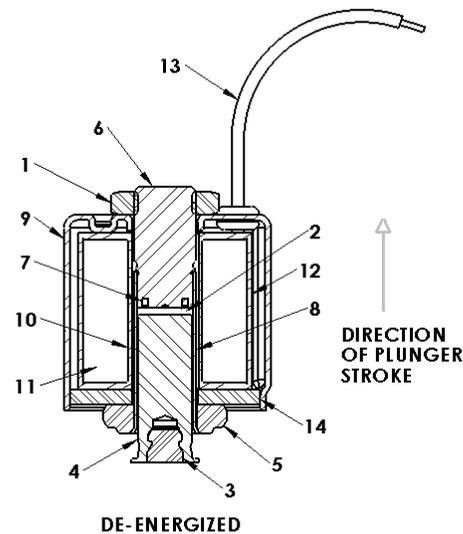
*Solenoid coil shown with magnetic field*

- In engineering, the term **solenoid** may also refer to a variety of transducer devices that convert electrical energy into linear motion.
- Electromechanical solenoids consist of an electromagnetically inductive coil, wound around a movable steel or iron slug (termed the armature or in a solenoid valve it is called the plunger). The coil is shaped such that the armature can be moved in and out of the center, altering the coil's inductance and thereby becoming an electromagnet. The armature is used to provide a mechanical force to some mechanism (such as controlling a pneumatic valve). Although typically weak over anything but very short distances, solenoids do generate enough force to overcome the internal forces found in small orifice valves and thus can be used to change the state of these valves.
- The force applied to the armature (or plunger) is proportional to the change in inductance of the coil with respect to the change in position of the armature, and the current flowing through the coil. The force applied to the armature will always move the armature in a direction that increases the coil's inductance.
- The magnetic field inside a solenoid is given by:

$$B = \mu_0 n I = \mu_0 \frac{NI}{h}$$

Where  $B$  is the magnetic field magnitude in teslas,  $n$  is the number of turns per meter,  $I$  is the current in amperes,  $N$  is the number of turns and  $h$  is the length of the solenoid in meters.

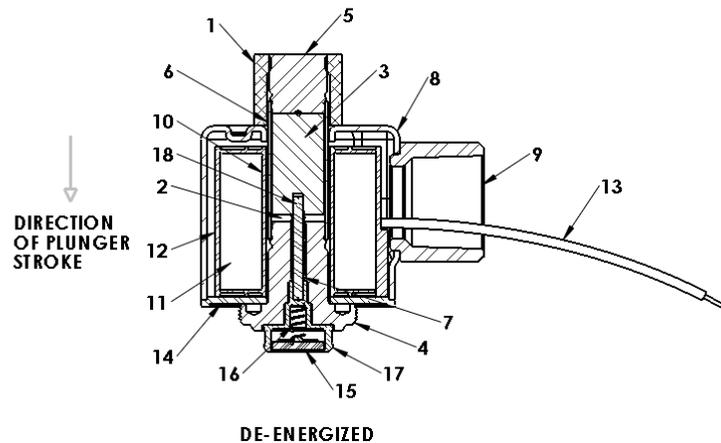
- **Solenoids convert** electrical energy into force and motion. When the coil is energized with electric current an electro-magnetic force is created around the coil. Enclosed solenoids are designed to direct that magnetic force through a steel housing surrounding the coil and into the stop and armature (plunger). The stop becomes a north or south pole face depending on the polarity of the coil. The armature becomes the opposite pole face. These opposite poles are attracted to one another and this creates the force and motion in the armature.
- **The amount of force** created is related to the strength of the magnetic field ( $B$ ). The magnetic field strength is proportional to the amount of electrical current applied. Other factors such as the number of turns of wire in the coil, the size of the solenoid, and the magnetic characteristics of the steel used will affect the amount of force developed.
- **The force is** also dependent on the air gap or stroke of the solenoid. The force is lowest at the maximum air gap and highest when the pole faces are fully seated. In general the force is inversely proportional to the square of the distance (gap) between pole faces.



## Cross Section of Solenoids

1. **Top Nut** - Used to hold down the Housing, Coil and Flux Plate.
2. **Stroke** - The distance the plunger will move when energized.
3. **Rubber Insert** - Used to seal against an orifice found in a valve body.
4. **Plunger** - High quality, magnetic steel, typically 430F grade stainless steel, acts as the armature and is the movable pole piece in the solenoid.
5. **Threaded Flange Nut** - Used to thread the sleeve assembly into a mating body, is welded to the Sleeve Tube. (Part of the Sleeve Assembly)
6. **End Stop** - High quality magnetic steel, typically 430F grade stainless steel, welded to the Sleeve Tube. Is used as the attracting pole for the Plunger. (Part of the Sleeve Assembly)
7. **Shading Ring** - An electrically conductive ring, typically of copper, pressed into the End Stop and used in AC powered solenoids to maintain force on the plunger during zero crossing of the coil current. (Part of the Sleeve Assembly)
8. **Sleeve Tube** - Nonmagnetic stainless steel that connects the End Stop and the Threaded Flange Nut. (Part of the Sleeve Assembly)
9. **Housing** - High quality magnetic steel with corrosion protected surface not only protects the coil but also serves as magnetic flux path around the outside of the coil.
10. **Molded Bobbin** - Typically made of a glass filled molded thermoplastic that insulates the windings from the Sleeve, Housing and Flux Plate. (Part of the Coil Assembly)
11. **Magnet Wire** - Insulated wire, automatically wound directly on bobbin. (Part of the Coil Assembly)
12. **Outer Coil Insulation** - Typically electrical tape and or plastic encapsulant that insulates the outer coil windings from metal housing and also holds coil wires in place. (Part of the Coil Assembly)
13. **Lead Wires** - To be connected to the switching electrical power source that is to drive the solenoid. (Part of the Coil Assembly)
14. **Flux Plate** - High quality magnetic steel with corrosion protected surface not only protects the base of the coil but also serves as magnetic flux path from the Housing to the Plunger.

Force created by solenoid - Energizing the coil in the picture above will cause an attraction force between the Plunger and the End Stop which will cause the movable Plunger to move in the upward direction.



1. **Top Nut** - Used to hold down the Housing, Coil and Flux Plate.
2. **Stroke** - The distance the plunger will move when energized.
3. **Plunger** - High quality, magnetic steel, typically 430F grade stainless steel, acts as the armature and is the movable pole piece in the solenoid. (Part of the Sleeve/Plunger Assembly)
4. **Threaded Flange Nut** - Used to thread the sleeve assembly into a mating body, is welded to the Sleeve Tube. In a push solenoid, it is also the attracting pole for the Plunger. (Part of the Sleeve/Plunger Assembly)
5. **End Stop** - Non magnetic steel, typically 303 grade stainless steel, welded to the Sleeve Tube. Is used as the resting stop for the Plunger. (Part of the Sleeve/Plunger Assembly)
6. **Sleeve Tube** - Nonmagnetic stainless steel that connects the End Stop and the Threaded Flange Nut. (Part of the Sleeve/Plunger Assembly)
7. **Return Spring** - Used to hold the Plunger in the open position. (Part of the Sleeve/Plunger Assembly)
8. **Housing** - High quality magnetic steel with corrosion protected surface not only protects the coil but also serves as magnetic flux path around the outside of the coil.
9. **Conduit Boss** - Attached to the Housing and used to connect to electrical trade conduit.
10. **Molded Bobbin** - Typically made of a glass filled molded thermoplastic that insulates the windings from the Sleeve, Housing and Flux Plate. (Part of the Coil Assembly)
11. **Magnet Wire** - Insulated wire, automatically wound directly on bobbin. (Part of the Coil Assembly)
12. **Outer Coil Insulation** - Typically electrical tape and or plastic encapsulant that insulates the outer coil windings from metal housing and also holds coil wires in place. (Part of the Coil Assembly)
13. **Lead Wires** - To be connected to the switching electrical power source that is to drive the solenoid. (Part of the Coil Assembly)
14. **Flux Plate** - High quality magnetic steel with corrosion protected surface not only protects the base of the coil but also serves as magnetic flux path from the Housing to the Plunger.
15. **Rubber Insert** - Used to seal against an orifice found in a valve body.
16. **Poppet Spring** - Used to aid in holding the Rubber Insert down to seal against an orifice found in a valve body when the solenoid is energized.
17. **Poppet** - Connected to the push rod and used to house the Rubber Insert.
18. **Push rod** - Non magnetic stainless steel used to transfer force and motion from the Plunger to the Poppet.

Force created by solenoid - Energizing the coil in the picture above will cause an attraction force between the Plunger and the End Stop which will cause the movable Plunger to move in the downward direction.

### **Solenoid Connected to a Valve Body**

The mechanical force created by a solenoid can be used to change the state of a valve.

A solenoid valve has two main parts: the solenoid and the valve body. The solenoid converts electrical energy into mechanical energy which, in turn, changes the state of the valve mechanically.

## Valve Type and Function

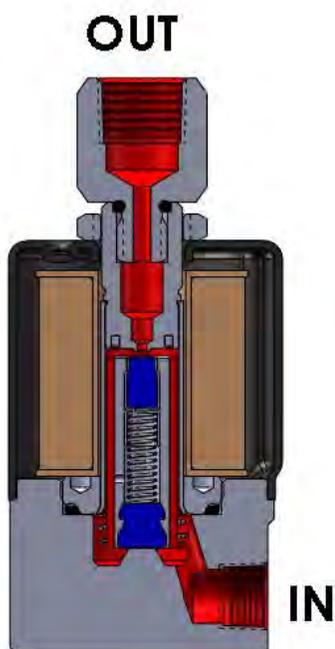
- The basic Peter Paul valves are electromagnetically actuated direct operating, solenoid valves with resilient inserts that seal upon a finely machined orifice. (Note in the drawings below, the color red indicates media in the valve.)

### 2-Way Valve

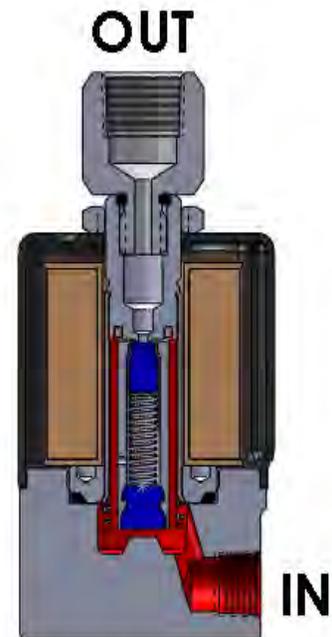
- A valve that has a single orifice which may be normally open or normally closed

### 2-Way Normally Open Traditionally Plumbed

- A traditionally plumbed 2 way normally open valve the inlet port is the body cavity port and the outlet port is the sleeve port. In the de-energized state, flow travels from the inlet port to the outlet. In the energized state, the flow is blocked by the plunger at the sleeve orifice.
- In the energized state, the inlet pressure creates a sticking force between the top of the plunger and the sleeve orifice. (Force = Inlet pressure x orifice area). In this style valve, the external spring must be strong enough to break away the plunger from the top orifice upon de-energizing.



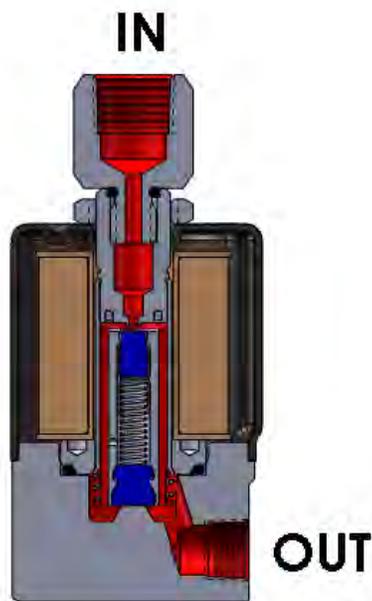
**2 WAY NORMALLY OPEN  
DE-ENERGIZED**



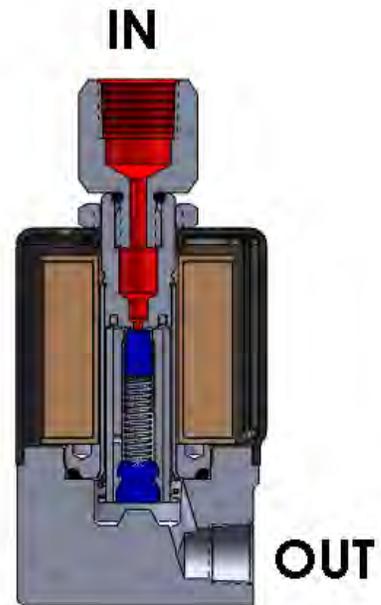
**2 WAY NORMALLY OPEN  
ENERGIZED**

## 2-Way Normally Open Reverse Plumbed

- A reversed plumbed 2 way normally open valve the outlet port is the body cavity port and the inlet port is the sleeve port. In the de-energized state, flow travels from the inlet port to the outlet. In the energized state, the flow is blocked by the plunger at the sleeve orifice.
- In the energized state, the inlet pressure creates a force on the top of the plunger top seal. (Force = Inlet pressure x orifice area). In this style valve, the internal spring must be strong enough to hold back the inlet pressure without cracking open.



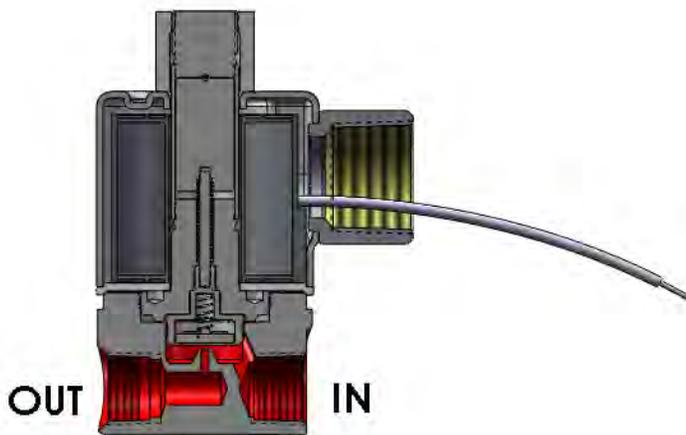
**2 WAY NORMALLY OPEN  
REVERSE PLUMBED  
DE-ENERGIZED**



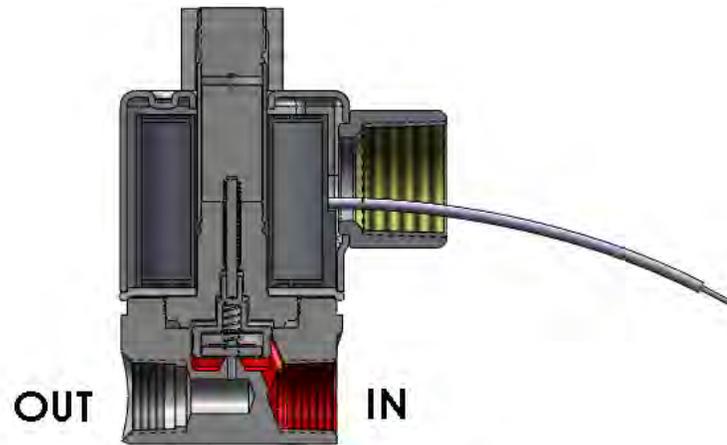
**2 WAY NORMALLY OPEN  
REVERSE PLUMBED  
ENERGIZED**

## 2-Way Normally Open All Ports in Body

- A 2 way normally open, all ports in body, valve contains both ports in the body. The inlet port is the cavity port and the outlet port is the orifice port. In the de-energized state, flow travels from the inlet port to the outlet. This style valve requires the solenoid to push the plunger down onto the orifice. In the energized state, the flow is blocked by the plunger at the body orifice.
- In the energized state, the inlet pressure creates a sticking force between the top of the plunger and the body orifice. (Force = Inlet pressure x orifice area). In this style valve, the return spring must be strong enough to break away the plunger from the body orifice upon de-energization.



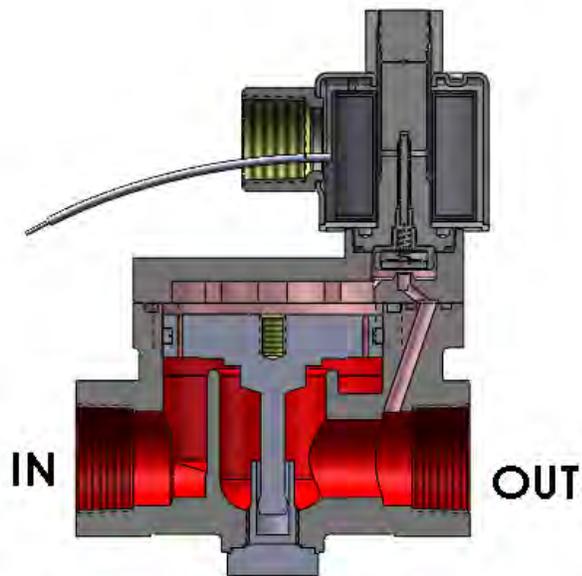
**2 WAY NORMALLY OPEN  
ALL PORTS IN BODY  
DE-ENERGIZED**



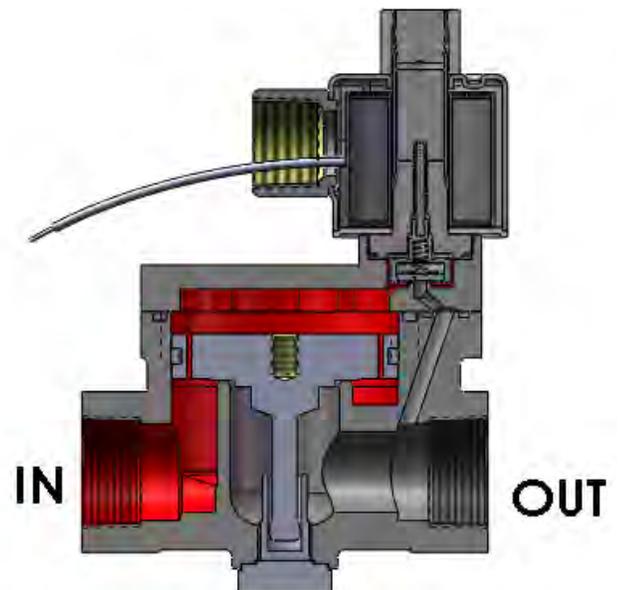
**2 WAY NORMALLY OPEN  
ALL PORTS IN BODY  
ENERGIZED**

## 2-Way Normally Open Pilot Operated

- In a pilot operated 2 way normally open valve the inlet port is the body cavity port and the outlet port is the body orifice port. In the de-energized state, pilot flow creates an imbalance of pressure on two sides of a diaphragm or piston and causes it to shift open. The pilot pressure is controlled by a 2 way normally open solenoid similar the “all ports in body” version. In this state, flow travels from the inlet port to the outlet port.
- In the energized state, pilot flow to the diaphragm or piston is blocked causing the reverse imbalance in pressure to close the diaphragm or piston to the orifice.



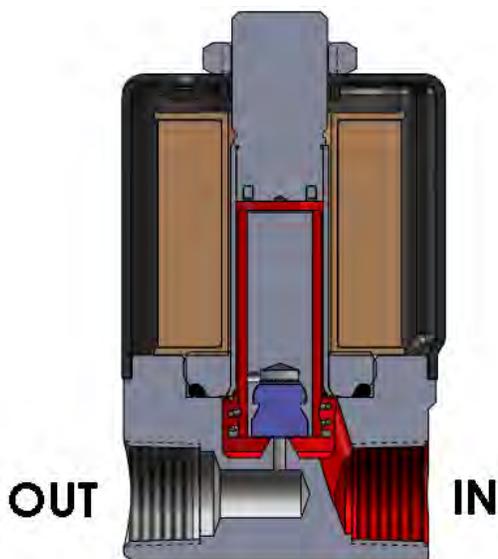
**2 WAY NORMALLY OPEN  
PILOT OPERATED  
DE-ENERGIZED**



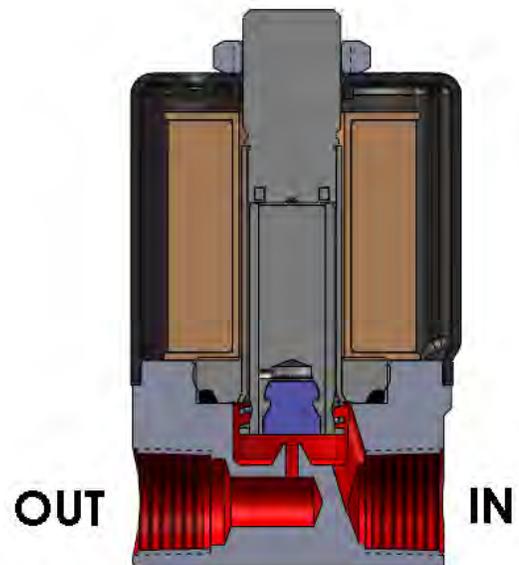
**2 WAY NORMALLY OPEN  
PILOT OPERATOR  
ENERGIZED**

## 2-Way Normally Closed Traditional Plumbed

- A 2 way normally closed traditionally plumbed valve contains both ports in the body. The inlet port is the cavity port and the outlet port is the orifice port. In the energized state, flow travels from the inlet port to the outlet.
- In the de-energized state, the inlet pressure creates a sticking force between the bottom plunger seal and the body orifice. (Force = Inlet pressure x orifice area). In this style valve, the force generated by the solenoid must be strong enough to break away the plunger from the body orifice upon energizing.
- Since the pressure acts to aid the sealing between the plunger seal and orifice, inlet pressure excursions beyond the rating of the valve will not cause internal leaking through the orifice. For this reason, this style valve can be considered a Safety Shutoff Valve.



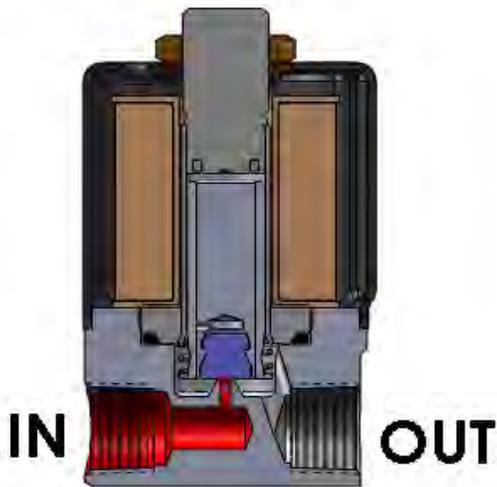
**2 WAY NORMALLY CLOSED  
DE-ENERGIZED**



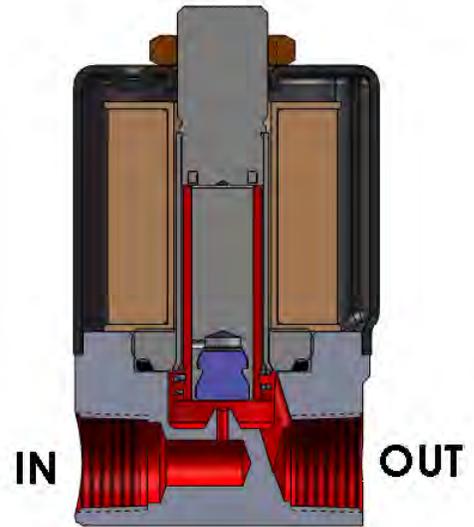
**2 WAY NORMALLY CLOSED  
ENERGIZED**

## 2-Way Normally Closed Reverse Plumbed

- A 2 way normally closed reversed plumbed valve contains both ports in the body. The inlet port is the orifice port and the outlet port is the cavity port. In the energized state, flow travels from the inlet port to the outlet.
- In the de-energized state, the inlet pressure creates a force on the bottom of the plunger seal. (Force = Inlet pressure x orifice area). In this style valve, the external spring must be strong enough to hold back the inlet pressure without cracking open.



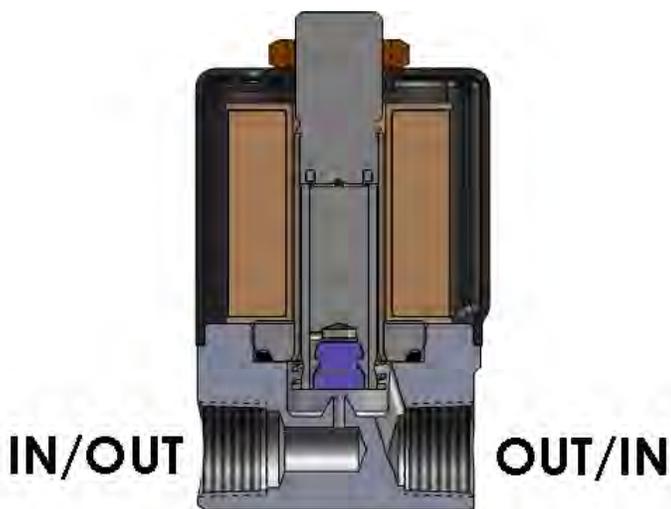
**2 WAY NORMALLY CLOSED  
REVERSE PLUMBED  
DE-ENERGIZED**



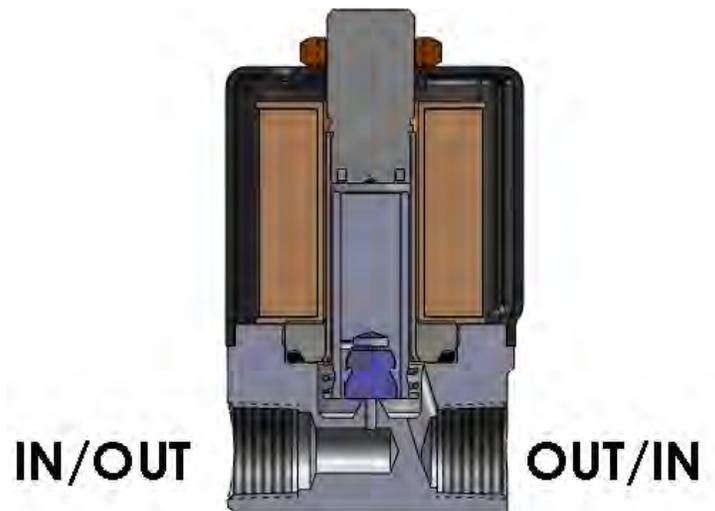
**2 WAY NORMALLY CLOSED  
REVERSE PLUMBED  
ENERGIZED**

## 2-Way Normally Closed Bi-Directional

- A 2 way normally closed bi-directional valve contains both ports in the body. Either port can be the inlet or outlet. In the energized state, flow travels from one port to the other depending on pressure differential direction.
- Depending on the direction of the differential pressure, the pressure will either aid in sealing across the orifice (pressure over seat) or create a force under the plunger which will have to be held back by the external plunger return spring.



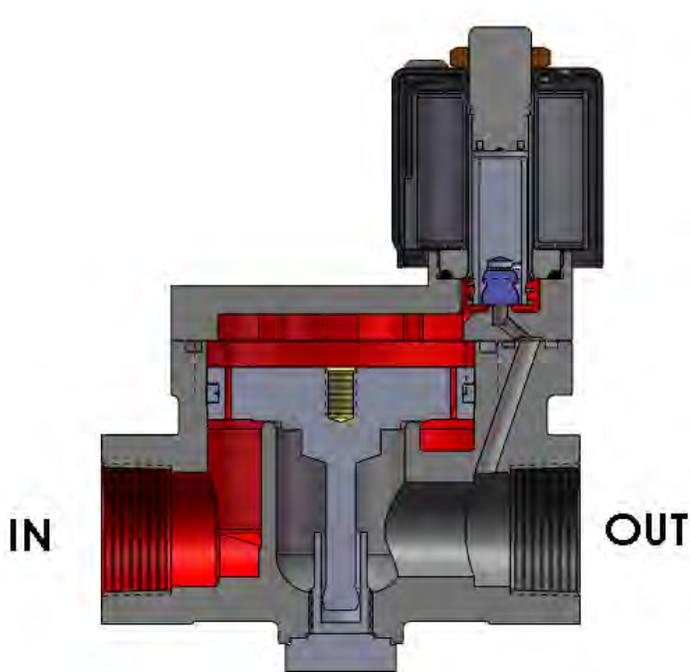
**2 WAY NORMALLY CLOSED  
BI-DIRECTIONAL  
ENERGIZED**



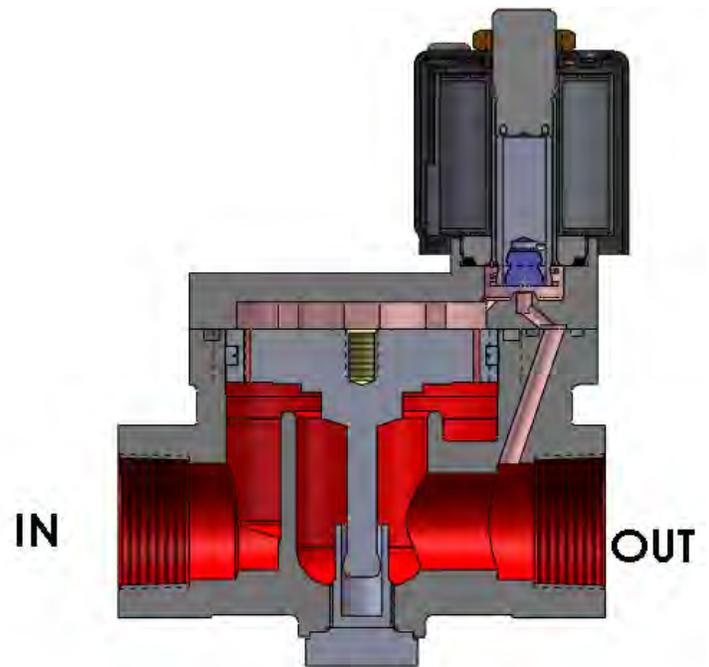
**2 WAY NORMALLY CLOSED  
BI-DIRECTIONAL  
DE-ENERGIZED**

## 2-Way Normally Closed Pilot Operated

- In a pilot operated 2 way normally closed valve the inlet port is the body cavity port and the outlet port is the body orifice port. In the energized state, pilot flow creates an imbalance of pressure on two sides of a diaphragm or piston and causes it to shift open. The pilot pressure is controlled by a 2 way normally closed solenoid traditionally plumbed. In this state, flow travels from the inlet port to the outlet port.
- In the de-energized state, pilot flow to the diaphragm or piston is blocked causing the reverse imbalance in pressure to close the diaphragm or piston to the orifice.



**2 WAY NORMALLY CLOSED  
PILOT OPERATED  
DE-ENERGIZED**



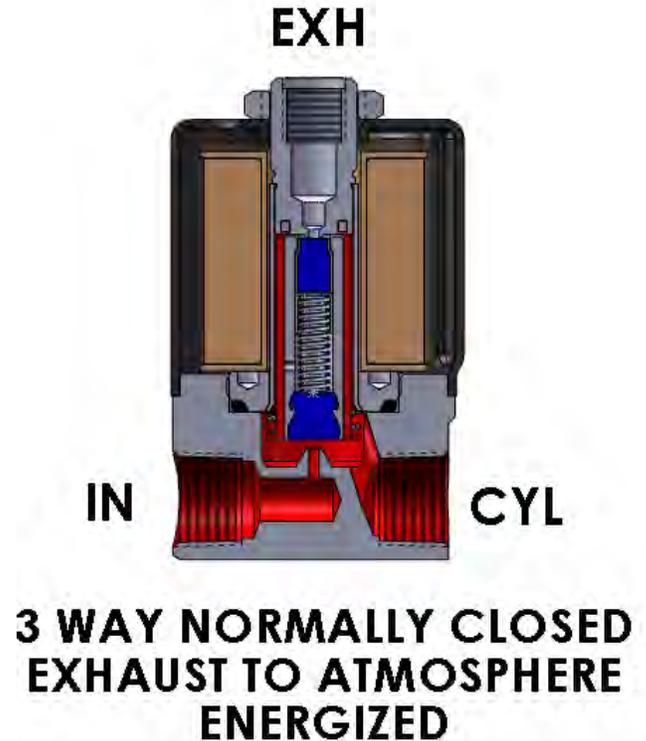
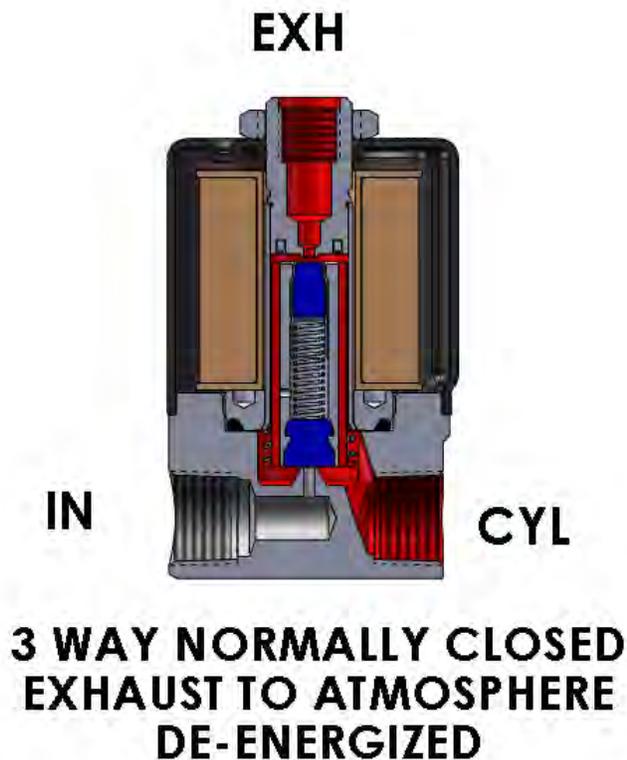
**2 WAY NORMALLY CLOSED  
PILOT OPERATOR  
ENERGIZED**

### 3-Way Valve

- A valve that has two orifices and three ports. One orifice is always open when the other is closed and one port is always open to one of the other two ports. Flow is controlled by opening or closing either of the two orifices.

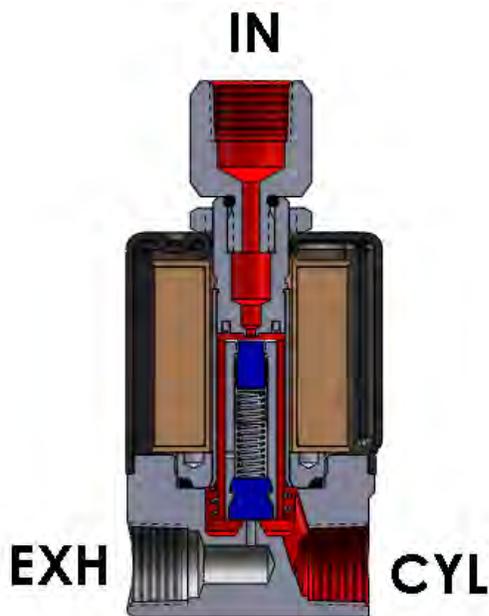
### 3-Way Normally Closed

- A valve in which the inlet orifice is closed and the exhaust orifice is open to the cylinder port in the de-energized position. In this position, no flow can exist between the inlet and cylinder ports and full flow can exist between the cylinder and exhaust ports.
- In the de-energized state, the inlet pressure creates a force on the bottom of the plunger seal. (Force = Inlet pressure x orifice area). In this style valve, the external spring must be strong enough to hold back the inlet pressure without cracking open.
- In the energized state, the inlet pressure creates a sticking force between the top of the plunger and the sleeve orifice. (Force = Inlet pressure x orifice area). In this style valve, the external spring must be strong enough to break away the plunger from the top orifice upon de-energizing.

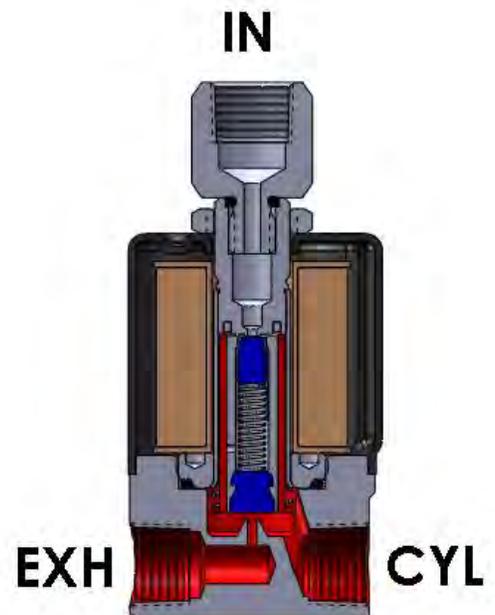


### 3-Way Normally Open

- A valve in which the inlet orifice is open and the exhaust orifice is closed in the de-energized position. In this position, full flow can exist between the inlet and cylinder ports and no flow can exist between the cylinder and exhaust ports.
- In the de-energized state, the inlet pressure creates a sticking force between the bottom plunger seal and the body orifice. (Force = Inlet pressure x orifice area). In this style valve, the force generated by the solenoid must be strong enough to break away the plunger from the body orifice upon energizing.
- In the energized state, the inlet pressure creates a force on the top of the plunger top seal. (Force = Inlet pressure x orifice area). In this style valve, the plunger internal spring must be strong enough to hold back the inlet pressure without cracking open.



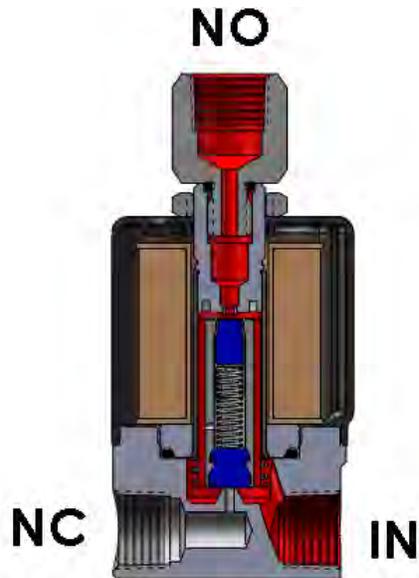
**3 WAY NORMALLY OPEN  
DE-ENERGIZED**



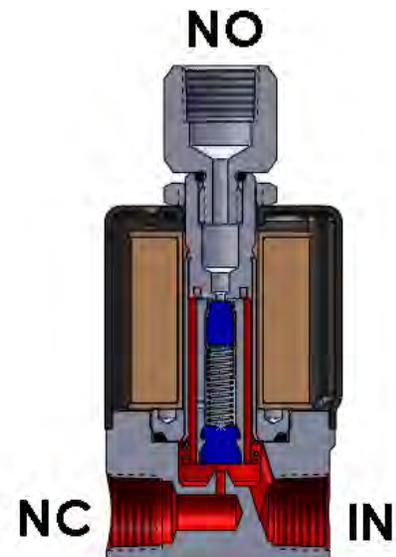
**3 WAY NORMALLY OPEN  
ENERGIZED**

### 3-Way Directional Control

- A valve in which the inlet is open to the normally open port when the coil is de-energized and open to the normally closed port when the coil is energized.
- In the de-energized state, the inlet pressure creates a sticking force between the bottom plunger seal and the body orifice. (Force = Inlet pressure x orifice area). In this style valve, the force generated by the solenoid must be strong enough to break away the plunger from the body orifice upon energizing.
- In the energized state, the inlet pressure creates a sticking force between the top of the plunger and the sleeve orifice. (Force = Inlet pressure x orifice area). In this style valve, the external spring must be strong enough to break away the plunger from the top orifice upon de-energizing.



**3 WAY DIRECTIONAL CONTROL  
DE-ENERGIZED**

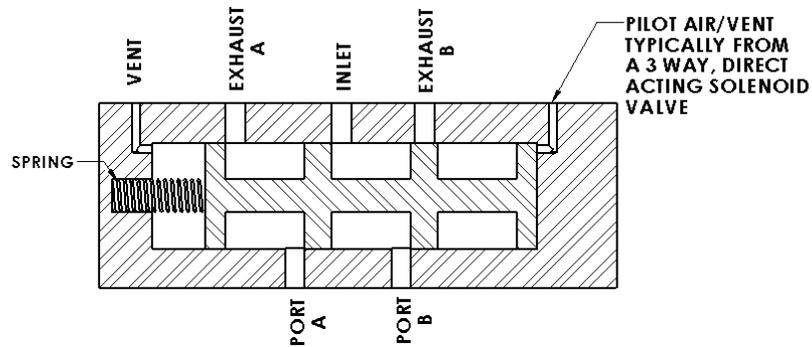


**3 WAY DIRECTIONAL CONTROL  
ENERGIZED**

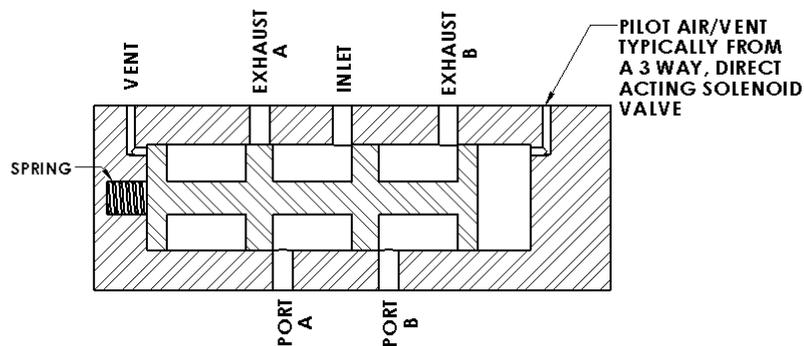


## 4-Way valves

- 4-Way valves are essentially two 3-way valves in one unit. Today, most 4 way valves are spool valves.
- In the de-energized state, the inlet port connects to the first of two outlet ports. The second outlet port is connected to an exhaust port.
- In the energized state, the inlet port connects to the second of two outlet ports. The first outlet port connects to an exhaust port.
- The typical application for a 4 way valve is to drive a cylinder. One of the outlet ports is connected to one side of the piston and the second outlet port is connected to the other side of the piston. This forces the piston in the cylinder to be either retracted or extended, depending on the state of the valve.



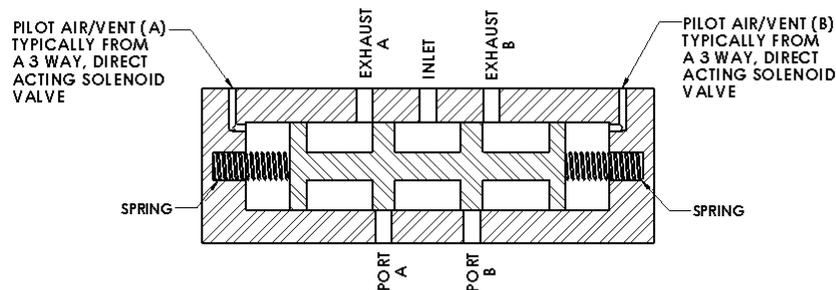
**4 WAY SPOOL VALVE  
SHOWN IN THE  
DE-ENERGIZED POSITION**



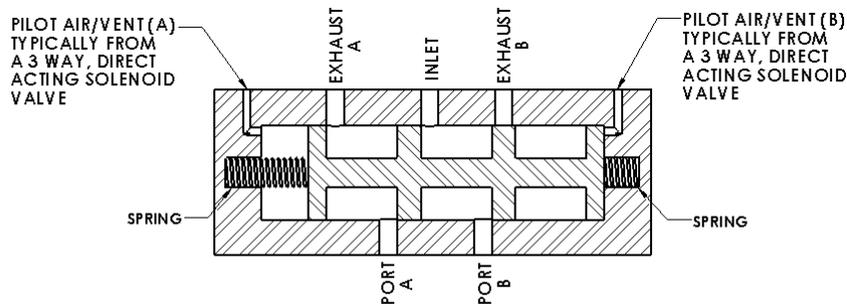
**4 WAY SPOOL VALVE  
SHOWN IN THE  
ENERGIZED POSITION**

## 5-Way valves

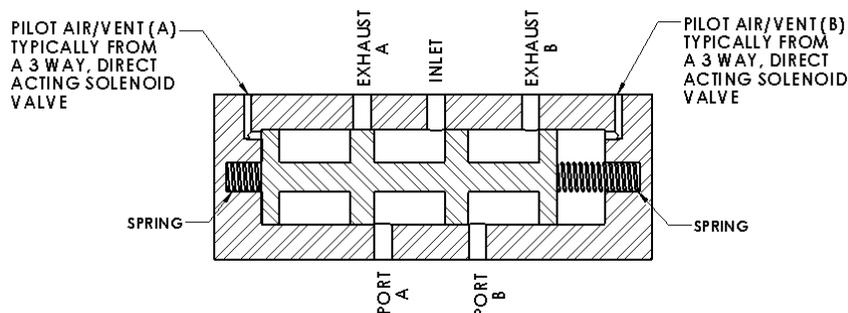
- 5-Way valves are essentially 3 position 4 way spool valves. They have two pilot solenoids.
- In the de-energized state, the spool is centered and sets both outlet ports to either inlet pressure, blocked or free vent to exhaust.
- With solenoid 1 energized, the inlet port connects to the first of two outlet ports. The second outlet connects to an exhaust port.
- With solenoid 2 energized, the inlet port connects to the second of two outlet ports. The first outlet connects to an exhaust port.
- Like a 4 way valve, the typical application for a 5 way valve is to drive a cylinder. One of the outlet ports is connected to one side of the piston and the second outlet port is connected to the other side of the piston. This forces the piston in the cylinder to be either retracted or extended when one of the two solenoids is energized. If the valve is de-energized during extraction or retraction of the cylinder, it will stall mid-stroke. At this point the outlet ports are either set to inlet pressure, blocked or free vent to exhaust.



**5 WAY SPRING CENTERED SPOOL VALVE  
SHOWN IN THE DE-ENERGIZED,  
SPRING CENTERED POSITION  
WITH ALL PORTS BLOCKED**



**5 WAY RIGHT SPOOL VALVE  
SHOWN IN THE ENERGIZED,  
SPOOL RIGHT POSITION**



**5 WAY LEFT SPOOL VALVE  
SHOWN IN THE ENERGIZED,  
SPOOL LEFT POSITION**

## Other Valves

- Proportional Valves - The valves are termed proportional because output flow is a function of input current. Typically proportion valves are not exactly linear in relation to input current. Despite their nonlinear response, the valves are an inexpensive way to control position, velocity, or force on equipment requiring high-speed response at high flow rates.
- Servo Valves - Like a smart proportional valve. Typically with an output feedback loop to add tighter control than a typical open loop proportional valve.

## Strengths and Weaknesses of Valve Types

- Direct acting Valves
  - Strengths
    - Very fast response time (these valves typically shift states in approximately 20 mS)
    - Do not require pressure differential across the valve or external pilot pressure to shift states. This allows the valve to operate from zero psi to its maximum operating pressure differential.
    - Typically small in size
    - Simpler design with fewer components
  - Weaknesses
    - Limited flow vs. pressure potential as the shifting force of the valve is limited to the force of the solenoid
    - Difficult and complicated to make into a 4 or 5 way style valve
- Pilot operated Valves
  - Strengths
    - Very high flow potential and the solenoid only shifts the pilot pressure
  - Weaknesses
    - Typically limited to 2 way valves
    - Many designs require pilot pressure to shift, and pressure differential across the valve to stay shifted. This limits the low operating pressure limit and is also puts the added constraint of a minimum flow requirement.
    - More complicated, with more components than a direct acting valve
    - Cannot shift as fast as a direct acting valve
- Spool Valves
  - Strengths
    - Very high flow potential as the spool can be shifted by pilot pressure
    - Easily configured into 4 way and 5 way valves
    - While pilot operation is typically used, there is no low limit flow requirement needed to keep the valve shifted as in the pilot operated valves
  - Weaknesses
    - Typically uses pilot pressure to shift, thus limiting the low operating pressure limit
    - Limited shifting speed
    - More complicated with more components than a direct acting valve

## Application Considerations

- Wetted materials - media compatibility
- Media and ambient temperatures plus self heating from the coil
- Media viscosity

- Pressure capabilities
    - Maximum operating pressure differential (MOPD)
    - Proof pressure
    - Burst pressure
  - Flow
    - Gas flow - (sonic vs. subsonic)
    - Liquid flow
    - Flow coefficient (Cv) is typically used to size a valve
  - Electrical characteristics
    - AC vs. DC voltage input
    - Maximum power input
  - Other environmental factors
    - Moisture
    - Hazardous Location
  - Lubrication
  - Agency approvals - UL, CSA, ATEX, FM, NSF
  - Other valve types/options
    - Latching
    - Diode suppressed/rectified
- Typical units of measure
    - Viscosity
      - Poise
      - Stokes
    - Power
      - Watts
      - VA
    - Pressure (both total pressure and maximum operating pressure differential inlet to outlet)
      - PSI (pounds per square inch)
      - Pascals
      - Atmospheres
      - Bar
    - Flow
      - CFM (cubic feet per minute)
      - GPM (gallons per minute)

For more information about solenoid valves, please contact Sales at [info@peterpaul.com](mailto:info@peterpaul.com).

#### ABOUT PETERPAUL

Peter Paul Electronics, founded in 1947, is a premier manufacturer of solenoid valves including high flow, explosion proof, high pressure, plastic, safety and mini valves. PeterPaul configures possibilities from solenoid valves that operate with power as low as 1/2 watt and pressure ratings from vacuum to as high as 5000 psi. PeterPaul is located in New Britain, Connecticut and Fajardo, Puerto Rico. High quality design, innovative research and product development set PeterPaul apart from other manufactures. Continuous improvement is in the fabric of the company on all levels with people having years of experience, dedication and pride.

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