FUNDAMENTAL PRINCIPLES OF PRESSURE REGULATORS

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INTRODUCTION

The following paper will concentrate on the fundamentals and principles of natural gas pressure regulators. In the gas regulator's conception it was mainly a device used to reduce high pressure to a more usable lower pressure. Today, more is expected from the performance of the pressure regulator. Pressure reduction is no longer the only function needed. The regulator is considered an integral measurement instrument that must adhere to the stringent codes put forth by the U.S. Federal Department of Transportation and many state Public Utility Commissions.

In order to understand the principles of pressure regulation this paper will focus on:

I. OPERTION
II. DROOP VS. BOOST
III. CHANGING IN INLET PRESSURE VS. MECHANICAL ADVANTAGE
IV. SAFETY MECHANISMS
V. KEYS TO SELECTION
VI. CONCLUSIONS

REGULATOR CLASSIFICATIONS

With few exceptions, gas pressure regulators can be classified into either of the following two categories:

1. Self-Operated Regulators (also known as Spring-Loaded)
2. Pilot Regulators
   - Constant-Loaded (a.k.a. Pilot-Loaded)
   - Pilot Operated (a.k.a. Two-Path Regulation)
   - Pilot Unloading (a.k.a. Pressure Unloading)

The Pilot Regulator category can further be classified into the three sub-categories of Constant-Loaded, Pilot Operated, and Pilot Unloaded. Make no mistake; these three design are vastly different and, thus, will exhibit significantly different performance characteristics. Each of these designs is covered in more detail later in the paper.

REGULATOR DEFINITION

A pressure regulator is a feedback control mechanism designed to maintain a constant downstream pressure through the manipulation of gas flow. By definition, a regulator is composed of three essential components (see Figure 1 illustration):

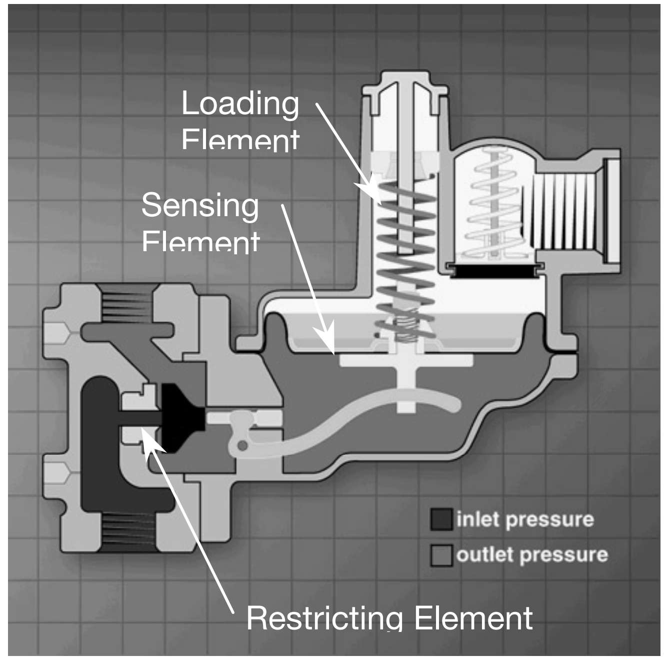


FIGURE 1.

1. ***Restricting Element*** — A restriction which allows gas to flow through the regulator at a reduced pressure to meet downstream demand. In most cases this consists of a resilient valve seat (plug) and a sharp edged orifice.
2. ***Measuring Element*** — A device that continuously senses changes in downstream pressure caused by changes in downstream demand and transmits a signal to open or close the restricting element accordingly. This is typically an elastomeric diaphragm.
3. ***Loading Element*** — Adjustable force which is continuously compared to the downstream pressure by the measuring element to determine what signal (open/close) to transmit to the restricting element. In pilot regulators the loading element is gas pressure.

SPRING-LOADED REGULATOR OPERATION

The main function of any regulator is to provide a flow of gas through the regulator to match the downstream demand while holding pressure constant. In a spring-loaded regulator three devices are employed to achieve this — a restricting device (usually an orifice); a sensing device (diaphragm); and a loading device (spring or pressure). Tying these three things together is a mechanical linkage (usually called the valve stem and/ or lever) that acts like a "see-saw." The linkage works to balance the forces associated with the three above devices.

A pseudo free-body diagram gives a representation of this balancing act is shown in Figure 2.

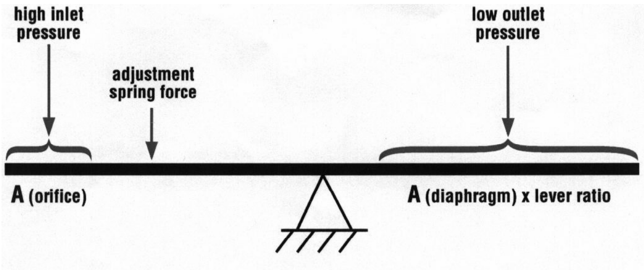


FIGURE 2. Regulator Force Balance

In all regulators two types of forces exist: 1) opening and 2) closing forces. These two forces act on the mechanical linkage with one trying to close the valve (shutting off gas flow) while the other works to open the valve (increasing gas flow). Under steady operation the sums of the opening and closing forces are always equal but opposite in direction giving a static equilibrium condition. As in any static equilibrium condition, the valve will remain in a fixed position until one of the forces change, upsetting the equilibrium. The valve will then reposition again until the forces are again in equilibrium. In a spring-loaded regulator, the sum of forces on the mechanical linkage can be expressed as follows:

Opening Forces = Closing Forces

or

$$F_i + F_s = F_o$$

Where:
- F_i = Inlet Pressure Force
- F_s = Spring Force
- F_o = Outlet Pressure Force

This equation assumes there are no frictional effects inside the regulator.

The opening forces consist of one mechanical and one pneumatic load. The high-pressure inlet gas creates a pneumatic force (F_i) pushing on the face of the valve seat forcing open the valve. An adjustable spring force (F_s) assists the high inlet pressure by pushing on the sensing device (diaphragm), opening the valve to maintain the set pressure. These forces can be calculated as follows:

$$F_s = [K][x] \quad \text{(Hooke's Law)}$$

Where: K = Spring Constant (lb./in.)
x = Spring Compression (in.)

$$F_i = [P_1][A_o]$$

Where: P_1 = Inlet Pressure
A_o = Orifice Area

The downstream pressure under the diaphragm creates a closing force (F_o) pushing against the diaphragm trying to close off the flow of gas. This force is calculated as:

$$F_o = \begin{bmatrix} outlet \\ pressure \end{bmatrix} \text{X} \begin{bmatrix} Effective \\ diaphragm \\ area \end{bmatrix}$$

In normal operation, the diaphragm will sense the outlet pressure force change and provide a force to the linkage. The linkage moves to control the flow through the valve to maintain the set outlet pressure. For instance, if the outlet pressure drops from the set pressure, the force under the diaphragm F_o decreases allowing the spring force F_s to reposition the diaphragm. This downward travel acts to move the valve seat away from the orifice, bringing the outlet back to approximately the desired set pressure. If the outlet pressure increases, the reverse happens. The linkage responds to the increased outlet pressure force and tends to restrict the orifice. The flow is reduced and the outlet pressure once again returns approximately to the set pressure.

In a perfect world our loading element (the spring) would supply a constant force, there would be no friction within the regulator or material hysteresis. If this were the case the regulator would supply a constant outlet pressure over an infinite range of gas flows. However, this performance is unattainable. Hindrances like 1) spring force linearity (Hooke's Law) and 2) the change in effective diaphragm area as the valve travels, effect the performance of the regulator. In Figure 3 typical spring-loaded regulator performance is shown.

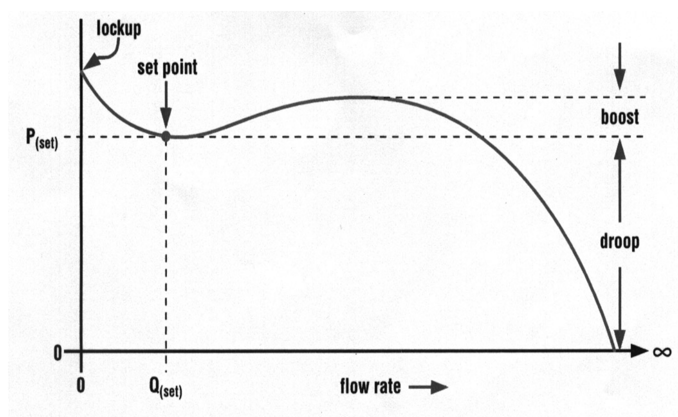


FIGURE 3. Typical Spring-Loaded Regulator Performance

The performance loss due to these effects is called pressure droop. Droop, and outlet pressure loss below set with increasing flow, is an ever-present problem in the performance of the regulator. To combat the effects of droop, a method called "boost" is employed. A better understanding of these principles will follow in the next section.

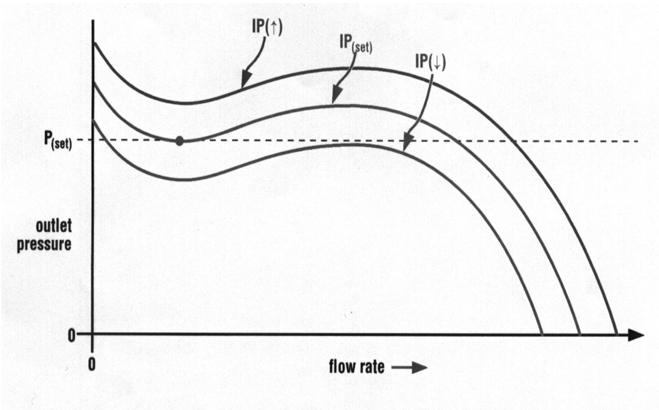


FIGURE 4. Inlet Pressure Effect on Performance

DROOP VS. BOOST

One contributor to droop is spring effect. Spring effect is a result of the reduction in spring force when the diaphragm and valve are in the wide-open position (fully down). The reduction in the spring force requires a lower outlet pressure to balance it. The second contributor to droop is diaphragm effect. As with spring effect, the wide open valve position (fully down) is again the problematic diaphragm position. The effective diaphragm area increases giving the outlet pressure more area to act upon, which in turn means a lower outlet pressure is needed to balance the "see-saw."

Acting together, both spring and diaphragm effect can cause a considerable mount of droop. To combat this performance deficiency, raising the outlet pressure to compensate is necessary. Boost is a method that uses gas velocity at high flow to create a low pressure under the diaphragm relative to the downstream pressure. This lower "sensed" pressure aids in the lowering of the diaphragm causing the valve to open and elevating the outlet pressure. The boosting needed to overcome the negative droop can be attained by various methods; angled valve seats, pitot tubes, and loading rings to name a few. Droop is not the only factor which effects the outlet pressure adversely. Varying inlet pressure can be a nuisance as well.

CHANGING IN INLET PRESSURE VS. MECHANICAL ADVANTAGE

As discussed earlier, one of the forces in the balancing act is the inlet pressure acting on the valve seat through the orifice opening. As the inlet pressure drops, the force trying to push open the valve also declines. This in turn allows the valve seat to reposition closer to the orifice thus decreasing the flow rate and downstream pressure. Again, the regulator needs to overcome this obstacle.

Mechanical advantage can answer this dilemma. This advantage, know as power ratio, directly relates to the diaphragm size and linkage ratio or the amount of travel of the diaphragm with respect to the valve seat. The larger diaphragm gives more force at a given pressure and combined with the lever ratio will equalize the outlet pressure over a range of changing inlet pressures.

Figure 4 shows a typical example of the effects of changing inlet pressure. Raising the inlet pressure from set pressure (curve "set") tends to increase the outlet pressure (curve "↑"). A reduction in inlet is observed in the bottom curve ("↓").

SAFETY MECHANISMS

Under normal operation a regulator will deliver service around the clock. But in the event of a regulator failure, what type of safety features exist?

Even though a regulator is built to give a constant outlet pressure, what happens if the valve fails to make the pressure reduction? An internal relief valve is incorporated into most self-operated regulators that have no other means of pressure relief.

In the instance that a foreign object gets trapped between the valve seat and the orifice preventing a positive shut off, pressure can continually build exceeding the set pressure.

If this pressure is allowed to increase, a dangerously elevated pressure situation will occur. This is where an internal relief valve steps in. The relief valve (Figure 5), usually a spring-loaded device, will allow the outlet to build to a small pre-determined amount over the set pressure before it opens, relieving gas through the diaphragm to the atmosphere. This relief pressure is typically not adjustable. The "odorous" gas smell will alert the customer and a service call will be made to repair the malfunction.

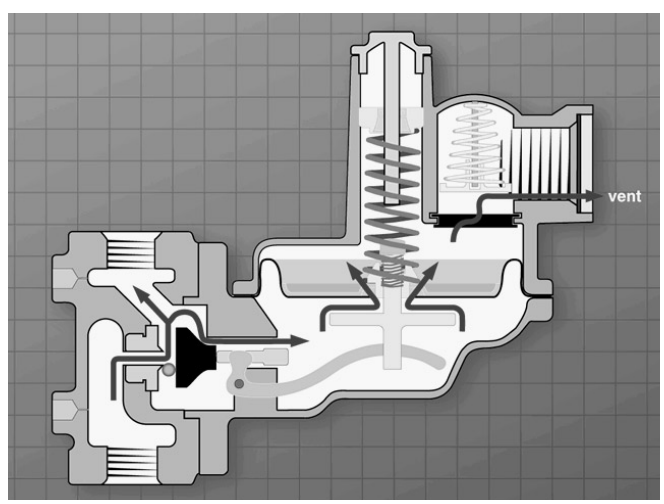


FIGURE 5. Internal Relief

Another built-in safety feature is the restricting orifice. As gas passes through the reduction in area there is a natural pressure drop. This drop varies with the area of the orifice opening. The smaller the opening, the larger the pressure drop. This translates to a smaller pressure buildup downstream in a failure situation. Safety is the key when dealing with a device that regulates the delivery of volatile gases to business and homes around the world.

PRINCIPLES OF PILOT REGULATORS

Why Use A Pilot Regulator?

Self-operated regulators may take a variety of forms. They can be single ported, double ported, balanced or unbalanced. All types have one common limitation which is "spring effect," resulting in some control inaccuracy. Self-operated regulators are exceptional devices for their simplicity, performance and cost. However, when more accurate regulation is desired, spring effect along with other mechanical factors will cause the self-operated style to fall short of expectations and needs. These shortcomings can be solved, by replacing the spring with a more constant diaphragm loading force. The result is a significant accuracy increase throughout the entire range of flow as shown in Figure 6.

CONSTANT-LOADED REGULATORS

A constant force from gas pressure can be used in place of a simple loading spring to eliminate this "spring effect." Constant-loaded regulators were designed with "straight line" regulation in mind (Figure 6).

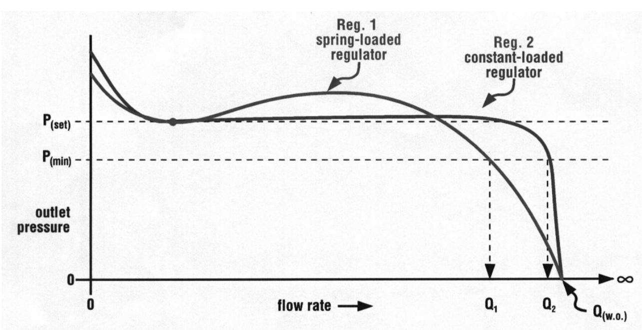


FIGURE 6. Spring vs. Pilot Regulator

Constant-loaded regulators use the outlet pressure from an additional pilot regulator as the constant loading force needed (Figure 7). The pilot regulator can supply a virtually constant pressure to the diaphragm throughout its range of movement. This constant force adds to the usable capacity range of a regulator by eliminating any "droop" caused by the loading spring. Outlet pressure will remain stable for essentially the full valve travel of the main regulator, achieving accuracy of ±1% of the absolute outlet pressure or better. Increased flow rates are also expected results with the constant-loaded regulators. The increased capacity does not occur without some disadvantages, however.

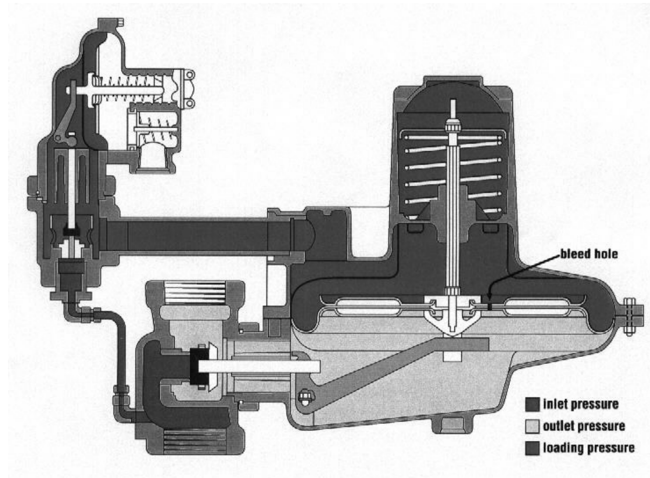


FIGURE 7. Pilot Loaded Regulator

Constant-loaded regulators respond poorly to fast off or "shock" loads. The nature of the design causes slow response to sudden load decreases. When the regulator is asked to shut off flow quickly, it takes time for this pressure difference to be communicated to the pilot through the bleed hole in the main diaphragm. The pilot relies on its pressure sensing through a bleed hole in the diaphragm and thus is not directly sensing and responding to the downstream pressure.

Constant-loaded regulators also require higher lock-up pressures under "no flow" conditions. The increased lock-up is needed to fully close the main valve as well as the pilot valve. This adds to the additional lock-up force needed. In special applications these characteristics can not be tolerated, therefore the need for a spring-loaded design is required.

PILOT-OPERATED REGULATORS

To obtain the advantage of both the spring-loaded and constant-loaded regulator performance, one must explore the use of "pilot-operated regulators." With the use of a more complex pilot and pressure sensing lines, the pilot-operated regulator can make rapid changes to downstream demand since the pilot is continuously sensing the downstream pressure. However, this design is still slower than the spring-loaded design due to the number of mechanical steps the regulator must undergo in order to open or close. Due to the gain and accuracy of the pilot, these regulators can control pressure with flat line response without many of the shortcomings of the constant-loaded style.

There are two basic types of pilot-operated regulators that will be discussed in the following:

1. Dual-path control
2. Pressure Unloading system

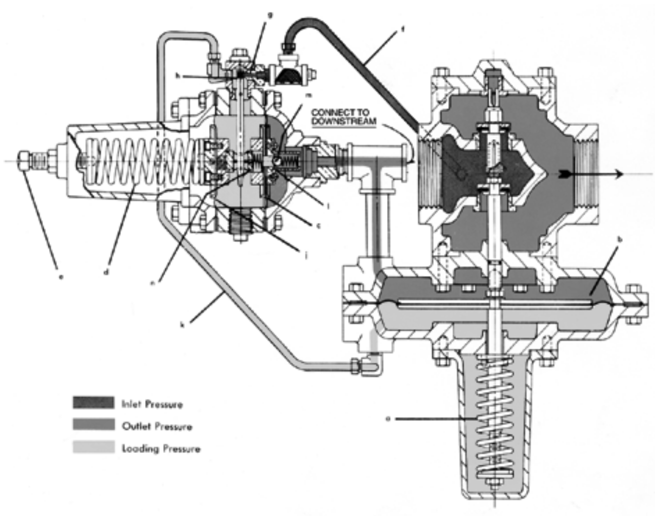


FIGURE 8. Dual-Path Regulator

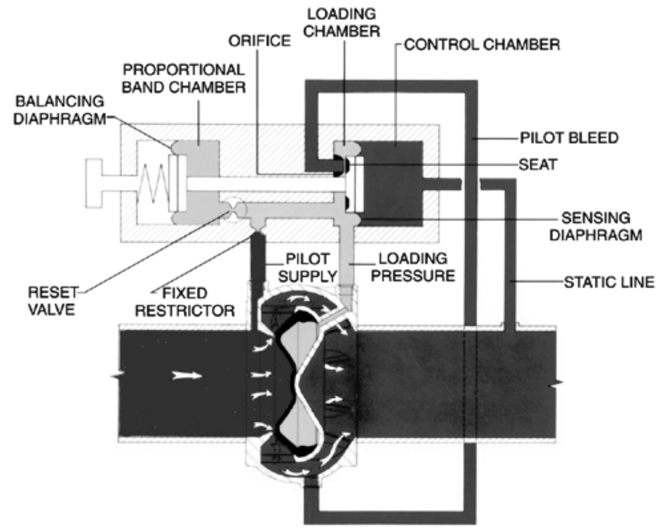


FIGURE 9. Pressure Unloaded Regulator

DUAL-PATH CONTROL

The first style of pilot-operated is a dual-path control system (Figure 8). The dual-path system incorporates a fixed and a variable orifice within the control system. The loading pressure that is generated between the fixed and variable orifice gives the pilot its “gain” and ability to quickly position the main valve with accuracy. With a small downstream pressure change, a high gain pilot can completely position the main operating valve from closed to fully open. This quick re-positioning of the valve MUST be controlled to insure stability.

As the load varies, the main valve will tend to respond quickly to re-position its valve; however, it is uncontrolled and can become unstable. The solution to this problem is to combine a high gain pilot with a slightly dampened main valve to give accurate and stable control. The sensing of the downstream pressure coupled with the loading pressure in the main case provide what might be called a shock absorbing quality. However, at higher inlet pressures some regulators of this design can still become unstable due to the high gain of the regulator. In these cases a pilot supply regulator must be employed in order to reduce the inlet pressure supplied to the pilot and, thus, desensitize the unit.

PRESSURE UNLOADING SYSTEM

The unloading regulator system is used mainly in the flexible element valves (Figure 9). The pilot functions to control the differential pressure across the flexible element causing it to open or close depending on the demand. This system also employs a fixed restriction and variable restriction. The fixed restriction is typically “tuned” to achieve a particular rate of response.

Upon a downstream demand increase, the pressure drop is sensed through the static line in the control chamber. Next, the pilot adjustment spring pushes the seat off the bleed orifice allowing the loading chamber pressure to escape downstream. The bleed orifice now exhausts loading pressure faster than it can be replenished due to the fixed restriction. The bleed orifice is then controlled by the pressure difference across the measuring element between the loading chamber and the control chamber. Finally, the reduced pressure behind the flexible element causes the flow to increase around the main valve’s annular seal restoring the set pressure.

Upon a no flow condition, outlet pressure rises forcing the pilot seat to close the variable pilot orifice. The pressure in the loading chamber equalizes with the inlet pressure across the fix restriction. Finally, the resiliency of the rubber forms a positive no flow condition in the main valve.

The unloading pilot can supply exceptional accuracy only when the system is properly tuned to its application. Certain situations will cause stability problems that can be addressed by a few methods. One method is to provide an adjustable inlet restriction to control the speed of pilot response. Another method regulates the speed of response through an independent proportional band chamber. Both methods use pilot control to eliminate the source of instability.

KEYS TO SELECTION

Matching the regulator to the application is most important. Accurate knowledge of the system in which the regulator will be placed is very crucial. The following are the variables that must be understood in order to select an appropriate regulator:

- Minimum and Maximum Inlet Pressure
- Minimum and Maximum Capacity
- Rate of Load change
- Load Diversity

Values for the minimum and maximum inlet pressures, as well as the maximum capacity for the regulator, need to be clear and accurate. Other factors such as rate of load change and load diversity must be take into consideration. Rate of load change refers to the on/off nature of the equipment downstream. For example, some boilers are equipped with "snap-acting" burner valves that open and close very quickly which then requires that regulator be able to respond at the same rate. Loaded Diversity refers to the probability that all equipment downstream will be operating simultaneously. If this probability is low, sizing the regulator for the "total connected load" may cause over-sizing of the regulator and ultimately instability at low flow rates.

The following "rules of thumb" should be applied when sizing any regulator:

- Use minimum inlet pressure expected and maximum flow required when considering capacity needs
- Choose the smallest orifice available that can meet capacity requirements
- Use maximum inlet pressure expected when considering "lock-up" and relief performance
- Choose the lightest adjustment spring available that can meet outlet pressure requirements (i.e., choose set point at upper end of spring range)

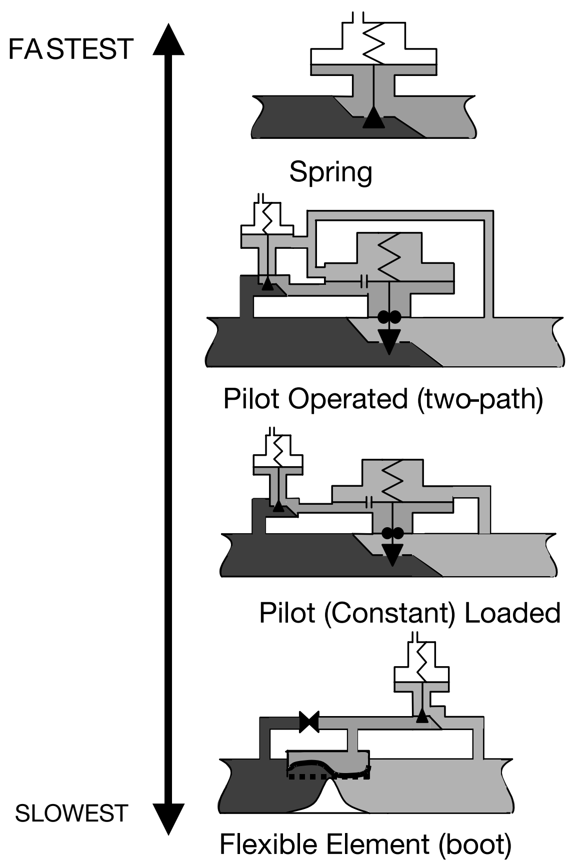


FIGURE 10. Regulator Rates of Response

Table 1— Regulator Summary Comparison

Parameter	Spring Loaded	Constant Loaded	Pilot Operated	Pressure Unloading
Typical Application	Service Regulator	Service Regulator	Service Regulator/ District	District/ Gate Station Regulator
Stability	Good	Good	Can be unstable	Can be unstable
Minimum Differential Required	No	Very little	Very little	Yes
Sensing Line Required	No	No	Some	Yes
Sensitive to gas contaminants	No	No	No	Yes
Variable Gain	No	No	Some	Yes
Speed of Response	Fast	Relatively Fast	Relatively Fast	Slow
Susceptible to inlet pressure swing	Yes	Yes	Yes	Yes
Product Cost	Low Cost	Moderate	Expensive	Expensive

The selection procedure then dictates the smallest orifice size to be implemented while allowing required flow capacity at minimum inlet pressures. The smallest orifice gives two benefits. First, it allows the smallest pressure buildup downstream in the event of a failure when using an internal relief type regulator. Secondly, it optimizes mechanical advantage by allowing less fluctuation in outlet pressure for a given inlet pressure change.

Another good practice is to use the lightest adjustment spring that will give you the outlet will minimize spring effect, which causes "droop." In addition, the internal relief valve has to work against the main adjustment spring to open. The relief valve will open at a lower outlet buildup given the lighter adjustment spring.

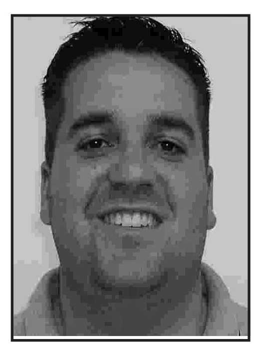
For spring-loaded regulator, the power ratio of a regulator is another selection criterion. This ratio, as previously discussed, is based upon diaphragm size and linkage or lever ratio. It is a measure of how well the regulator utilizes the downstream pressure to close against the upstream pressure. The larger the ratio the lower the lock-up pressure will be.

However, with increasing power ratios come cost hindrances. A larger power ratio means a physically larger regulator and a higher price.

When considering rate of loaded change, beware of the order of rate of response of various regulator types as shown in Figure 10.

CONCLUSIONS

Every type of regulator represents a compromise involving factors such as price, capacity, accuracy, stability, simplicity, safety and speed of response. Table 1 below summarizes the advantages and disadvantages of the various regulator designs available. It is important that manufacturers, utility engineers, and field service personnel alike understand the workings of self-operated and pilot regulators. A correct analysis of the application will give the customer clean, safe, and accurately controlled gas. Working closely with the manufacturer and matching the right regulator to the right application will also lead to a problem free life.



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