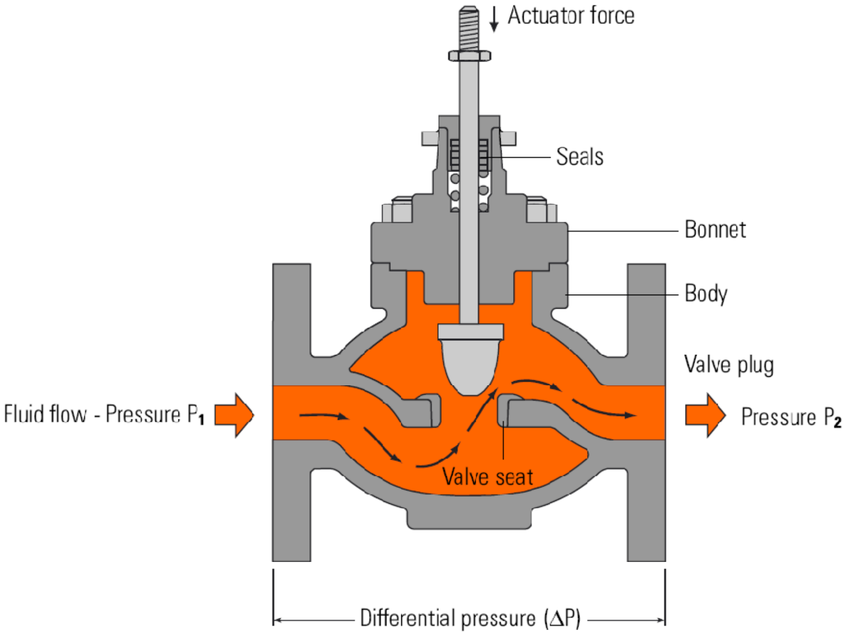
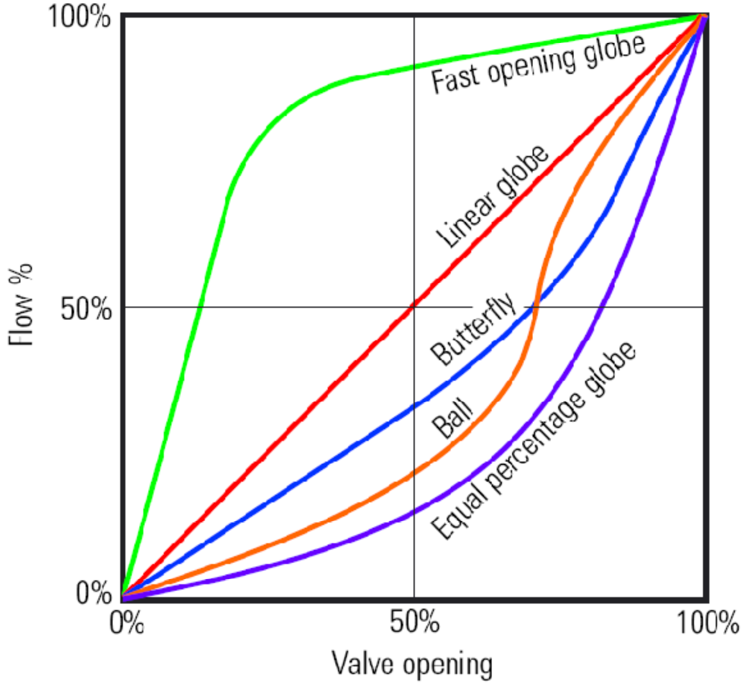
Chapter 7

CONTROL VALVES

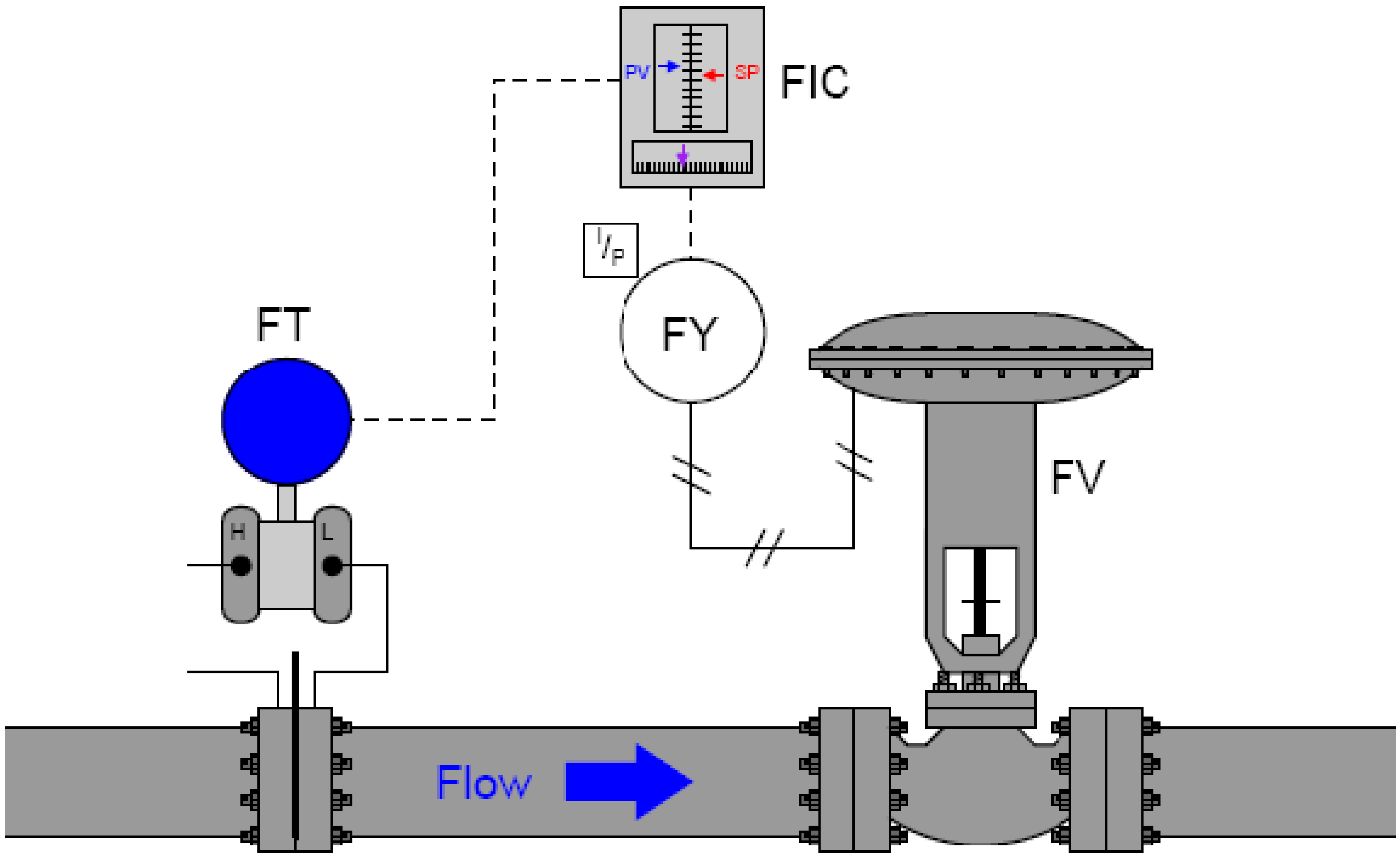




INTRODUCTION

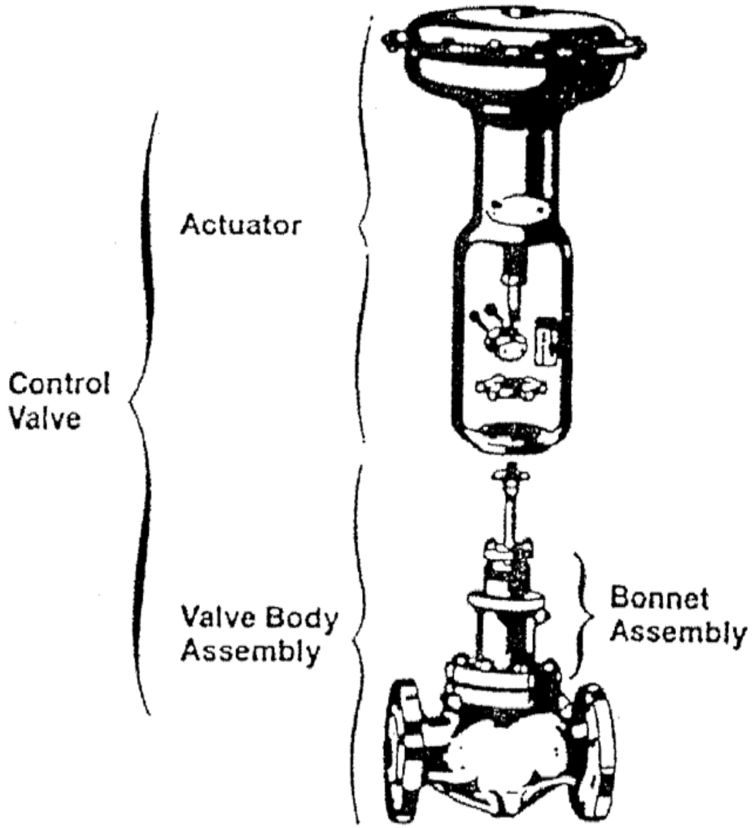
- In process systems, the final control element is normally a pneumatically actuated control valve, which is used to regulate the flow of a fluid. It provides the necessary power to translate the controller's output to the process. Pneumatics is used because of the original popularity of pneumatic control systems and the comparatively low operating pressures used, also for safe operation in the hazards facilities.

- As shown in the figure, in the basic components of a control loop, the control valve is subject to the harshest conditions. A control valve is also the most expensive item and the most prone to incorrect selection.

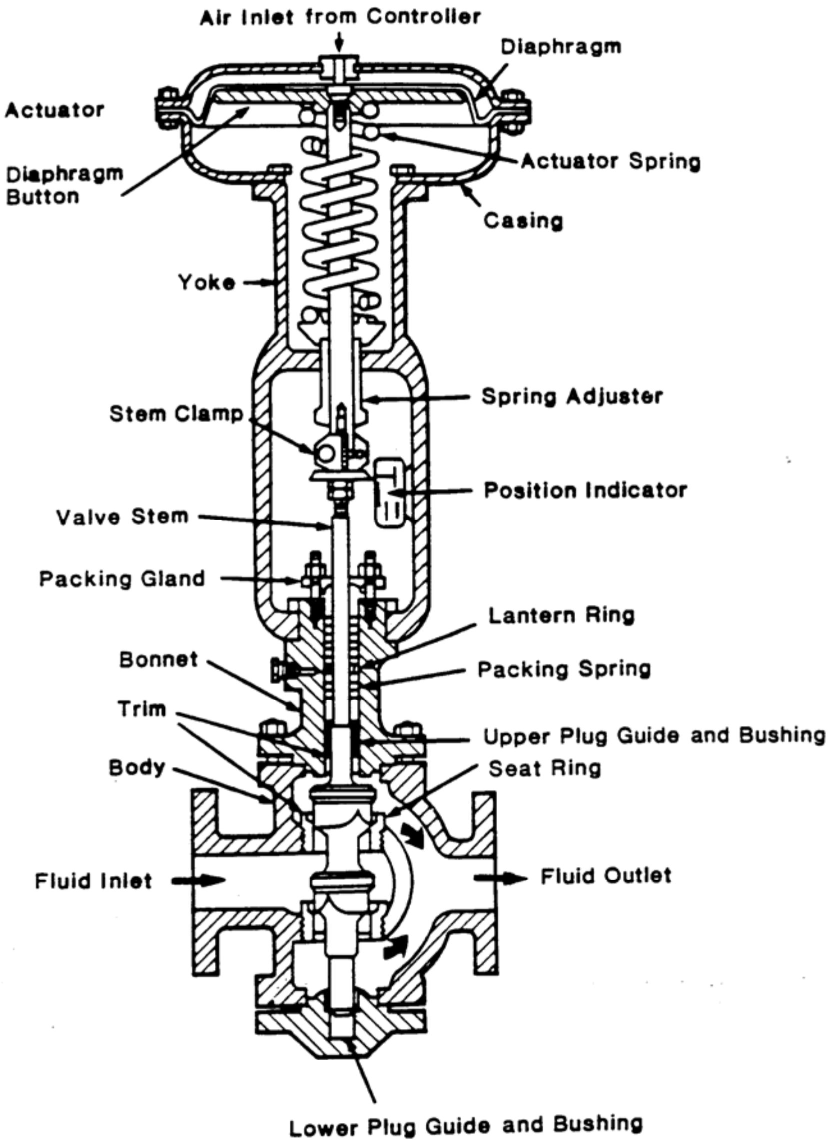

FIC
PV
SP
I/P
FY
FT
H
L
FV
Flow

Major Parts of the Control Valve

- The major parts of any control valves are:
  - » The actuator, and
  - » The valve body assembly
- There are also several types of body designs, flow characteristics, actuator types and trim designs.

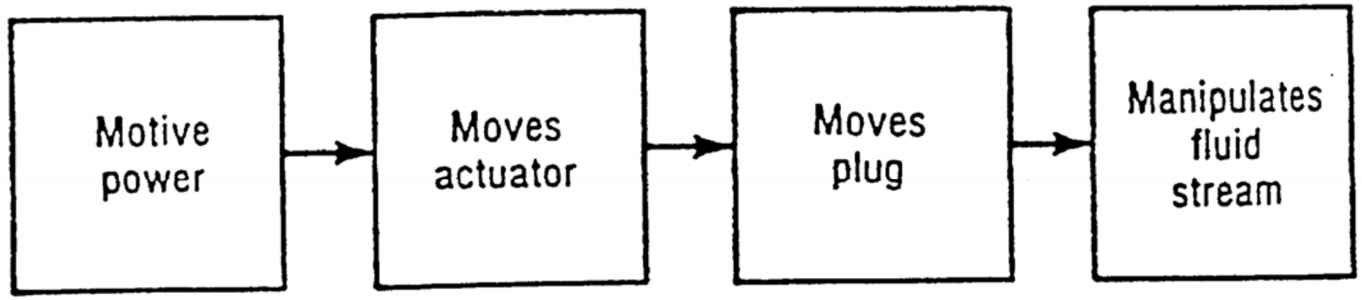


- **Control Valve Terminology**



Functional block Diagram of the control valve:

In most cases a control valve is expected to respond to a control signal to keep a process variable steady.



Control Valve Bodies

- Whilst a wide variety of valve types exist, this document will concentrate on those which are most widely used in the automatic control of industrial fluids.
- These include valve types which have slide and rotary stem movement.
  - » Sliding-Stem Valves
  - » Rotary-Stem Valves

Sliding-Stem Valves

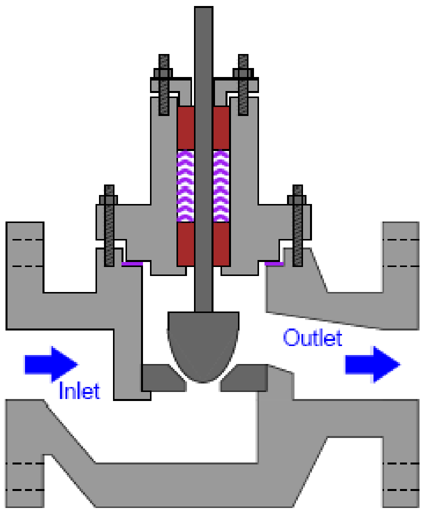
A sliding-stem valve body is one that actuates with a linear motion.

Most sliding-stem control valves are **direct-acting**, which means the valve opens up wider as the stem is drawn out of the body, and shuts off (closes) when the stem is pushed into the body.

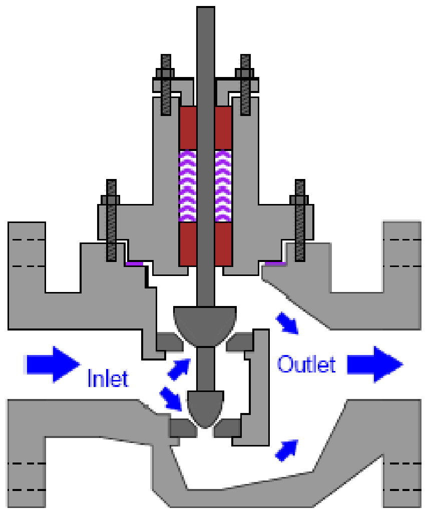
Reverse-acting valve body behaves the opposite: opening up as the stem is pushed in and closing off as the stem is drawn out.

Some examples of sliding-stem valve body designs are shown here:

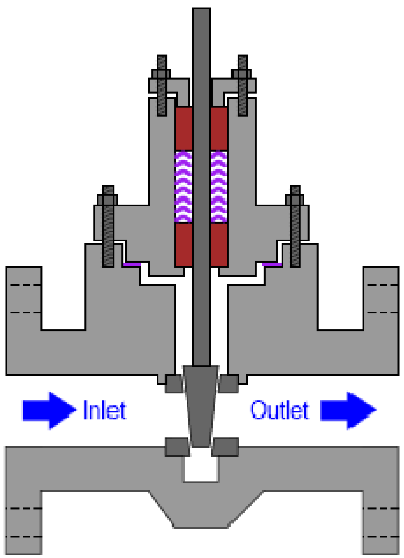
Single-ported globe valve



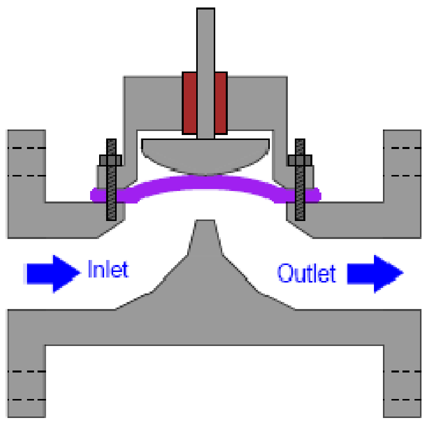
Double-ported globe valve



Gate valve

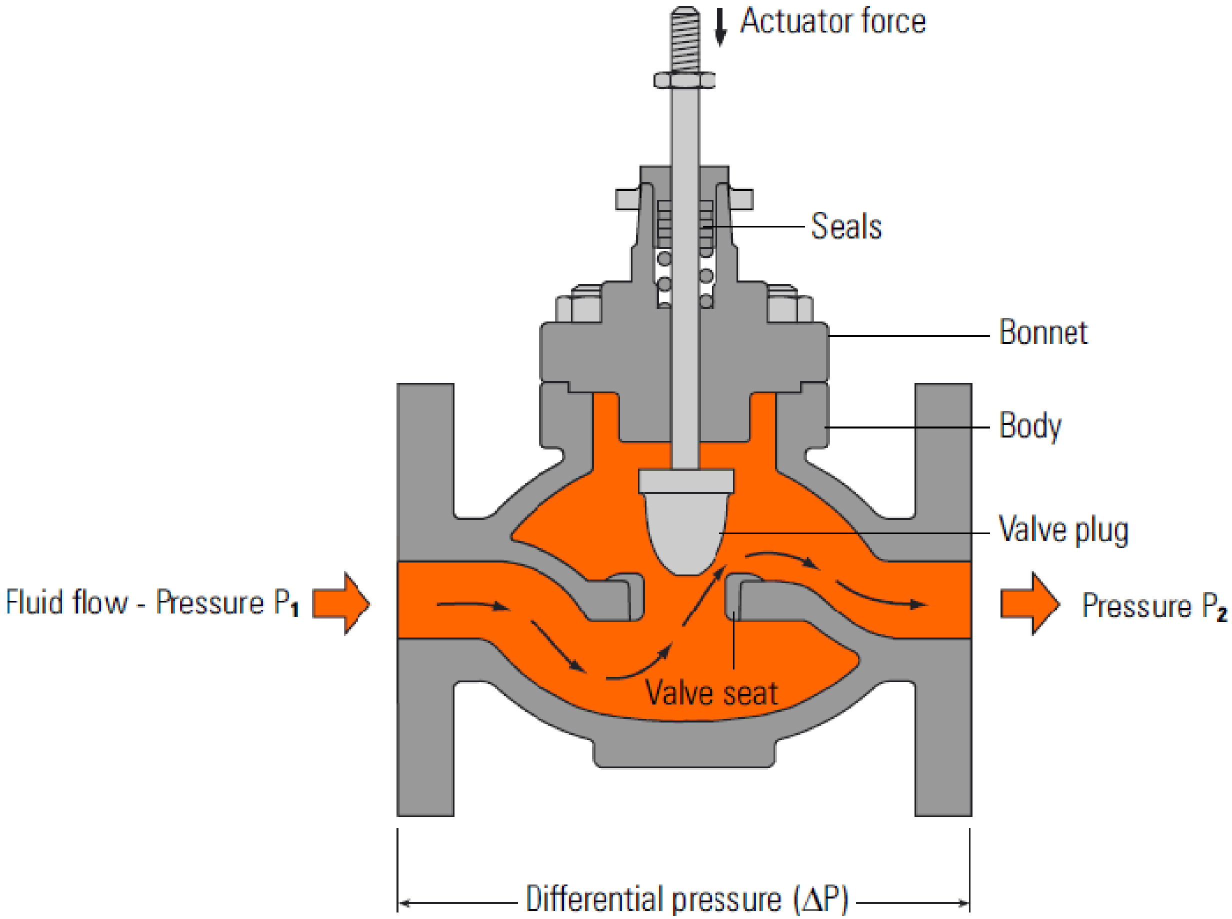


Diaphragm valve



Globe Valves

Globe valves restrict the flow of fluid by altering the distance between a movable plug and a stationary seat. Fluid flows through a hole in the center of the seat, and is more or less restricted by how close the plug is to that hole. The globe valve design is one of the most popular sliding-stem valve designs used in throttling service.

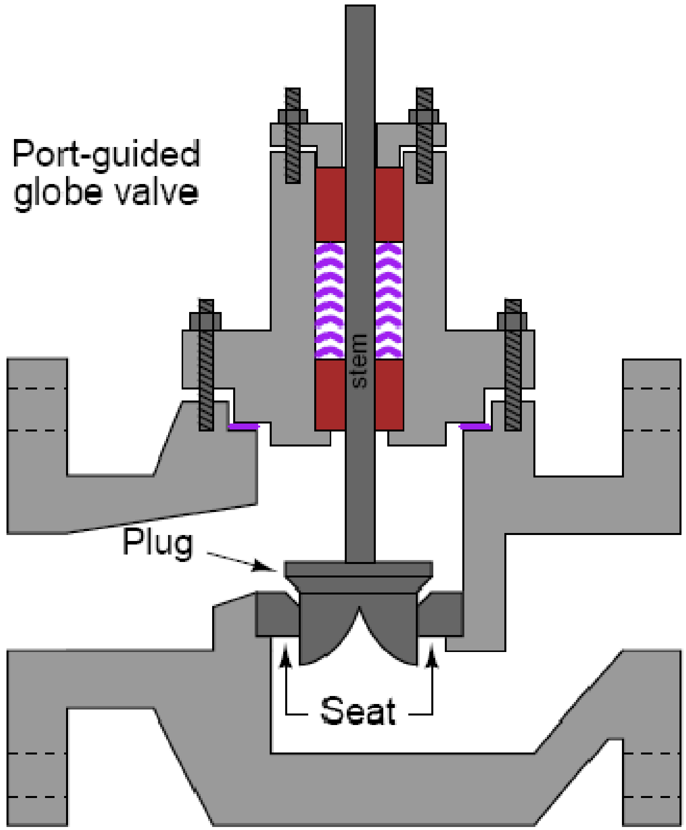


A set of three photographs showing a cut-away of globe valve body illustrates just how the moving plug and stationary seat work together to throttle flow in a direct- acting globe valve. The left-hand photo shows the valve body in the fully closed position, while the middle photo shows the valve half-open, and the right-hand photo shows the valve fully open:

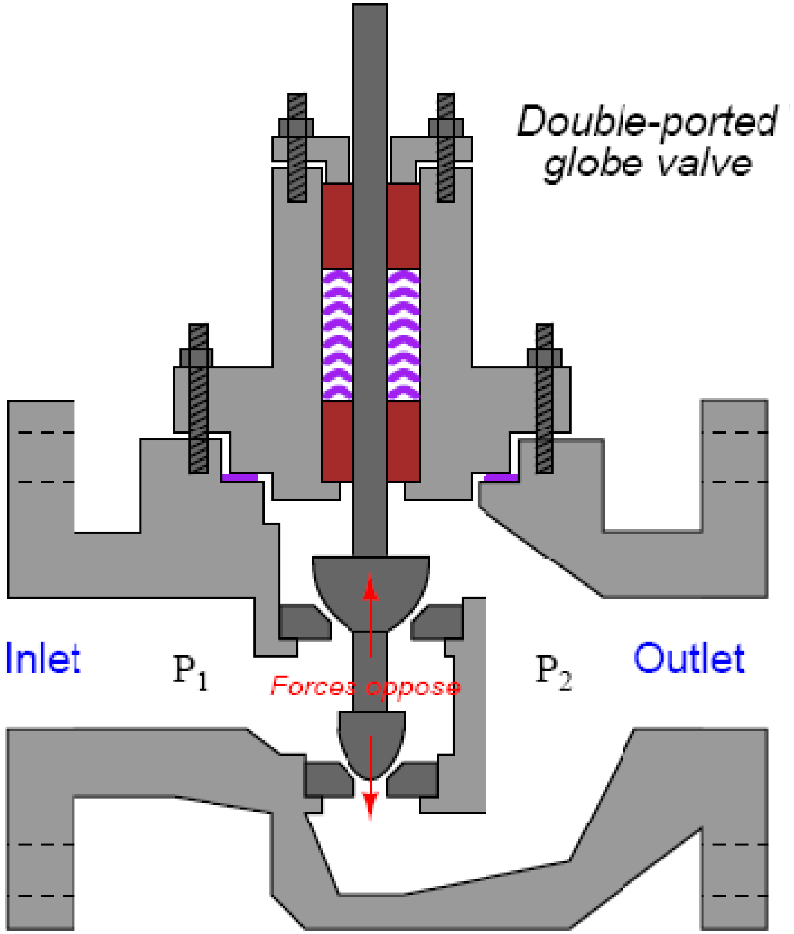
As you can see from these photographs, the valve plug is guided by the stem so it always lines up with the centerline of the seat. For this reason, this particular style of globe valve is called a stem-guided globe valve.

A variation on the stem-guided globe valve design is the needle valve, where the plug is extremely small in diameter and usually fits well into the seat hole rather than merely sitting on top of it. Needle valves are very common as manually-actuated valves used to control low flow rates of air or oil. A set of three photographs shows a needle valve in the fully-closed, mid-open, and fully-open positions (left-to-right):

Another variation on the globe valve is the port-guided valve, where the plug has an unusual shape that projects into the seat. Thus, the seat ring acts as a guide for the plug to keep the centerlines of the plug and seat always aligned, minimizing guiding stresses that would otherwise be placed on the stem. This means that the stem may be made smaller in diameter than if the valve trim were stem-guided, minimizing sliding friction and improving control behavior.



Some globe valves use a pair of plugs (on the same stem) and a matching pair of seats to throttle fluid flow. These are called double-ported globe valves. The purpose of a double-ported globe valve is to minimize the force applied to the stem by process fluid pressure across the plugs:



- Differential pressure of the process fluid ($P_1 - P_2$) across a valve plug will generate a force parallel to the stem as described by the formula F = P A, with A being the plug's effective area presented for the pressure to act upon. In a single-ported globe valve, there will only be one force generated by the process pressure.
- In a double-ported globe valve, there will be two opposed force vectors, one generated at the upper plug and another generated at the lower plug.
- If the plug areas are approximately equal, then the forces will likewise be approximately equal and therefore nearly cancel. This makes for a control valve that is easier to actuate (i.e. the stem position is less affected by process fluid pressures).

The following photograph shows a disassembled double-ported globe valve, with the double plug plainly visible on the right:

❖While double-ported globe valves certainly enjoy the advantage of easier actuation compared to their single-ported cousins, they also suffer from a distinct disadvantage: the near impossibility of tight shut-off.

❖With two plugs needing to come to simultaneous rest on two seats to achieve a fluid- tight seal, there is precious little room for error or dimensional instability.

❖Even if a double-ported valve is prepared in a shop for the best shut-off possible, it may not completely shut off when installed due to dimensional changes caused by process fluid heating or cooling the valve stem and body. This is especially problematic when the stem is made of a different material than the body.

❖ Globe valve stems are commonly manufactured from stainless steel bar stock, while globe valve bodies are commonly cast of iron.

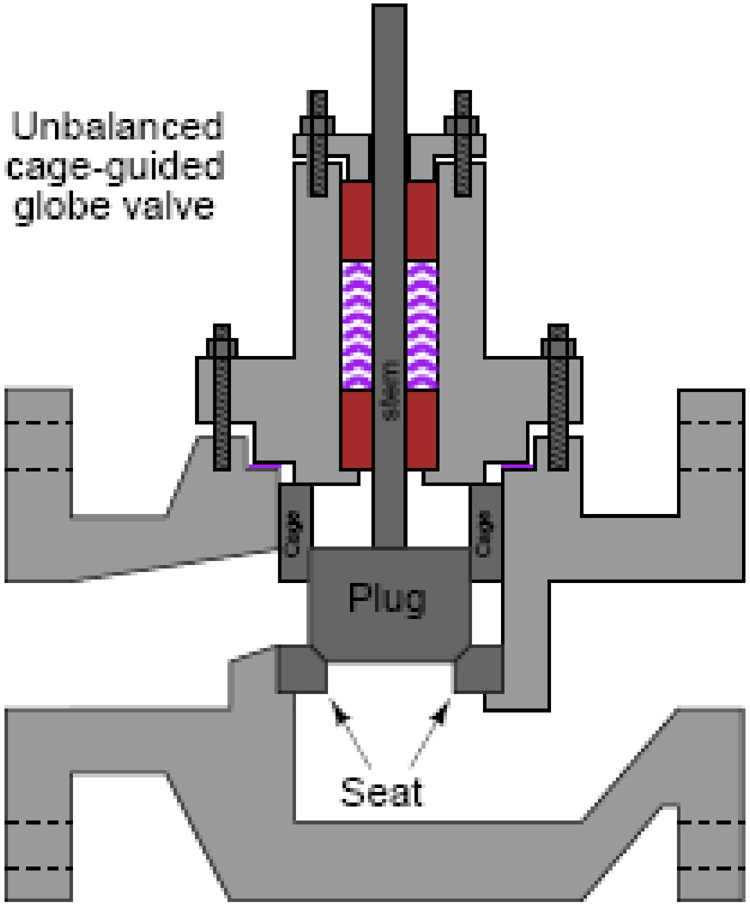
❖ A more modern version of the globe valve design uses a piston-shaped plug inside a surrounding cage with ports cast or machined into it. These cage-guided globe valves throttle flow by uncovering more or less of the port area in the surrounding cage as the plug moves up and down. The cage also serves to guide the plug so the stem need not be subjected to lateral forces as in a stem-guided valve design.

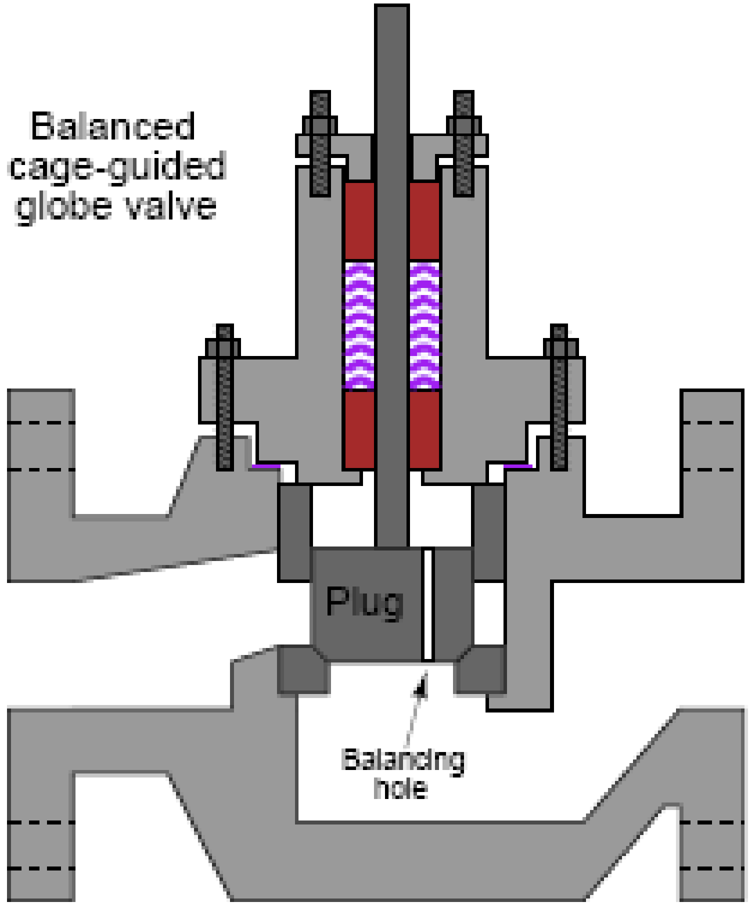
- An advantage of the cage-guided design is that the valve’s flowing characteristics may be easily altered just by replacing the cage with another having different size or shape of holes.

- Many different cage styles are available for certain plug (piston) sizes, which means the plug need not be replaced while changing the cage.

- This is decidedly more convenient than the plug change necessary for changing characteristics of stem-guided or port-guided globe valve designs.

- Cage-guided globe valves are available with both balanced and unbalanced plugs.
- A balanced plug has one or more ports drilled from top to bottom, allowing fluid pressure to equalize on both sides of the plug.
- his helps minimize the forces acting on the plug which must be overcome by the actuator

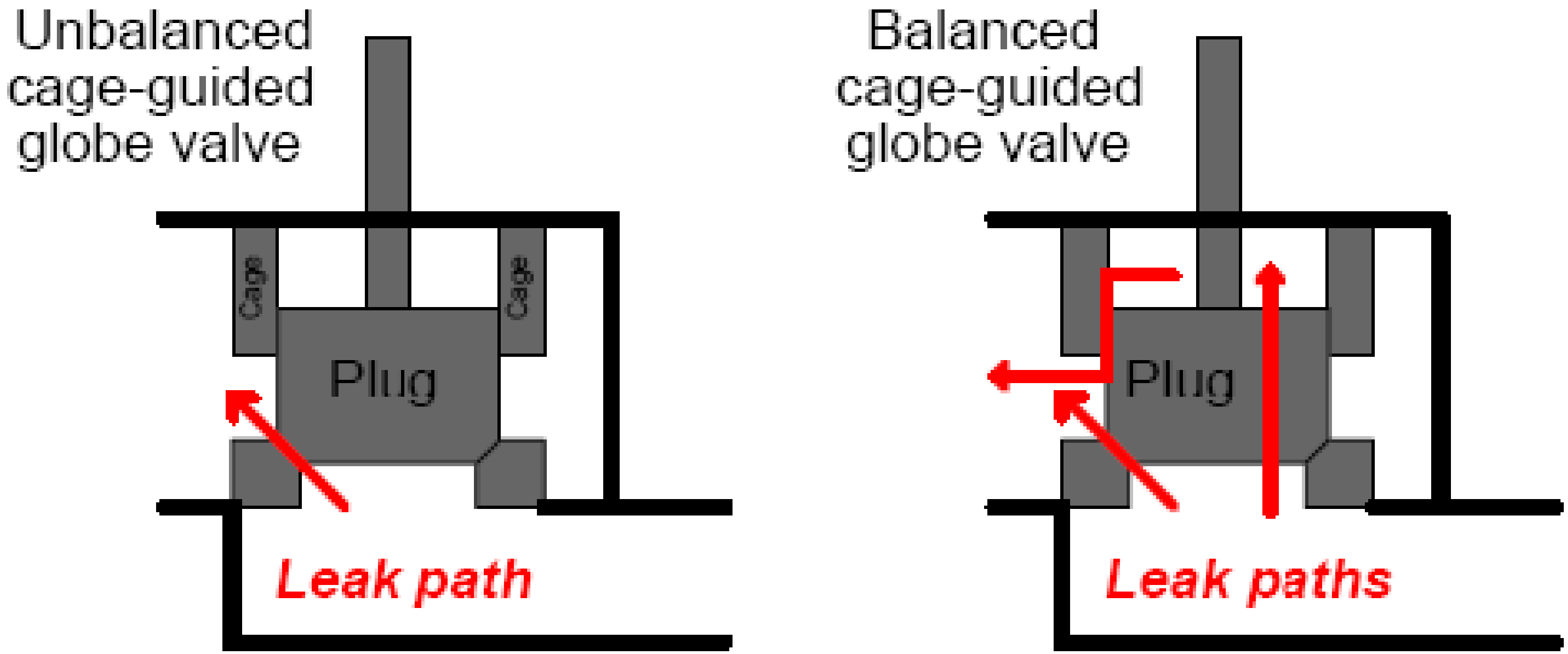

Unbalanced
cage-guided
globe valve
stem
Cage
Cage
Plug
Seat


Balanced
cage-guided
globe valve
Plug
Balancing
hole

Unbalanced plugs generate a force equal to the product of the differential pressure across the plug and the plug’s area (F = P A), which may be quite substantial in some applications.

Balanced plugs do not generate this same force because they equalize the pressure on both sides of the plug,

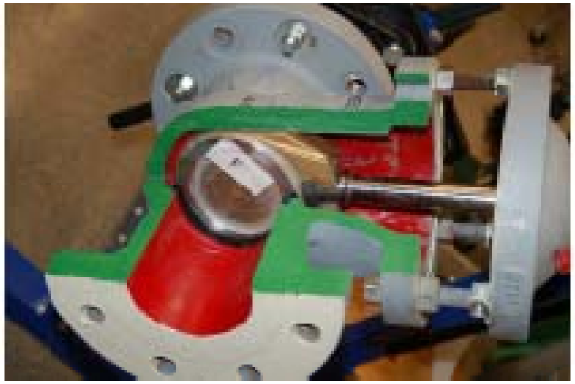
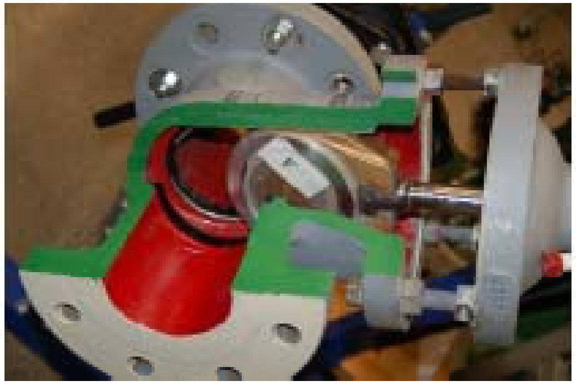
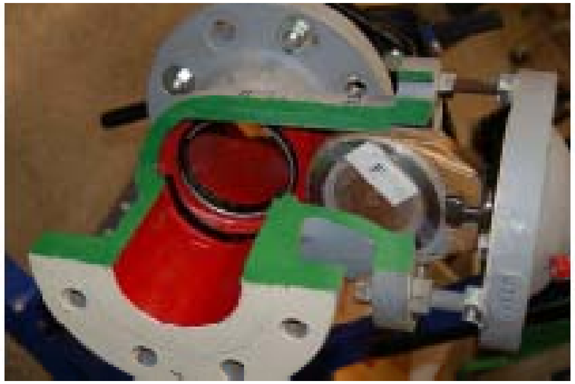
Unbalanced plugs exhibit the disadvantage of one more leak path when the valve is in the fully closed position (through the balancing ports, past the piston ring, and out the cage ports):


Unbalanced cage-guided globe valve
Cage
Cage
Plug
Leak path
Balanced cage-guided globe valve
Plug
Leak paths

Gate Valves

Gate valves work by inserting a dam ("gate") into the path of the flow to restrict it, in a manner similar to the action of a sliding door. Gate valves are more often used for on/off control than for throttling.

The following set of photographs shows a hand-operated gate valve (cut away and painted for use as an instructional tool) in three different positions, from full closed to full open (left to right):

Diaphragm Valves

Diaphragm valves use a flexible sheet pressed close to the edge of a solid dam to narrow the flow path for fluid.

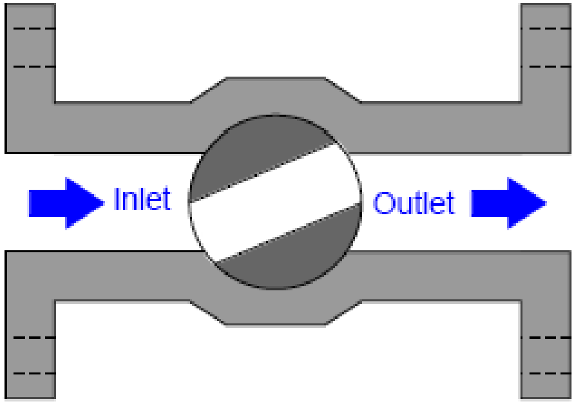
These valves are well suited for flows containing solid particulate matter such as slurries, although precise throttling may be difficult to achieve due to the elasticity of the diaphragm.

Rotary-Stem Valves

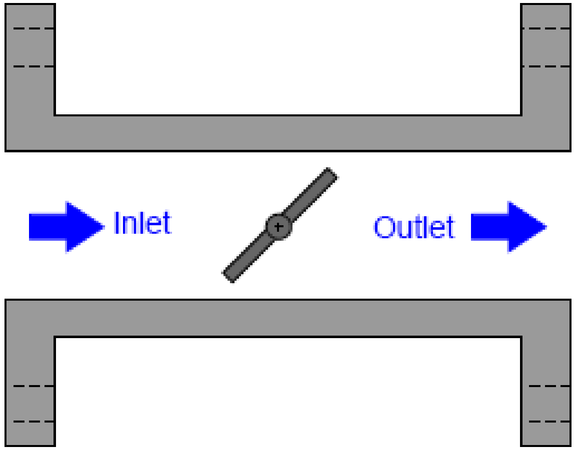
A different strategy for controlling the flow of fluid is to insert a rotary element into the flow path. Instead of sliding a stem into and out of the valve body to actuate a throttling mechanism, rotary valves rely on the rotation of a shaft to actuate the trim.

An important advantage of rotary control valves over sliding-stem designs such as the globe valve and diaphragm valve is a virtually obstruction-less path for fluid when the valve is wide-open.

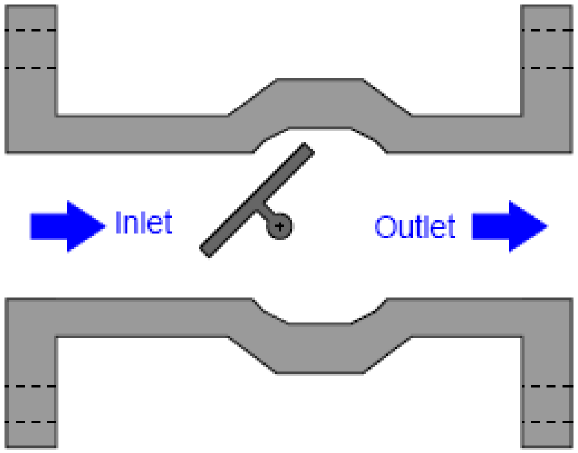
Ball valve



Butterfly valve



Disk valve



Ball Valves

In the ball valve design, a spherical ball with a passageway cut through the center rotates to allow fluid more or less access to the passageway. When the passageway is parallel to the direction of fluid motion, the valve is wide open; when the passageway is aligned perpendicular to the direction of fluid motion, the valve is fully shut (closed).

Simple ball valves with full-sized bores in the rotating ball are generally better suited for on/off service than for throttling (partially-open) service.

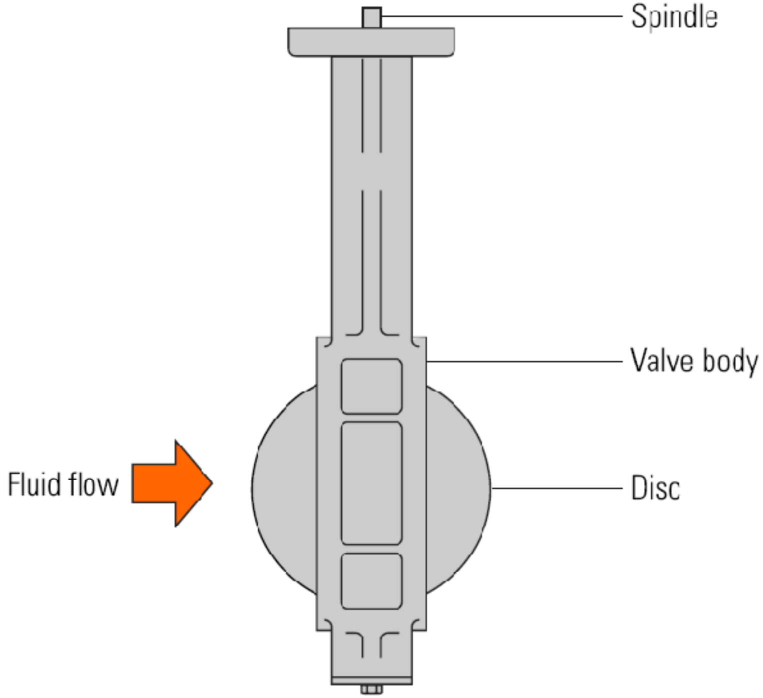
A better design of ball valve for throttling service is the characterized or segmented ball valve, shown in various stages of opening in the following set of photographs:

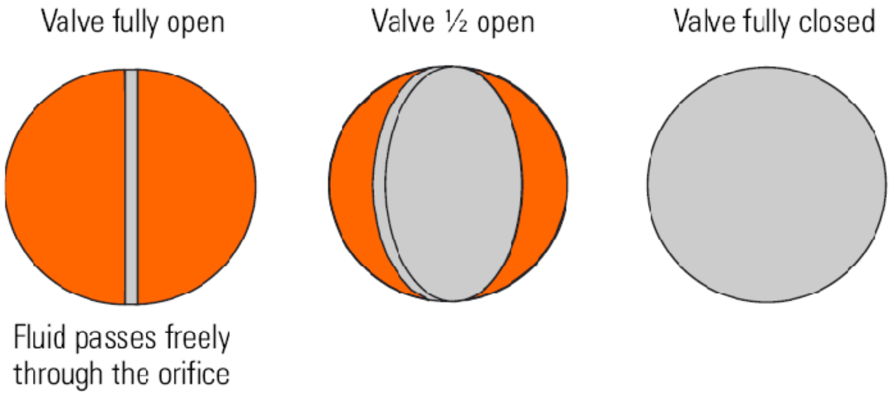
The V-shaped notch cut into the opening lip of the ball provides a narrower area for fluid flow at low opening angles, providing more precise flow control than a plain-bore ball valve.

Butterfly Valves

The figure is a simple schematic diagram of a butterfly valve, which consists of a disc rotating in trunnion bearings. In the open position the disc is parallel to the pipe wall, allowing full flow through the valve. In the closed position it is rotated against a seat, and perpendicular to the pipe wall.



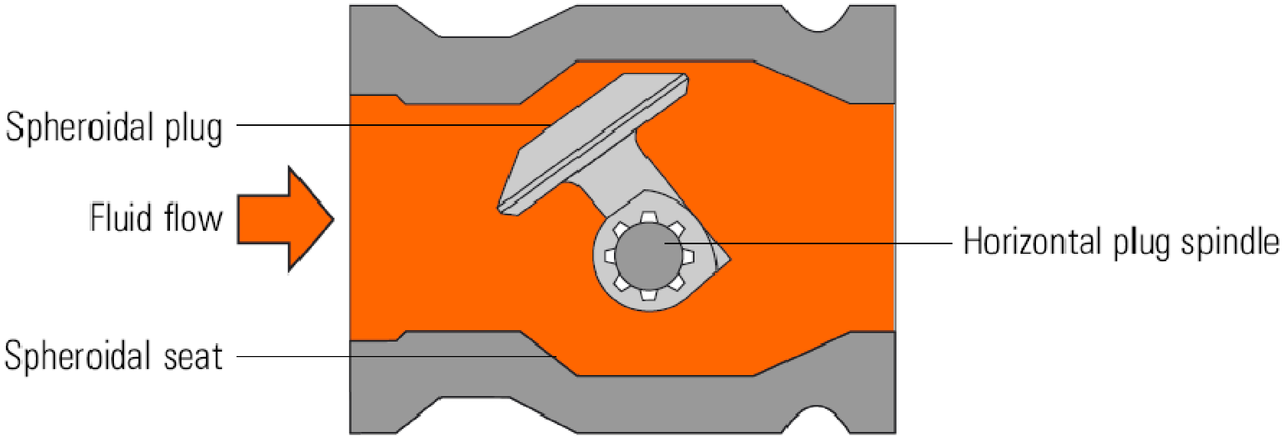
End view of the disc within the butterfly valve at different stages of rotation



Disk Valves

Disk valves (Eccentric disk valves, or high-performance butterfly valves) are a variation on the butterfly design intended to improve seat shut-off.

The disk’s center is offset from the shaft centerline, causing it to approach the seat with a “cam” action that results in high seating pressure. Thus, tight shut-off of flow is possible even when using metal seats and disks.


Spheroidal plug
Fluid flow
Spheroidal seat
Horizontal plug spindle

Dampers and Louvres

A damper (louvre) is a multi-element flow control device generally used to throttle large flows of air at low pressure.

Dampers find common application in furnace and boiler draft control, and in HVAC (Heating, Ventilation, and Air Conditioning) systems.

Common damper designs include parallel and radial. Parallel-vane dampers resemble a Venetian blind, with multiple rectangular vanes synchronously rotated to throttle flow through a rectangular opening.

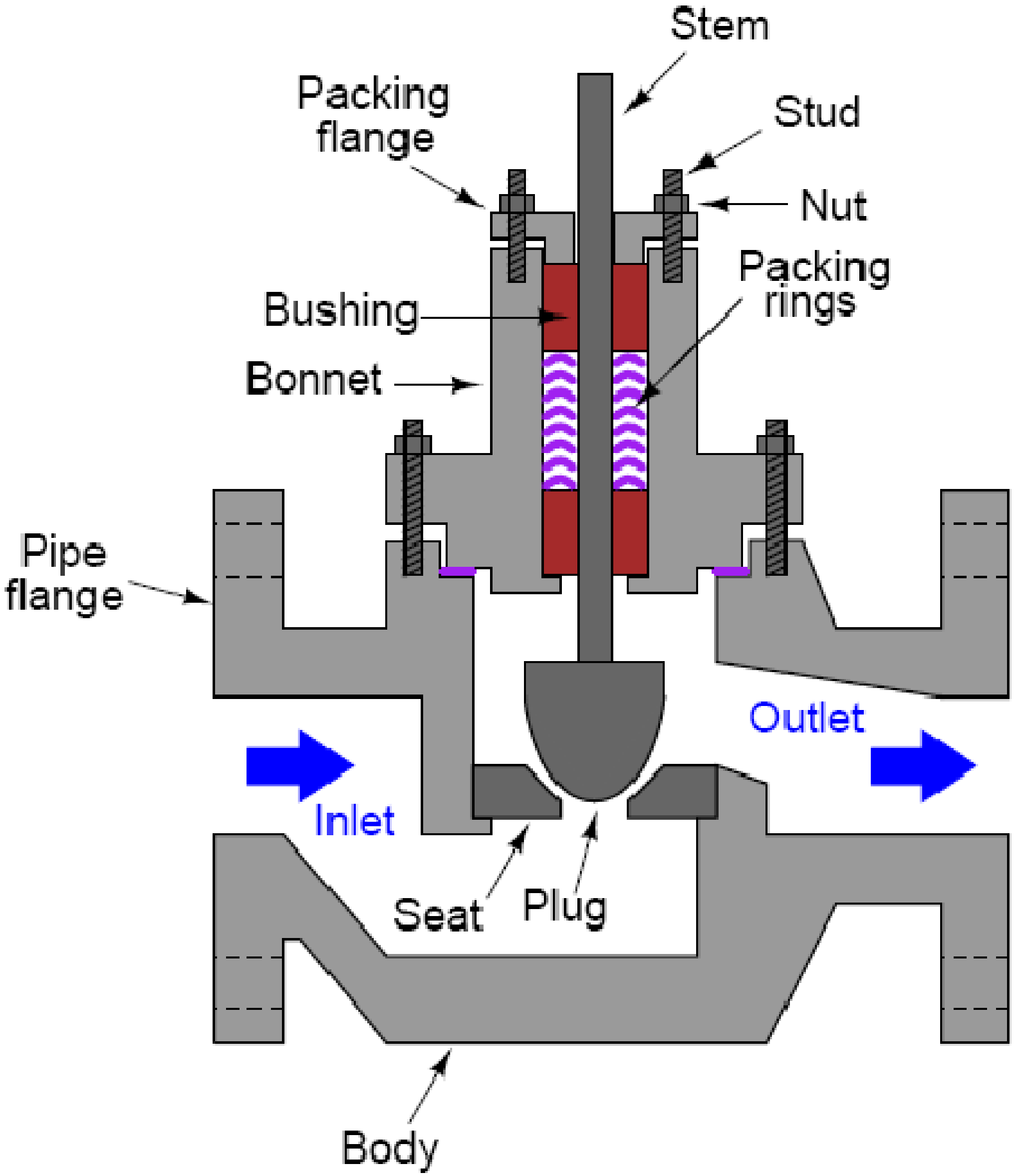
Radial-vane dampers use multiple vanes arranged like petals of a flower to throttle flow through a circular opening. A photograph of a radial-vane damper is shown here (note the levers and linkages on the periphery of the tube, synchronizing the motions of the eight vanes so they rotate at the same angle):

Dampers find use in many non-industrial applications as well. Take for instance these greenhouse vents, actuated by pneumatic (air-powered) piston actuators:

Valve Packing

Regardless of valve type, all stem-actuated control valves require some form of seal allowing motion of the stem from some external device (an actuator) while sealing process fluid so no leaks occur between the moving stem and the body of the valve. The general term for this sealing mechanism is packing.

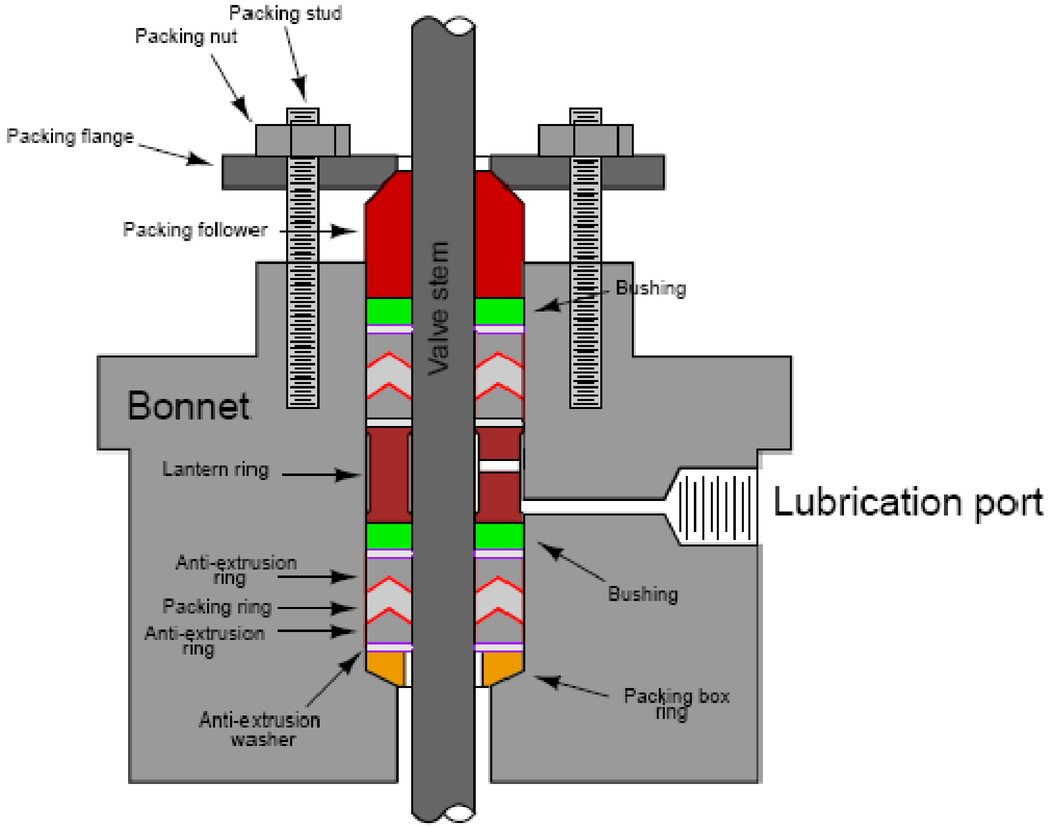
Packing in a sliding-stem valve fits in a section of the valve body called the bonnet, shown in this simplified diagram of a single-ported, stem-guided globe valve:


Stem
Packing
flange
Stud
Nut
Packing
rings
Bushing
Bonnet
Pipe
flange
Outlet
Inlet
Seat
Plug
Body

The packing material takes the form of several concentric rings, stacked on the valve stem like washers on a bolt. These packing rings are forced down from above by the packing flange to apply a compressive force around the circumference of the valve stem.

Two nuts threaded onto studs maintain proper force on the packing rings. Care must be taken not to over-tighten these nuts and over-compress the packing material, or else the packing will create excessive friction on the valve stem. Not only will this friction impede precise valve stem motion, but it will also create undue wear on the stem and packing, increasing the likelihood of future packing leakage.

A closer look at the bonnet shows a multitude of components working together to form a low- friction, pressure-tight seal for the moving valve stem:



The lantern ring acts as a spacer allowing lubricant introduced through the lubrication port to enter into both packing sets from the middle of the bonnet.

Photographs taken of an actual valve packing assembly removed from the bonnet (left), and re- assembled on the valve stem (right) reveal the structure of the packing and associated components.

In packing applications requiring external lubrication, a stem packing lubricator may be connected to the lubrication port on the bonnet. This device uses a long, threaded bolt as a piston to push a quantity grease into the packing assembly:

The two most common packing materials in use today are Teflon (PTFE) and graphite.

1. Teflon is the better of the two with regard to friction and stem wear. Teflon is also quite resistant to attack from a wide variety of chemical substances. Unfortunately, it has a limited temperature range and cannot withstand intense nuclear radiation (making it unsuitable for use near reactors in nuclear power plants).

2) Graphite is another self-lubricating packing material, and it has a far greater temperature range than Teflon as well as the ability to withstand harsh nuclear radiation, but creates much more stem friction than Teflon. Graphite packing also has the unfortunate property of permitting galvanic corrosion between the stem and bonnet metals due to its electrical conductivity. Sacrificial zinc washers are sometimes added to graphic packing assemblies to help mitigate this corrosion, but this only postpones rather than prevents corrosive damage to the stem.

Valve Seat Leakage

In many process applications, it is important that the control valve be able to completely stop fluid flow when placed in the “closed” position. Although this may seem to be a fundamental requirement of any valve, it is not necessarily so.

Many control valves spend most of their operating lives in a partially-open state, rarely opening or closing fully.

Given the common installation of manual “block” valves upstream and downstream of a control valve, there is usually a way to secure zero flow through a pipe even if a control valve is incapable of tight shut-off.

For some control valve applications, however, tight shut-off is a mandatory requirement.

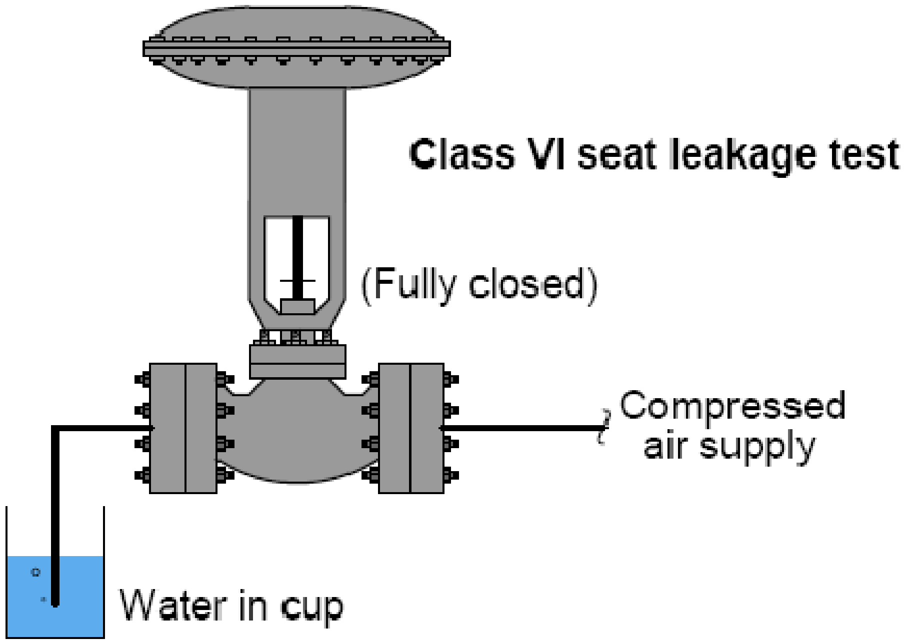
For this reason we have several classifications for control valves, rating them in their ability to fully shut off. Seat leakage tolerances are given roman numeral designations, as shown in this table:

Class	Maximum allowable leakage rate	Test pressure drop
I	(no specification given)	(no specification given)
II	0.5% of rated flow capacity, air or water	45-60 PSI or max. operating
III	0.1% of rated flow capacity, air or water	45-60 PSI or max. operating
IV	0.01% of rated flow capacity, air or water	45-60 PSI or max. operating
V	0.0005 ml/min water per inch orifice size per PSI	Max. operating
VI	Bubble test, air or nitrogen	50 PSI or max. operating

The “bubble test” used for Class VI seat leakage is based on the leakage rate of air or nitrogen gas past the closed valve seat as measured by counting the rate of gas bubbles escaping a bubble tube submerged under water.

For a 6 inch valve, this maximum bubble rate is 27 bubbles per minute (or about 1 bubble every two seconds):

It is from this leakage test procedure that the term bubble-tight shut-off originates. Class VI shut-off is often achievable only through the use of “soft” seat materials such as Teflon rather than hard metal-to-metal contact between the valve plug and seat. Of course, this method of achieving bubble-tight shut-off comes at the price of limited operating temperature range and the inability to withstand nuclear radiation exposure.



Control Valve Actuators

The purpose of a control valve actuator is to provide the motive force to operate a valve mechanism.

Both sliding-stem and rotary control valves enjoy the same selection of actuators:

pneumatic,
hydraulic,
electric motor, and
hand (manual).

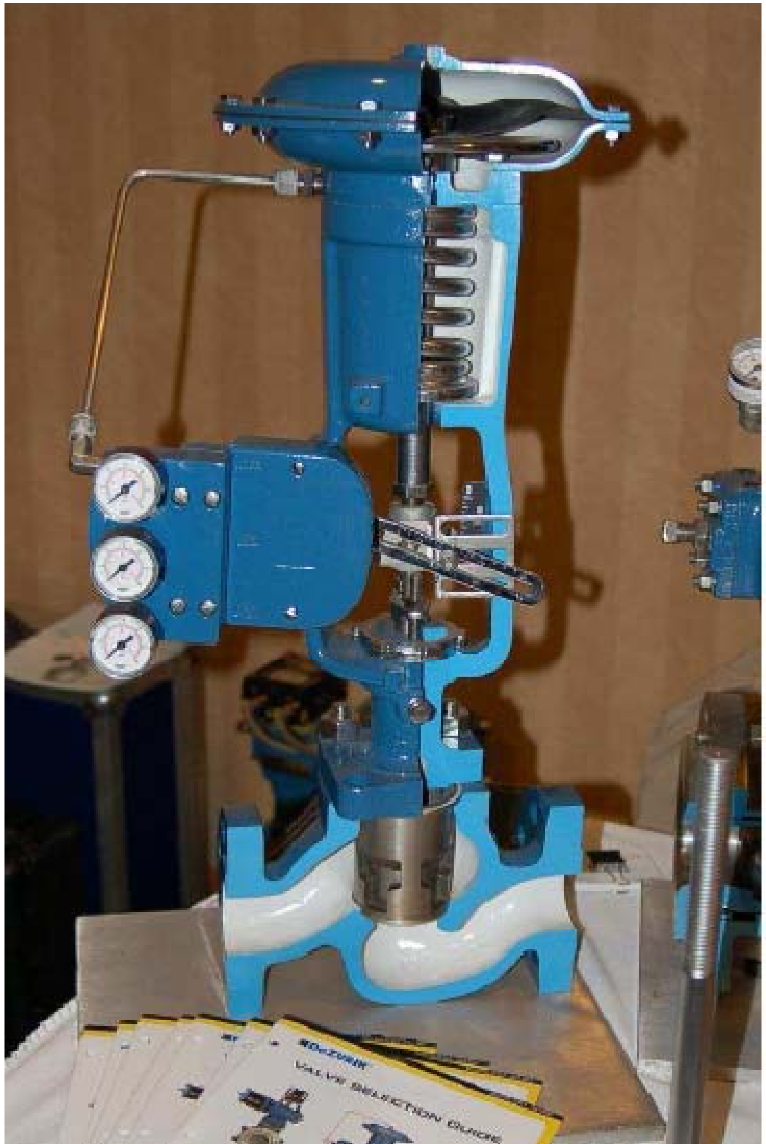
Pneumatic Actuators

Pneumatic actuators use air pressure pushing against either a flexible diaphragm or a piston to move a valve mechanism.

Photograph shows a cut-away control valve, with a pneumatic diaphragm actuator mounted above the valve body.

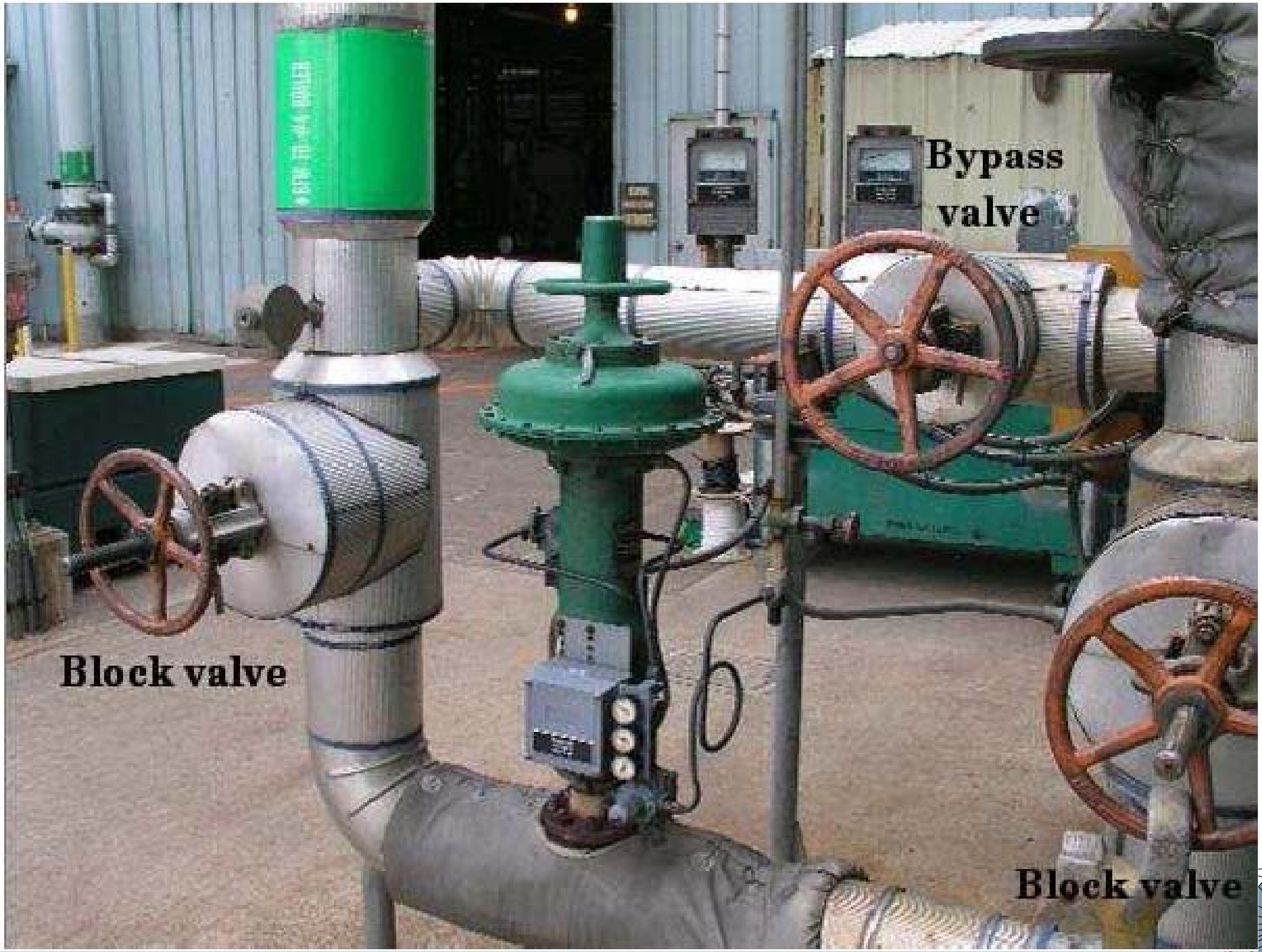
You can see the large coil spring providing default positioning of the valve (air pressure acting against the diaphragm moves the valve against the spring) and the rubber diaphragm at the very top.

Air pressure applied to the bottom side of the diaphragm lifts the sliding stem of the valve in the upward direction, against the spring's force which tries to push the stem down:

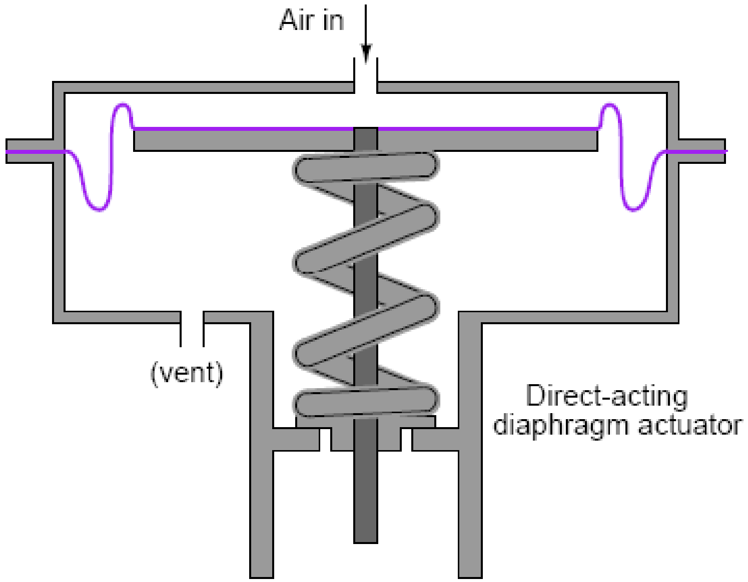


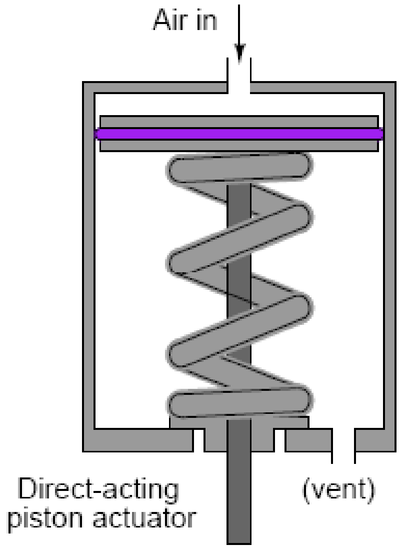
The air pressure required to motivate a pneumatic actuator may come directly from the output of a pneumatic process controller, or from a signal transducer (or converter) translating an electrical signal into an air pressure signal. Such transducers are commonly known as I/P or “I to P” converters, since they typically translate an electric current signal (I) of 4 to 20 mA DC into an air pressure signal (P) of 3 to 15 PSI.

Some pneumatic valve actuators are equipped with hand jacks which are used to manually position the valve in the event of air pressure failure. Photograph shows a sliding-stem control valve with pneumatic diaphragm actuator and a “handwheel” on the top:



Pneumatic actuators may take the form of pistons rather than diaphragms. Illustrations of each type are shown here for comparison:





Piston actuators generally have longer stroke lengths than diaphragm actuators, and are able to operate on much greater air pressures. Since actuator force is a function of fluid pressure and actuator area (F = P A), this means piston actuators are able to generate more force than diaphragm actuators. The combination of greater force and greater displacement yields more work potential for piston actuators than diaphragm actuators of equivalent size, since mechanical work is the product of force and displacement (W = F x).

Perhaps the greatest disadvantage of piston actuators as applied to control valves is friction between the piston’s pressure-sealing ring and the cylinder wall. This is not a problem for on/off control valves, but it may be a significant problem for throttling valves where precise positioning is desired.

Diaphragm actuators do not exhibit the same degree of friction as piston actuators because the elastic diaphragm rolls and flexes rather than rubs against a stationary surface as is the case with piston sealing rings.

A double-piston pneumatic actuator appears in photograph, providing the mechanical force needed to turn an on/off butterfly valve:

Photographs of a cut-away rack-and-pinion piston actuator (same design, just smaller) show how the pistons' linear motion is converted into rotary motion to actuate a rotary valve:

Another pneumatic piston actuator design uses a simple crank lever instead of a rack-and-pinion gear set to convert linear piston motion into rotary motion. Photograph shows such a piston actuator connected to a ball valve:

Hydraulic Actuators

Hydraulic actuators use liquid pressure rather than gas pressure to move the valve mechanism.

Nearly all hydraulic actuator designs use a piston rather than a diaphragm to convert fluid pressure into mechanical force.

The high pressure rating of piston actuators lends itself well to typical hydraulic system pressures, and the lubricating nature of hydraulic oil helps to overcome the characteristic friction of piston-type actuators. Given the high pressure ratings of most hydraulic pistons, it is possible to generate tremendous actuating forces with a hydraulic actuator, even if the piston area is modest. For example, an hydraulic pressure of 2,000 PSI applied to one side of a 3 inch diameter piston will generate a linear thrust of over 14,000 pounds (7 tons)!

In addition to the ability of hydraulic actuators to easily generate extremely large forces, they also exhibit very stable positioning owing to the non-compressibility of hydraulic oil. Unlike pneumatic actuators, where the actuating fluid (air) is “elastic,” the oil inside a hydraulic actuator cylinder does not yield appreciably under stress. If the passage of oil to and from a hydraulic cylinder is blocked by small valves, the actuator will become firmly “locked” into place. This may be a decided advantage for certain valve-positioning applications, where the actuator must resist forces generated on the valve trim by process fluid pressures.

A hydraulic piston actuator attached to a large shut-off valve (used for on/off control rather than throttling) appears in photograph. Two hydraulic cylinders may be seen above the round valve body, mounted horizontally. This valve actuator uses a rack-and-pinion mechanism to convert the hydraulic pistons’ linear motion into rotary motion to turn the valve trim:

Self-Operated Valves

A form of actuation worthy of mention is where the process fluid pressure itself actuates a valve mechanism. This self-operating principle may be used in throttling applications or on/off applications, in gas or liquid services alike. The process fluid may be directly tubed to the actuating element (diaphragm or piston), or passed through a small mechanism called a pilot to modulate that pressure before reaching the valve actuator. This latter design allows the main valve's motion to be controlled by an adjustable device (the pilot).

A very common application for pilot-operated control valves is gas pressure regulation, especially for fuel gas such as propane or natural gas used to fuel large industrial burners. This photograph shows a gas pressure regulator used for regulating the pressure of natural gas fueling an industrial burner:

Electric Actuators

Electric motors have long been used to actuate large valves, either in on/off mode or in throttling services.

Advances in motor design and motor control circuitry has brought motor-operated valve (MOV) technology to the point where it regularly competes with legacy actuator technologies such as pneumatic.

An electric actuator appears in the next photograph, providing rotary actuation to a ball valve.

This particular electric actuator comes with a hand crank for manual operation, in the event that the electric motor (or the power provided to it) fails:

The photograph shows a different brand of valve actuator (Rotork) turning a large butterfly valve.

Hand (Manual) Actuators

Valves may also be actuated by hand power alone. The following valves are all “manual” valves, requiring the intervention of a human operator to actuate:

Valve Failure Mode

An important design parameter of a control valve is the position it will “fail” to if it loses motive power.

For electrically actuated valves, this is typically the last position the valve was in before loss of electric power.

For pneumatic and hydraulic actuated valves, the option exists of having a large spring provide a known “fail-safe” position (either open or closed) in the event of fluid pressure (pneumatic air pressure or hydraulic oil pressure) loss.

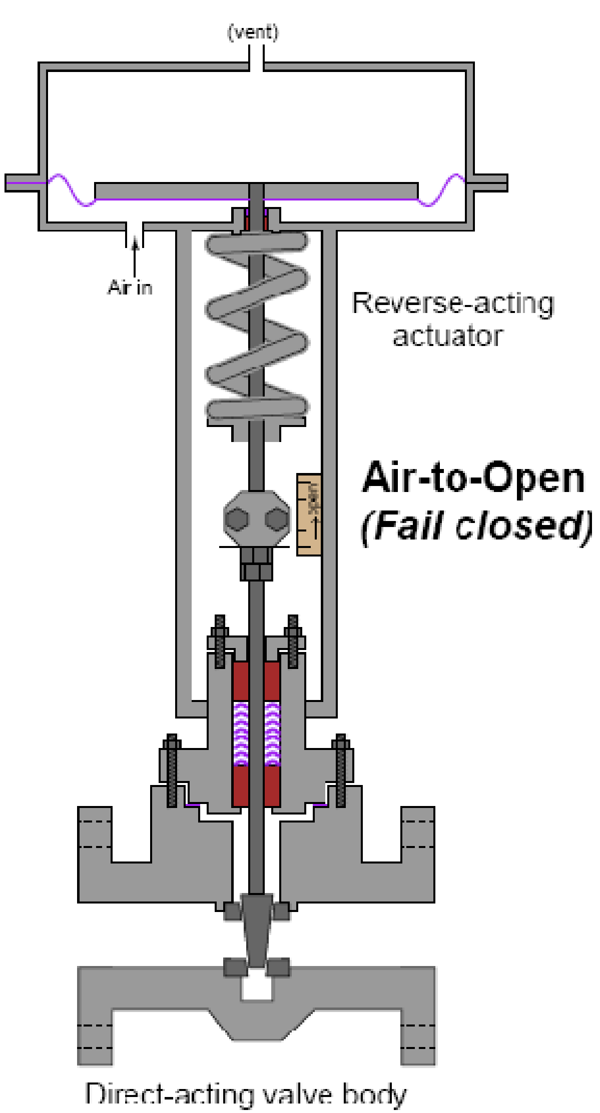
The fail-safe mode of a pneumatic/spring valve is a function of both the actuator’s action and the valve body’s action.

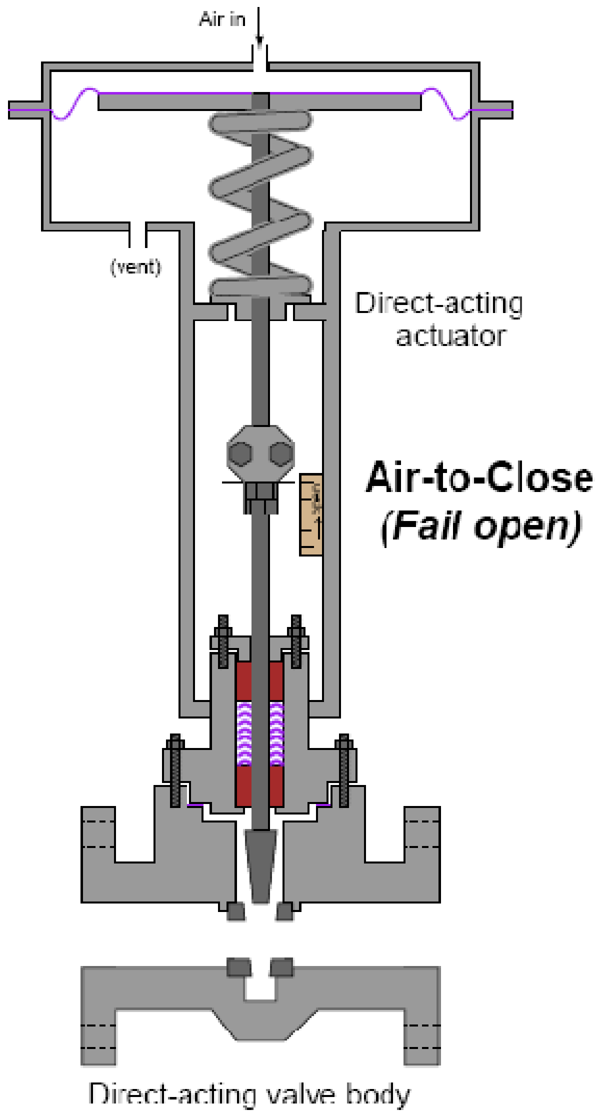
For sliding-stem valves, a direct-acting actuator pushes down on the stem with increasing pressure while a reverse-acting actuator pulls up on the stem with increasing pressure.

Sliding-stem valve bodies are classified as direct-acting if they open up when the stem is lifted, and classified as reverse-acting if they shut off (close) when the stem is lifted.

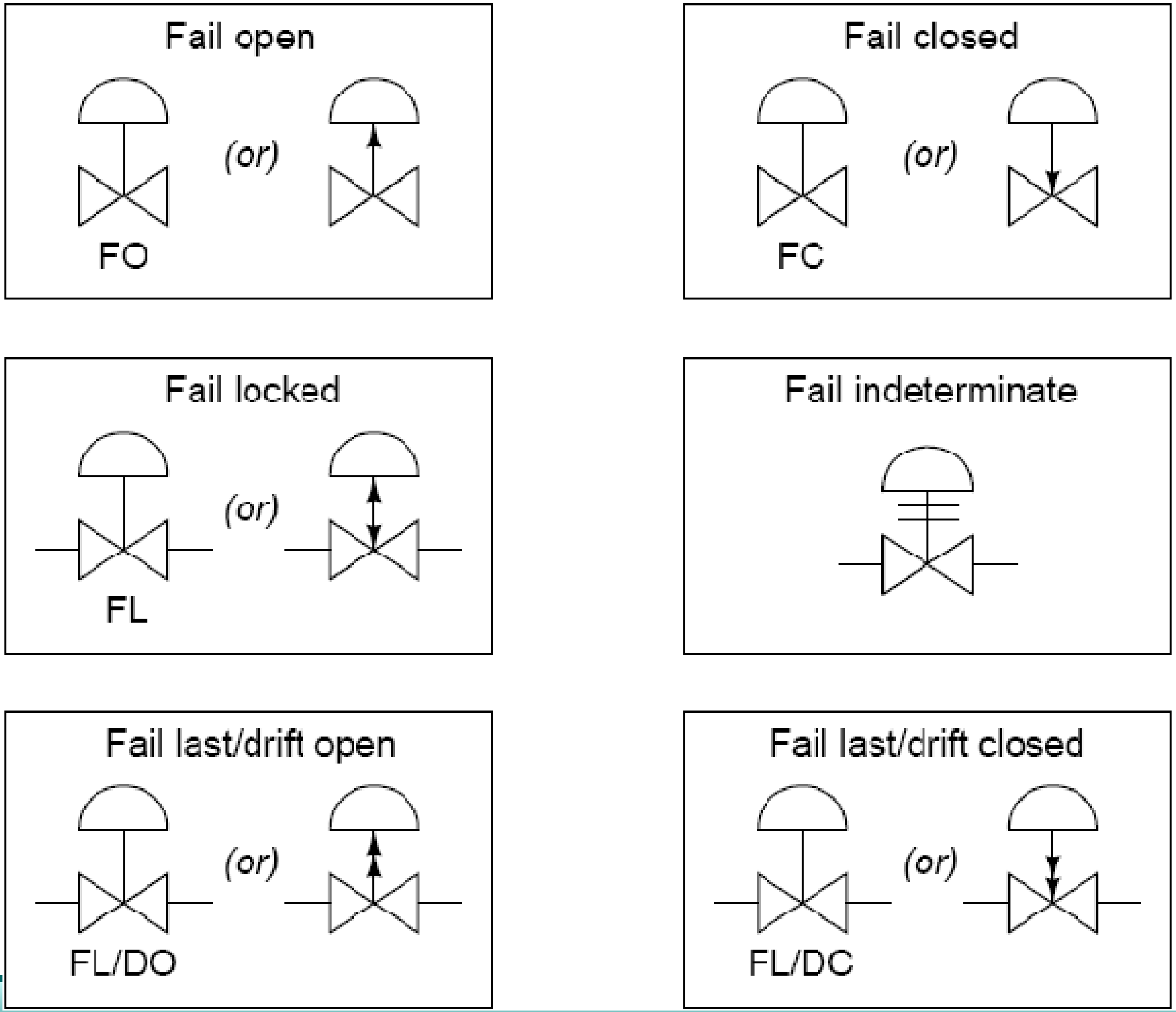
Thus, a sliding-stem, pneumatically actuated control valve may be made air-to-open or air-to-close simply by matching the appropriate actuator and body types.

The most common combinations mix a direct-acting valve body with either a reverse- or direct-acting valve actuator, as shown in this illustration:





Valve fail mode may be shown in instrument diagrams by either an arrow pointing in the direction of failure (assuming a direct-acting valve body where stem motion toward the body closes and stem motion away from the body opens the valve trim) and/or the abbreviations “FC” (fail closed) and “FO” (fail open). Other failure modes are possible, as indicated by this set of valve symbols:



For example, consider this automated cooling system for a large power-generating engine: Clearly, it is more hazardous to the engine for the valve to fail closed than it would be for the valve to fail open. If the valve fails closed, the engine will surely overheat from lack of cooling. If it fails open, the engine will merely run cooler than designed, the only negative consequence being decreased efficiency. With this in mind, the only sensible choice for a control valve is one that fails open (air-to-close).