Study Unit

# Pneumatics, Part 2

By

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# Preview

In the last unit, you learned about many of the common components used in pneumatic systems and some of their features, functions, and schematic symbols. In this unit, you'll continue to study these components in more detail, including how they're selected, how the right size is determined, how the components function together to make a practical system, and how a system can be diagnosed for faults if it isn't working properly. You'll learn why pneumatic systems may have advantages over other types of mechanisms, and how to select, install, and maintain pneumatic-system components used in manufacturing or other environments.

We'll work with a simple pneumatic system as an example to familiarize you with basic techniques and calculations. You'll also learn hints and "rules of thumb" for the installation and maintenance of these systems, and you'll learn how systems behave when the components are interconnected.

**When you complete this study unit, you'll be able to**

- Determine pneumatic cylinder and air motor sizes
- Identify components and functions of pneumatic systems from schematic drawings
- Specify conductor and receiver sizes based on system requirements
- Calculate SCFM requirements for pneumatic loads
- Determine probable causes of failure for pneumatic applications
- Understand basic maintenance requirements of pneumatic systems

Contents

# Pneumatics, Part 2

## PNEUMATIC SYSTEMS AND APPLICATIONS

### Advantages and Applications of Pneumatic Power

A *pneumatic system* stores the potential energy of compressed air and then distributes it as kinetic energy to do the required work.

Pneumatic power offers several benefits to the designers and users of mechanical systems. For several applications, pneumatic power offers clear advantages over electrical or hydraulic systems. For example, pneumatic systems can be used in areas where spark hazards are severe, such as in areas containing dust, flammable liquids, or chemicals.

Pneumatic systems can be easily and accurately controlled. A single source of compressed air can supply many tools or machines with an abundant energy supply. Valves and manifolds can distribute air to the devices as it's needed. Motors and cylinders can be started, stopped, accelerated, and decelerated with great accuracy. Pneumatic components are lightweight compared with similar electrical and hydraulic motors and actuators. In addition, pneumatic forces can be multiplied and easily controlled, providing output forces from less than an ounce to many tons. Pneumatic motors can also provide full torque or force at zero or low speed (which electrical actuators and motors can't do) and can maintain the load without overheating.

Pneumatic power systems can be combined with electronic and computer controls to make truly unique applications. “Smart” pneumatic components combine the advantages of air motors and cylinders with the connectivity and integration potential of computers: networked computers for very sophisticated process control capability can control pneumatic components and systems. With advances in materials and new demands for efficient and low-cost manufacturing techniques, new ideas and uses for pneumatic systems are generated every day. A visit to the National Fluid Power Association Web site at http://www.nfpa.com will show you new applications and potential uses for pneumatic power, as well as new products that advance state-of-the-art pneumatic devices and controls.

In summary, pneumatic systems are generally

- Unaffected by extreme conditions of temperature and environmental conditions
- Unaffected by electrical interference from lightning, machinery, or power system circuitry
- Able to function with large variations of pressure
- Able to provide high torque or force at zero speed without overheating
- Able to operate without generating sparks, for use in explosive environments
- Able to generate complex movements at high speeds
- Relatively easy to maintain and service
- Relatively inexpensive to install

As your knowledge of pneumatic applications continues to advance, you’ll also need to learn much more about computers and networks to understand how advanced computer-controlled pneumatic systems are installed, operated, and maintained. However, the principle of their basic operation remains the same whether they’re controlled by a hand lever or a computer signal.

## Manufacturing Applications

The energy stored in pressurized air has been used in factories and early automation applications for many decades, and compressed air can be used to power equipment to perform almost any mechanical movement. The great power of pneumatic equipment is in its ability to adapt to rapid production processes, such as those found in automatic production lines using robots (Figure 1). Pneumatic systems serve various work-handling functions, including sorting, feeding, clamping, and tool movement (Figure 2). Pneumatic systems are found in industry for paper handling and packaging; in welding machines for clamping and wire feeding; in material handling for lifting with cranes; and in machines for bending, stamping, and punching.

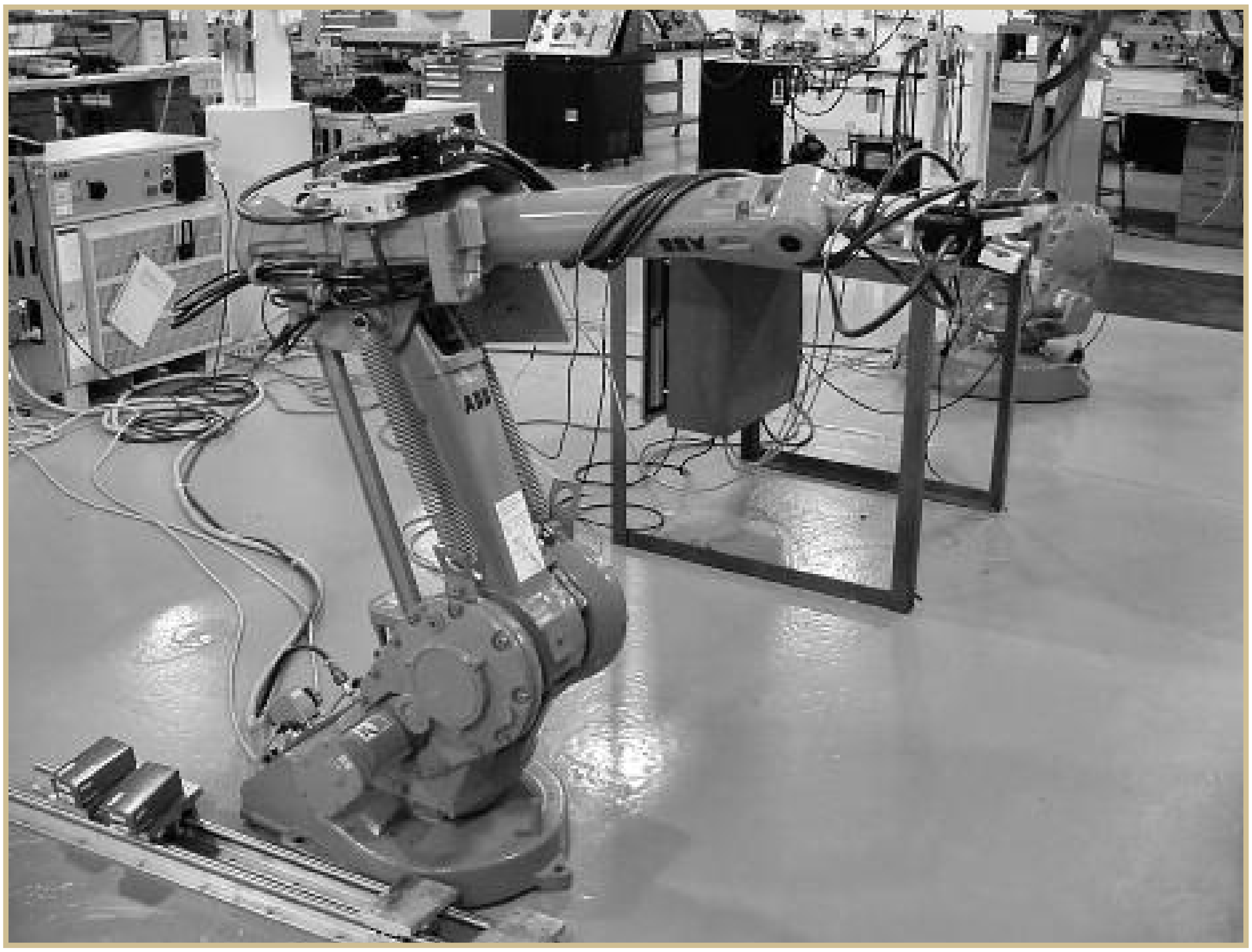


***FIGURE 1—Manufacturing applications for pneumatics include sophisticated work-handling robots.***

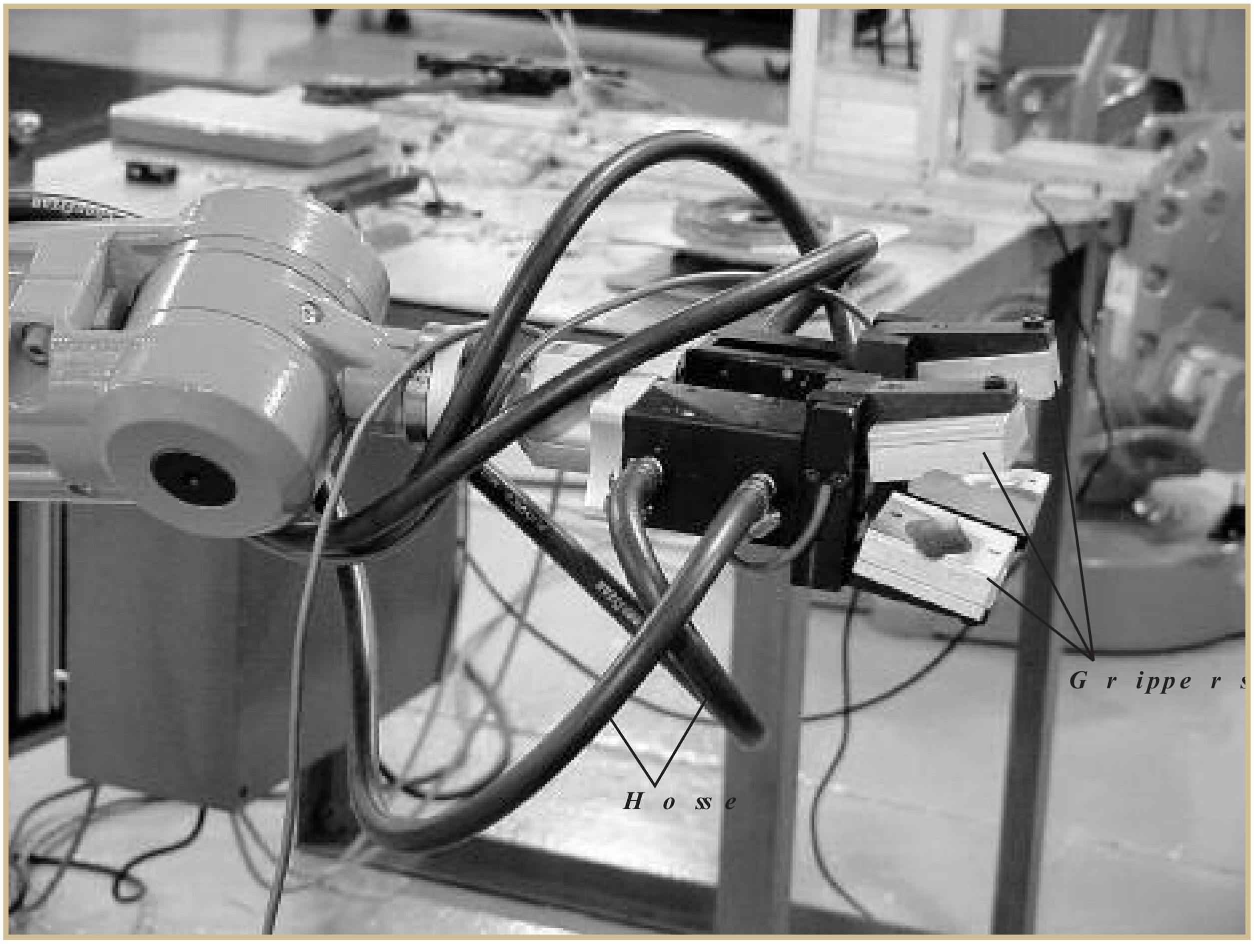



*FIGURE 2—A wide range of motions are available with different pneumatic actuators.*

Manufacturing applications vary in complexity, from the very simple "blow-off" for cleaning machines to heavy-duty robotics used in high-speed production-line applications (Figure 3). Pneumatic systems offer manufacturing facilities ease of energy distribution via pipes and tubing. And because of the relatively low maintenance requirements, many factories use pneumatic power for many functions you would normally think would be performed with electric power. Some typical applications include transporting materials such as powders or other small objects; lifting and moving production parts for manufacturing operations; "pick and place" operations for products that are individual parts or are in boxes or bottles; forming, moving, or sorting parts on conveyor lines; assembling parts for further processes, such as electronic circuit boards that are "stuffed" with components and then soldered automatically; and moving tools into position for production machining operations such as drilling.

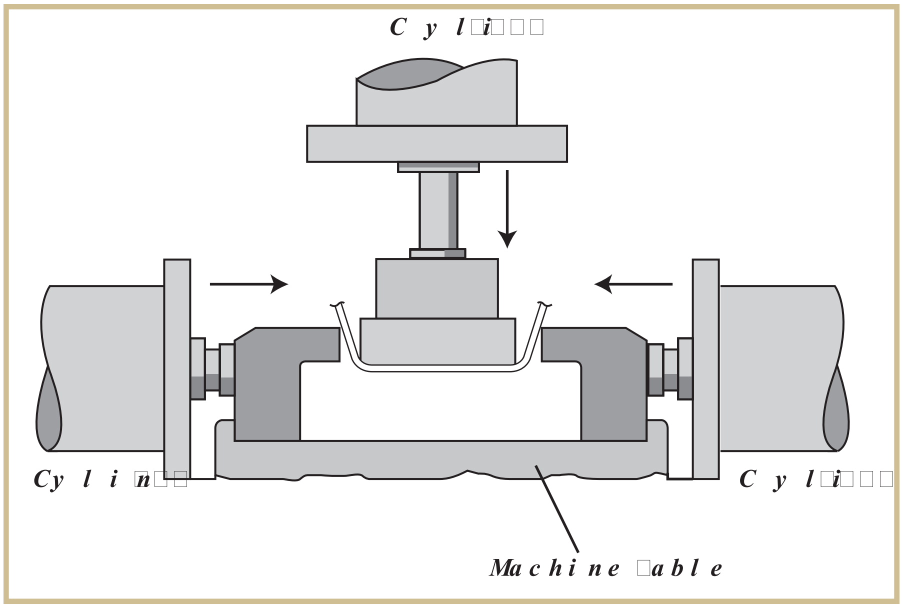


*FIGURE 3—Pneumatic cylinders and jigs can perform many manufacturing operations quickly and efficiently. Here a bracket is formed by three pneumatic cylinders.*

Production-line workers may also use air-powered tools such as wrenches and drills to assemble products on conveyor lines, such as automobiles.

## Pneumatic Tools

Pneumatic tools (Figure 4) are very popular for both industrial and commercial applications. Pneumatic wrenches, grinders, and chisels are common in vehicle repair shops, as are rotary and in-line sanders. Paint guns are used extensively in spray painting processes, and the air-handling equipment that controls dust can even be considered a pneumatic system. At construction sites, larger tools such as jackhammers are also air-powered and are served by trailer-mounted air compressor systems that supply air to many types of air tools.

Pneumatic tools have revolutionized the assembly of many products. In the construction industry, the time required for home construction has been significantly decreased due to the advent of air-powered nail guns (Figure 5) for framing and roofing applications. These devices are easily powered by portable compressors and greatly reduce labor time.

***FIGURE 4—A wide assortment of pneumatic tools has revolutionized many industries.***

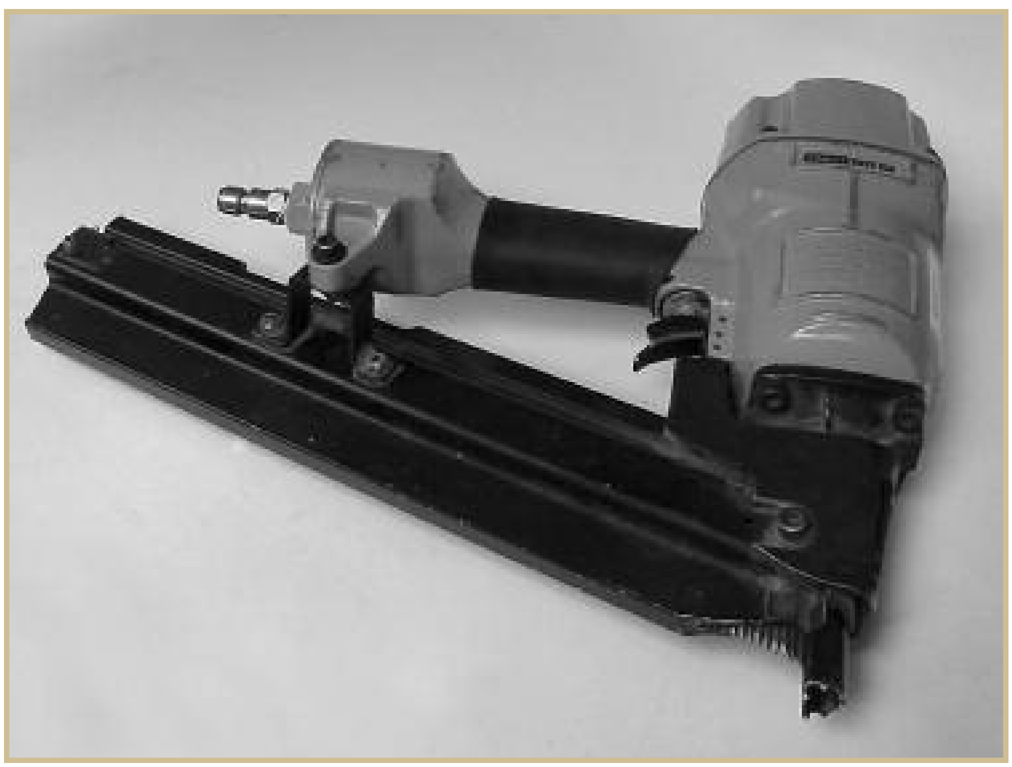


***FIGURE 5—In the construction industry, pneumatic tools accomplish much of the heavy fastening quickly and safely.***

### Other Applications

Other applications for pneumatic power range from the ordinary to the exotic. For example, you'll run across pneumatic systems in door-opening mechanisms for trains and buses. Vehicles such as trucks use brake systems that rely on an air supply to provide braking forces to large trailers. More exotic applications include aircraft landing gears, loading and unloading equipment, and door controls. One of the more unusual developments is called a *fluidic muscle,* by the Festo Corporation in Hauppage, New York. This device mimics the tensile forces of a muscle by applying air pressure inside a flexible tube of fiber mesh between two connectors. As the pressure increases, the mesh bulges outward, shortening the tube along its length and generating high *tensile* (pulling) forces. Fluidic muscles can be used to provide very high and precisely controlled forces for bending and forming operations in metalworking applications.

As you can see, there are endless possibilities for creative and effective uses of pneumatic power. In the future, you can expect to see pneumatic applications combined with computers, electrical controls, and high-tech sensors to create even more unusual but efficient approaches to problem solving in industrial and commercial environments.

## Basic System Requirements

As you learned in the previous unit, all pneumatic systems have some common elements that you'll need to know and understand to become an effective technician. We'll look at each group of components and learn proper selection and application techniques for a simple pneumatic system.

The first group is the *air preparation* components. These include the compressor, dryer, filters, regulators, and lubricators, which can often be combined in the same units. The person sizing the compressor needs to take into account all of the existing uses of air in the system, plus any expansion requirements that may occur in the future.

Industrial class pneumatic systems typically operate at approximately 90 psi pressure, and with low frictional resistance.

The next group of components is the *control valves. Valves* are the "control center" of a pneumatic system and are available in multiple configurations of ports and positions. Valve functions are designated by ports/positions—designations where, for example, a "5/3" valve indicates the valve has five ports and three possible positions. Depending on the complexity of their purpose, the valves can be individually placed in the circuit, or they can be stacked in islands or on manifolds where conductors can be shared to simplify installation and maintenance, as shown in Figure 6. The actuation methods range from electric signals such as computers, switches, or sensors to manual activation by hand or foot levers. Pneumatic valves (Figure 7) can operate other pneumatic valves by supplying pressure to one of the control ports (labeled X, Y, Z or 10, 11, 12). This is called *pilot operation,*

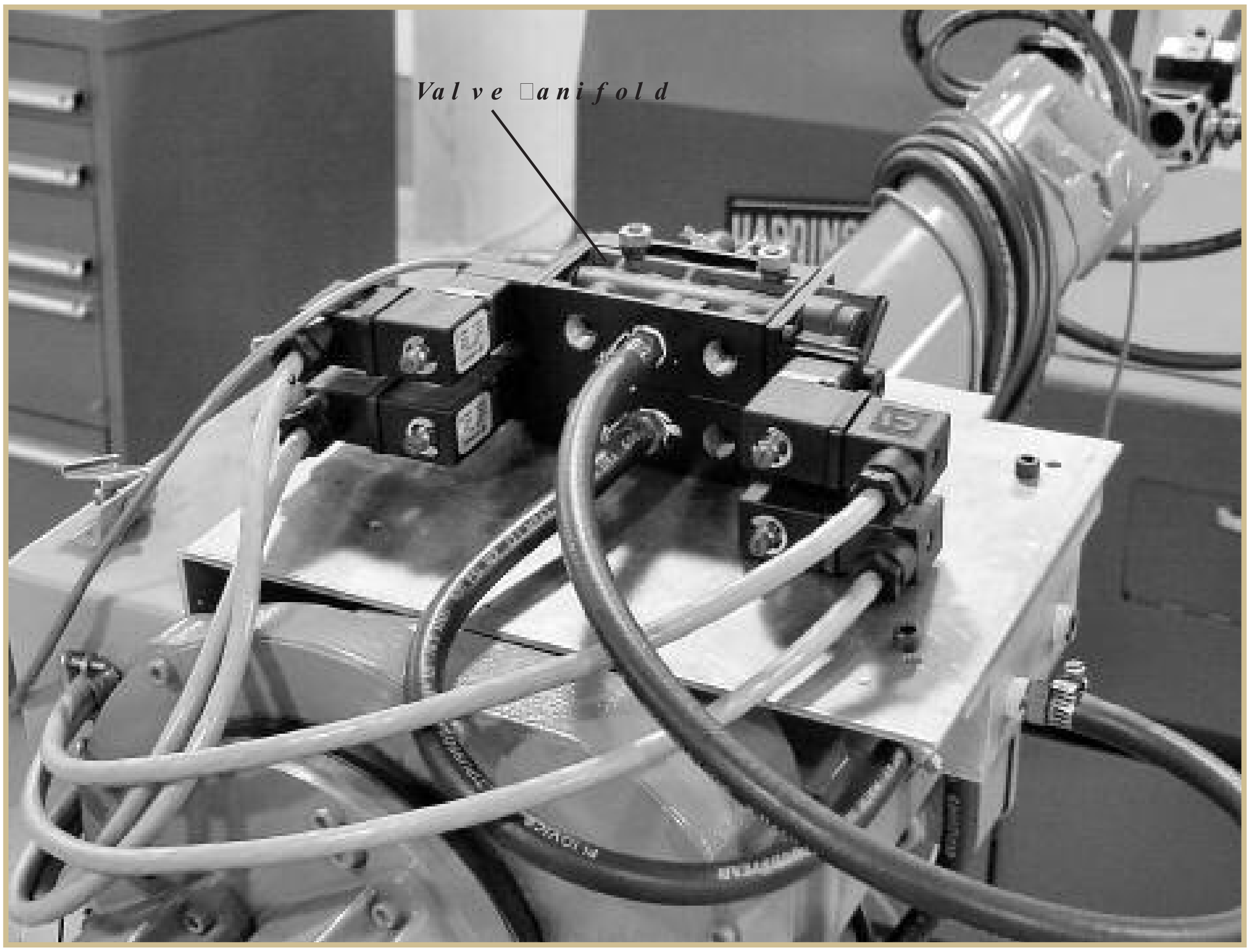
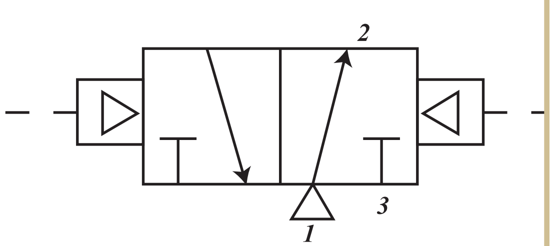



***FIGURE 6—The complexity of some equipment demands many controls to be mounted and connected efficiently. Valve manifolds like this one allow relatively few conductors to connect many system components.***

which is often used to cause events in specific sequences or at certain times. Special devices can "tweak" a circuit, such as time-delay valves, *one-shot devices* (valves that cycle one time and then stop until reset again for another cycle), and *shuttle valves* that can quickly redirect airflow. Shuttle valves are useful for operating a cylinder from two possible control valves, and isolate each valve from the other.

A valve's primary pressure port is identified with a *1* or *P* on the system schematic. Higher numbers, such as 10, 12, or 14, are typically used to identify the valve's control ports.

*(A)*




*(B)*

***FIGURE 7—(A) Pneumatic valves can be pilot-operated, as this one, and can be relatively small depending on the required airflow. (B) The schematic diagram of the valve indicates its form of activation. In this case, the open triangles at the inlet ports (dashed lines) indicate that the valve is pneumatically piloted.***

Sometimes valves can have two methods of operation, as in cases where a valve may be operated either from an electric signal from a sensor, or by a hand lever (Figure 8). On the body of the valve, you'll find a schematic symbol that illustrates the proper application for that valve. If the schematic symbol shows two components in series, both components must be present. This corresponds to a logical AND operation. If the symbols are drawn side by side, *either* method will operate the valve, corresponding to a logical OR operation. This is shown in Figure 9. You'll learn more about pneumatic logic applications later.

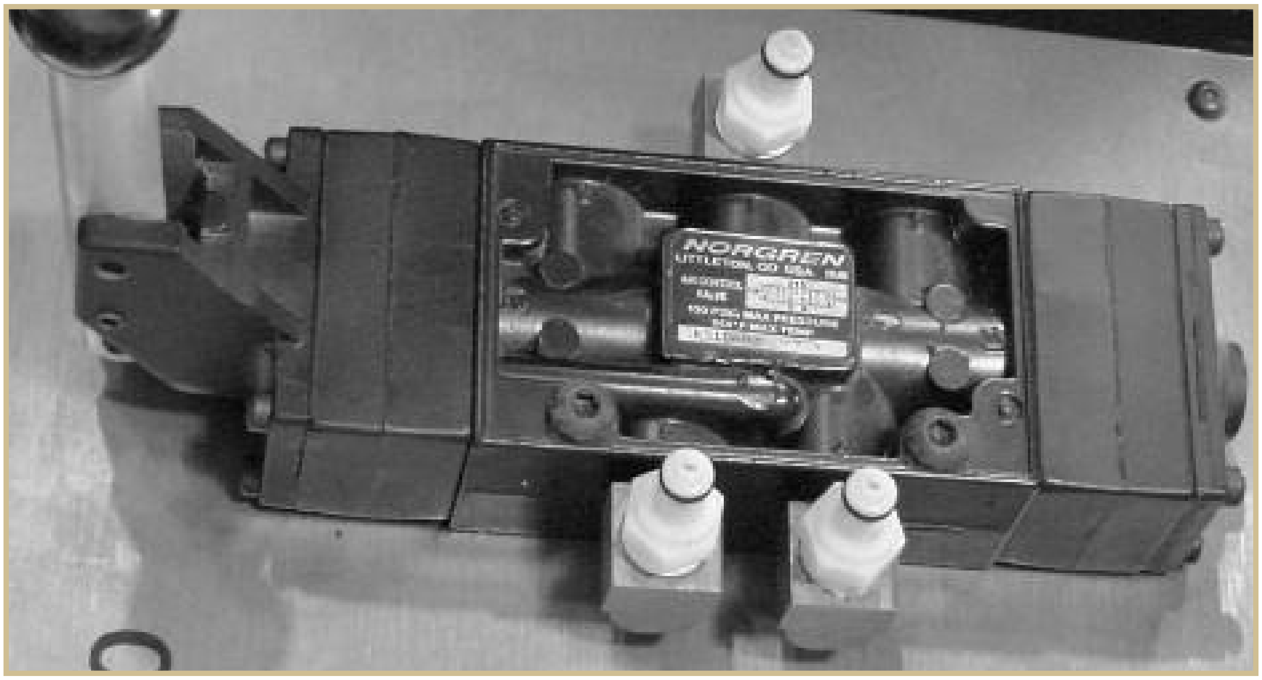



***FIGURE 8—Pneumatic circuits are often activated by hand controls.***

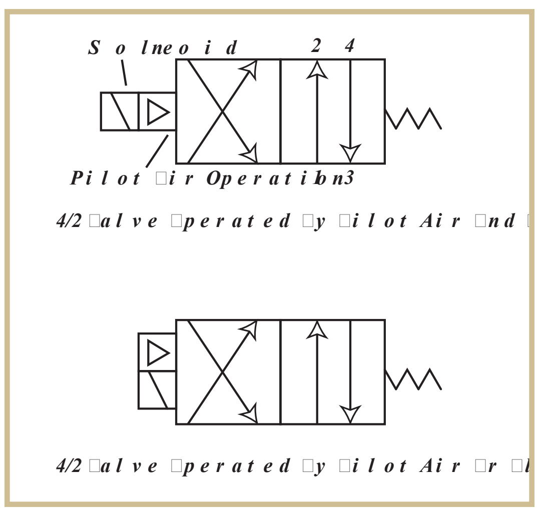



***FIGURE 9—Pneumatic valves can be operated from multiple sources to implement different logic functions such as AND or OR.***

The last category of pneumatic components is *output devices.* These are the "muscles" of the circuit and the components that do the work by acting on the load that's served by the system. Typical output devices are air motors and cylinders, air tools, rotary actuators, presses, holding clamps, and robot arms. Components which may be attached to these devices are accessories such as mufflers (silencers), position switches (often built in), quick-exhaust valves to speed up actuation cycles, and sensors such as position (LVDT) or velocity (LVT) indicators. Pneumatic circuit design starts with determining how much work is to be done, how often or how many cycles per minute are necessary, and how big the pneumatic output device has to be to accomplish all of the tasks.

## Schematic Diagrams for Pneumatic Circuits

We've talked about individual pneumatic components and some of their important features, but it isn't until they're connected together that they can perform useful functions. When engineers conceive a manufacturing process and design the components to perform the required tasks, they'll draw (probably on a computer) a road map of how the components are connected together and controlled by the manufacturing personnel. This road map, known as a *pneumatic system schematic* or *pneumatic circuit diagram,* also serves to guide maintenance people to analyze the proper operation of the system, develop preventive maintenance schedules, list replacement parts, and troubleshoot the system when it isn't working properly. A pneumatic circuit diagram serves the same purposes as an *electrical schematic,* which is a shorthand guide to the layout of the components.

There are standards that specify how pneumatic schematics are to be drawn. The American National Standards Institute (ANSI) publishes standards for many industries, including the fluid power industry, as does the International Standards Organization (ISO). The ISO standard for fluid power symbols is ISO 1219-1. Many of the symbols for these and other standards are similar, and you're likely to encounter diagrams drawn to various standards. Since pneumatics are used worldwide for many applications, many countries have adopted similar standards; however, companies that do business in other countries often find they must conform to the buyer's standards. Here are some general things you should know about drawing conventions for schematics:

- Schematic diagrams are drawn to communicate the purpose and connections of a pneumatic system. The components in the circuit are *not* drawn in any relation to the physical location of the components or conductors.

- Circuit diagrams are drawn in their initial state as they are before the system is pressurized or before a start signal is applied.

- Cylinders and control valves are usually drawn horizontally, and the lines representing conductors are drawn with as few crossovers as possible to avoid confusion.

- Port numbers or letters are shown on control valves.

- Compressors and primary air-treatment components often don't appear on schematics showing system functions. Entry points for pressurized air are shown simply as circles (or sometimes unfilled arrow heads) on the schematics.

The diagram in Figure 10 is a simple circuit illustrating a sample pneumatic application for a two-cylinder circuit that lifts and moves a load. This diagram follows a numbering system from the ISO standards that help technicians and engineers to read and interpret schematic drawings. It isn't the only one used, and you'll need to consult your own facility's standards to be able to determine how to draw and label diagrams.

By studying the schematic for systems you encounter, you'll be able to learn about drawing conventions and how components are connected to accomplish specific tasks. The first point to notice about the circuit in Figure 10 is that the compressor and primary conditioning equipment aren't shown. The point of high-pressure entry is represented as a circle with a dot inside below the component marked *0.1* on the schematic. Individual components are labeled with numbers

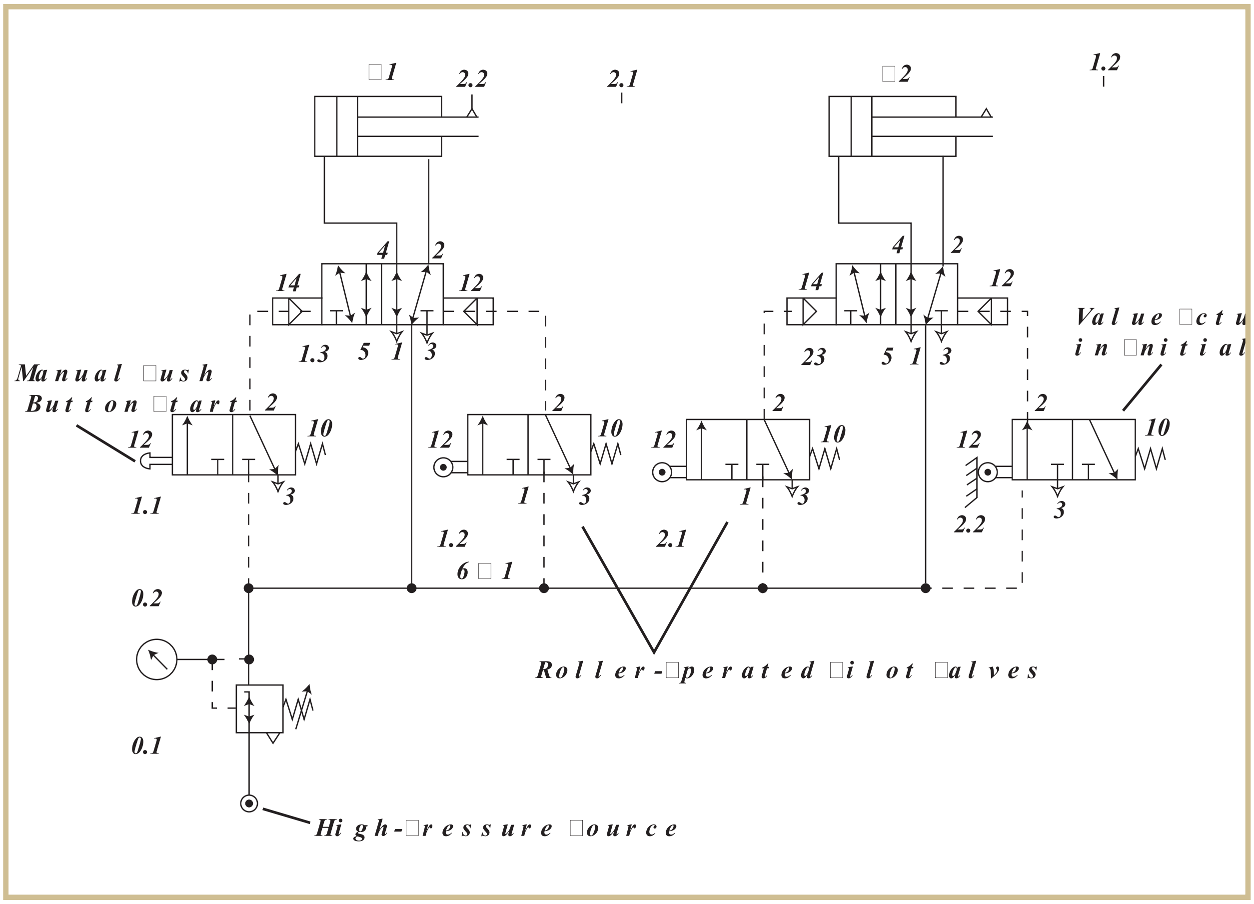



**FIGURE 10—This is a typical schematic diagram showing various symbols and connection methods for a sample pneumatic application.**

that are associated with their function and the sequence with which they operate. In this case, *0.1* is a pressure regulator, and *0.2* is the system pressure gauge. It has a prefix of *0* because it doesn't contribute to a sequence of operation. Sometimes the pressure may be marked on the side by the regulator symbol. Also, some conventions will have the conductor size labeled next to each run of piping.

The central components of this application are the two cylinders marked *Z1* and *Z2,* although many times they're labeled *Cylinder 1, Cylinder 2,* and so on. Other components are marked according to the number of the sequence step (1.x, 2.x, 3.x, and so on), with a second number that's consecutive starting from the bottom of the schematic. Thus, you see valve numbers *1.1, 1.2,* and *1.3* and *2.1, 2.2,* and *2.3* in the schematic. All components that control *Cylinder 1* have a component number that begins with *1.* In this system, valves

*1.3* and *2.3* are the valves that supply the air to move the cylinders; therefore, they'll require conductors. You'll learn how to determine the size of the cylinders, valves, and conductors in a later section of this unit.

Valves *1.1, 1.2, 2.1,* and *2.2* are control valves that supply pilot signals to main valves *1.3* and *2.3.* Notice that the conductors are shown as dotted lines. This is the symbol for pilot air. Since it's a signal, smaller conductors can be used. These valves are also mechanically operated by rollers that are physically connected in some way to the cylinder rods. Valve *1.1* is the start valve that initiates the sequence, and it's operated by a hand-push button. Notice that all the valves are spring-returned.

Notice the numbered marks at the rod sides of the cylinder. These are called *marking strokes* and are indications of where mechanically actuated valves are located. The numbers refer to the valve that's operated at the rod position. For example, at cylinder *Z1,* the rod will extend to contact valve *2.1,* which in turn operates cylinder *Z2*. If a valve (or other component) is only operated under power in one direction, an arrow is added to the marking stroke that shows the direction of travel to actuate (Figure 11). Valves that aren't started in their neutral position when the circuit is energized, but rather are started in their actuated state, appear that way in the drawing. For example, valve *2.2* is a mechanically operated valve that has a spring return when not actuated. However, it starts in this circuit in the actuated position. Notice that the schematic shows the valve positioned to the right, indicating that "something" is contacting the roller actuator. This tells you that the valve is initially pushed to the right by the rod of cylinder *Z1*. Notice the marking stroke at *Z1* showing the number *2.2.* This indicates that when the rod of *Z1* is retracted, valve *2.2* is actuated.

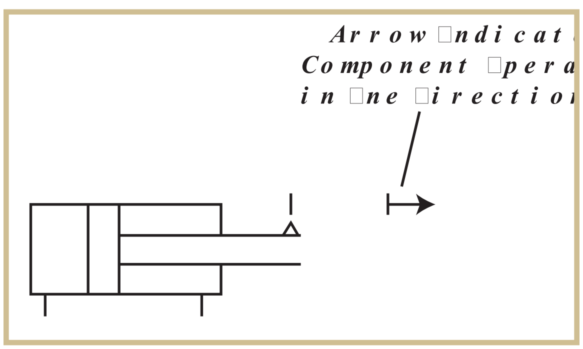



***FIGURE 11—Marking strokes next to cylinder symbols indicate positions of switches and valves, as well as in which directions of travel the valve can be actuated.***

Try to follow the sequence that occurs when start valve *1.1* is pushed:

Initially, pressure is applied to the rod ends of cylinders *Z1* and *Z2,* so that they're both retracted. Valve *2.2* is actuated; valves *1.1, 1.2,* and *2.1* are all in their neutral or unactuated state.

To start the cycle, valve *1.1* is depressed. Valve *1.3* is shifted to the right, the rod end of *Z1* is exhausted, and pressure is applied to the extend (left) side of *Z1*. Valve *1.3* stays shifted to the right even after *1.1* is released because pilot port *12* is connected to the exhaust port. Releasing *1.1* connects port *14* to exhaust, thereby allowing it to be moved when valve *1.2* is actuated.

Cylinder *Z1* begins to extend. Valve *2.2* is deactuated, causing the pilot air to port *12* of *2.3* to be exhausted. This will allow the valve to be shifted by *2.1.*

The cylinder *Z1* rod reaches the roller mechanism and actuates *2.1.*

Valve *2.1* shifts to the right, causing valve *2.3* to shift to the right. This connects the rod end of *Z2* to the exhaust port and applies pressure to the extend side of *Z2.*

The rod of *Z2* reaches the roller of valve *1.2* and actuates the valve. Valve *1.2* shifts to the right, pressurizing pilot port *12* of valve *1.3,* causing it to move back to the left.

This causes valve *1.3* to exhaust the extend side of cylinder *Z1,* retracting the rod from the extend position. This deactuates valve *2.1,* returning it to its starting position (shifted to the left).

Pilot port *14* of valve *2.3* is exhausted, and the rod from *Z1* retracts until it actuates valve *2.2*. Pressure is applied to the rod side of *Z2,* causing it to retract.

All components have now returned to their original positions.

The simplified functional diagram in Figure 12 indicates the positions of the various components during the cycle. If you study the diagram, you'll see how the components change position in relation to each other to cause the intended actions of the cylinders. These functional diagrams can be quite complex, but they can be used to troubleshoot circuits that fail or exhibit decreased performance.

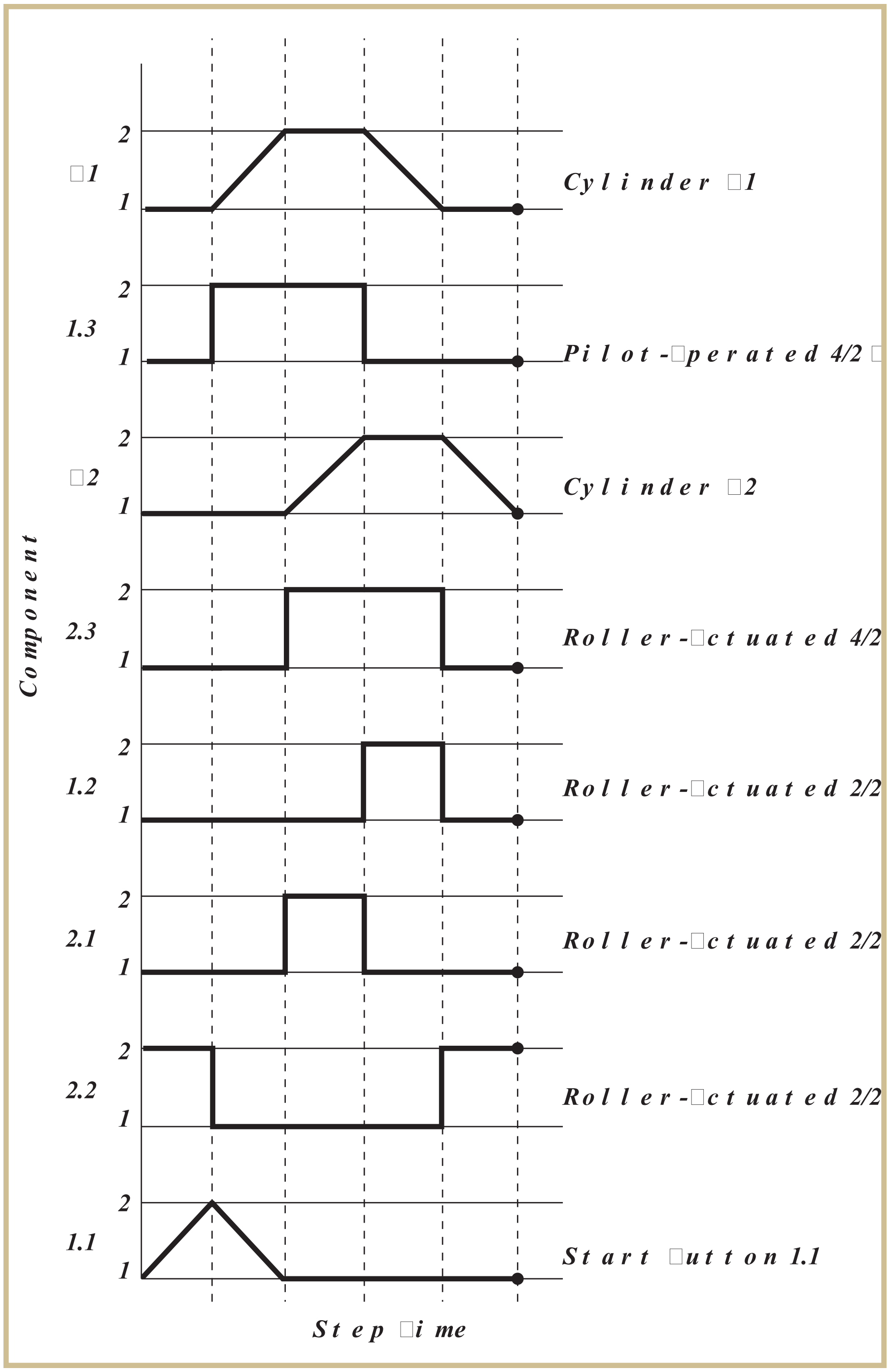



***FIGURE 12—A simplified functional diagram can illustrate how components function in relation to each other.***

This is a fairly simple circuit that illustrates how various components are connected to accomplish a task. You'll see many other examples of pneumatic circuit configurations. Figure 13 shows a common method of allowing cylinders to be retracted or extended quickly using what are called *quick-exhaust valves* (also known as *shuttle valves*). They're valves with a sliding ball or spool that's moved off its seat when air

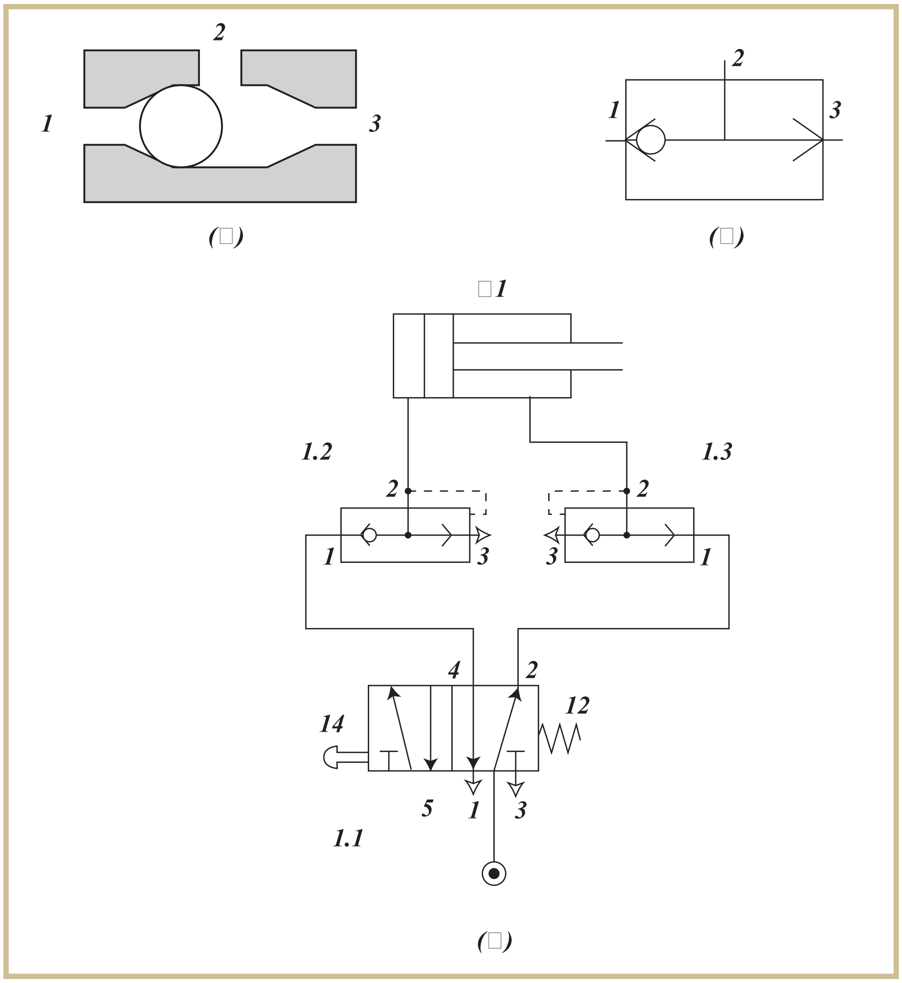



***FIGURE 13—Quick-exhaust valves can speed up cylinder motions by dumping air close to the cylinder instead of directing it back through a valve.***

from the cylinder tries to flow through to the exhaust port. The dotted lines indicate that the initial actuation is from pressure on the cylinder side of the valve.

Figure 14 shows a common way of regulating the speed of extension and retraction with flow-control valves. This example shows regulation in both directions, although it's often done in only one. Notice that the flow control occurs in the unpressurized side of the cylinder. Pressure supplied to the rod or piston end of the cylinder flows relatively freely through the check valve, while the air exiting the cylinder on the opposite side must go through the metered orifice. This slows its exit. Cylinders that are controlled by limiting the incoming air often suffer from erratic operation. The rule of thumb for controlling cylinder speeds is "when in doubt, meter out"—meaning that exiting airflow, not incoming pressurized flow, is controlled to limit speed of operation.

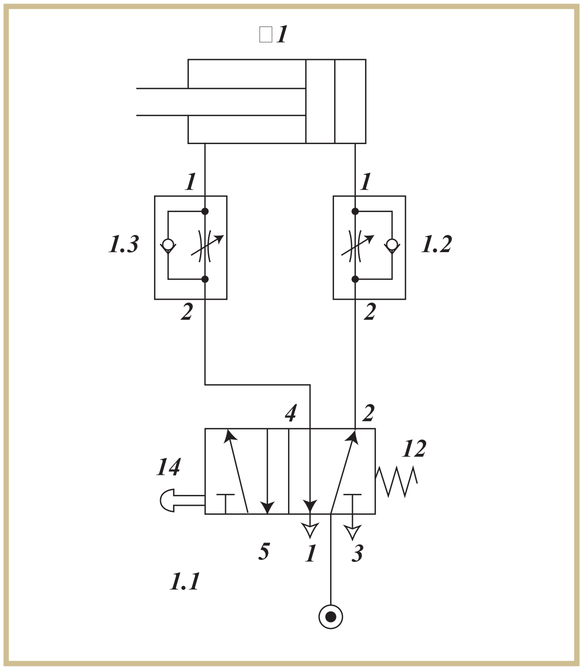



***FIGURE 14—Cylinder speeds can be controlled by forcing air to flow through variable restrictions.***

Figure 15 shows a diagram of a shuttle valve, which supplies air pressure from one of two different sources and isolates the port that isn't supplying air. Figure 16 shows an example of a sequence valve. These valves are actuated on a time delay after pressure is supplied. They actually contain a small reservoir that must fill with air before it allows pressure to build up and actuate the valve.

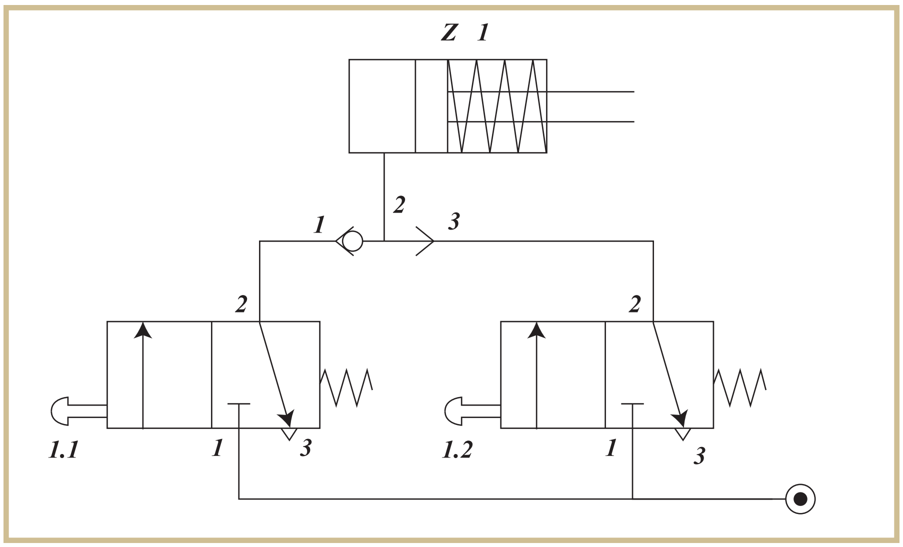



***FIGURE 15—Shuttle valves can allow the operation of a pneumatic component from two or more sources and isolate the source not being used.***

These are a few examples of the components and circuits you'll encounter as you become more familiar with pneumatic applications. As we move into more advanced applications that incorporate electrical and electronic control, the schematics will also have electrical diagrams associated with the components. These often are separate from the component connections and may be in the form of *ladder diagrams* that show electrical sequence.

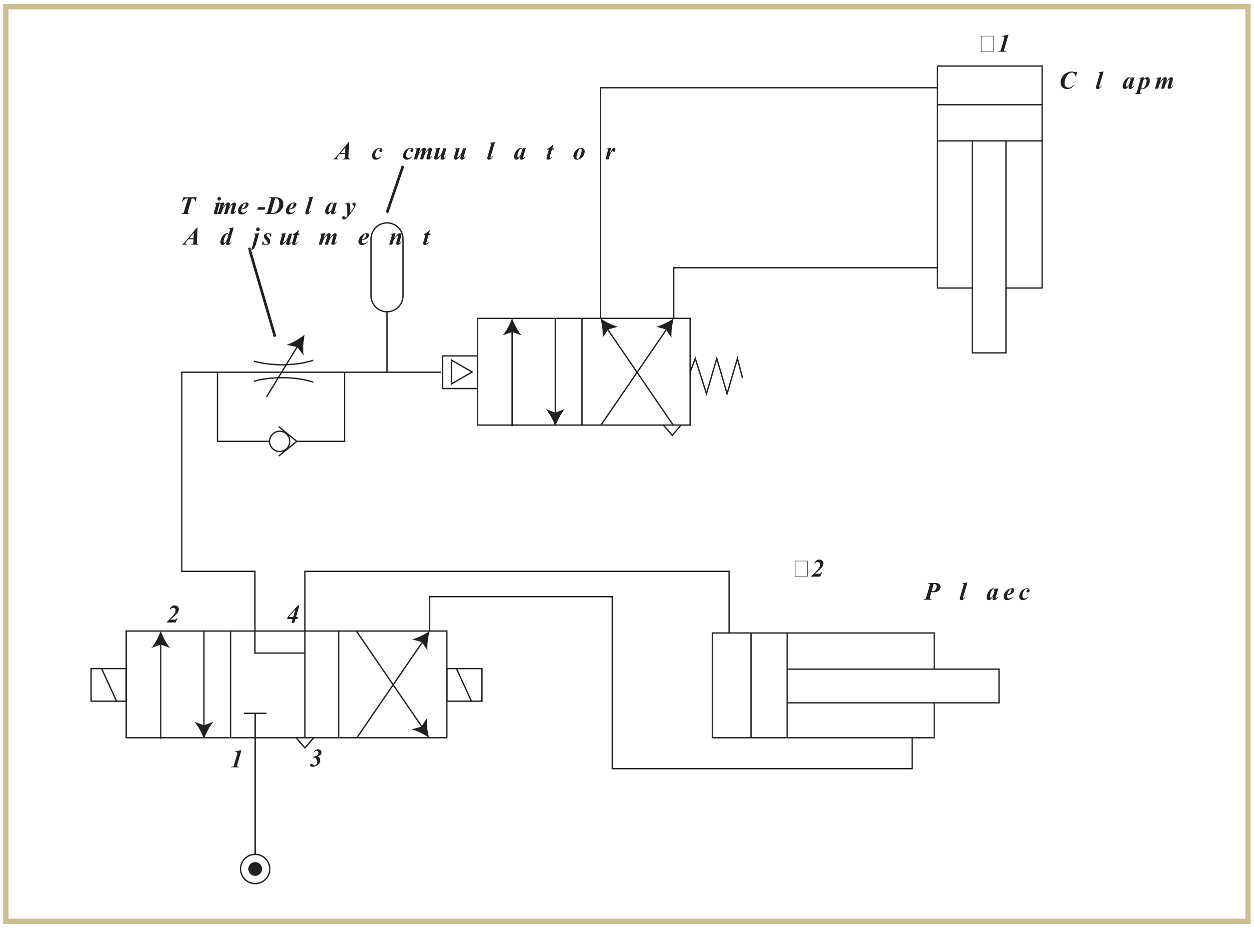



*Figure 16—Sequence valves allow a time delay from the initial pressurization until actuation occurs.*

You’re just about ready to start your study of pneumatic components. Now take a few moments to review what you’ve just learned by completing *Self-Check 1.*

# Self-Check 1

**At the end of each section of *Pneumatics, Part 2*, you'll be asked to pause and check your understanding of what you've just read by completing a "Self-Check" exercise. Answering these questions will help you review what you've studied so far. Please complete *Self-Check 1* now.**

1. One of the major advantages of pneumatic power is its relatively low ________ requirements.

2. Control of a pneumatic system can be greatly enhanced by connecting to a/an ________.

3. Compressors, dryers, filters, lubricators and ________ are among the major components of an air preparation system.

4. A/an ________ valve is operated by air pressure.

5. A circle with a dot in the center is used to indicate a high-pressure air ________ point in the system.

6. The pressure port on a valve is always labeled with the number ________ or the letter ________.

7. Pneumatic components are always drawn in their initial ________ states.

8. Limiting the speed of cylinders is usually accomplished with ________.

**Check your answers with those on page 93.**

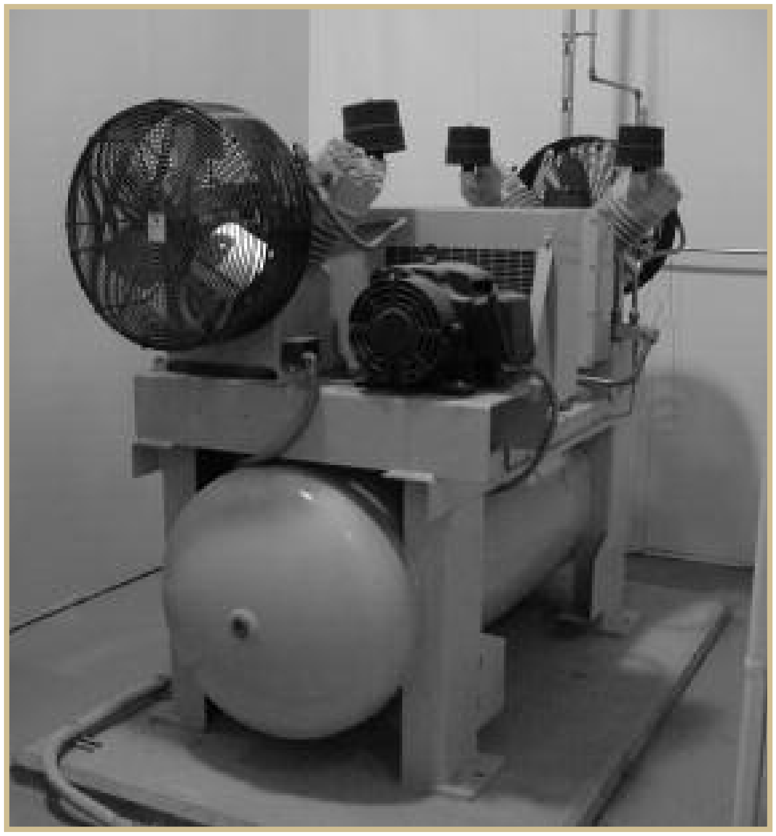
# SIZING AND INSTALLATING PNEUMATIC COMPONENTS

## Compressor and Receiver Selection

The heart of the pneumatic system consists of the compressor, receiver, and primary air-conditioning equipment. The selection of a compressor and receiver depends on the amount of air that needs to be delivered to the system and the allowable duty cycle of the compressor motor. Portable units are often powered by gasoline and diesel engines, which usually run the whole time the system is operational. Stationary compressors, however, are powered by electric motors using either single- or three-phase electric power. The motor is switched on and off by pressure sensors on the receiver that signal the motor to start or stop based on the pressure in the receiver. A low-pressure signal causes the compressor motor to turn on, charging the receiver with additional high-pressure air, until a preset maximum pressure is reached. The motor then turns off, and the receiver supplies compressed air to the system. When enough air has been consumed to cause the pressure in the receiver to drop to the minimum pressure point again, the motor turns on. Selecting a compressor and receiver requires you to know how much air is needed by the system, as well as what the allowable duty cycle of the compressor motor should be. The compressor may also need to be located in a separate room to control noise levels and possible plant-air contamination problems (Figure 17).

Motors usually have a nameplate (Figure 18) attached to the side giving voltage, phase, temperature, and duty cycle specifications. Permanent electrical connection of the motor to the facility wiring should only be done by a qualified electrician who knows how to select the proper wire sizes and installation hardware.

*FIGURE 17—This compressor and receiver is located in its own room to isolate the noise and prevent contamination of the air supply. Notice the cleanliness of the room environment, which aids in spotting troubles.*



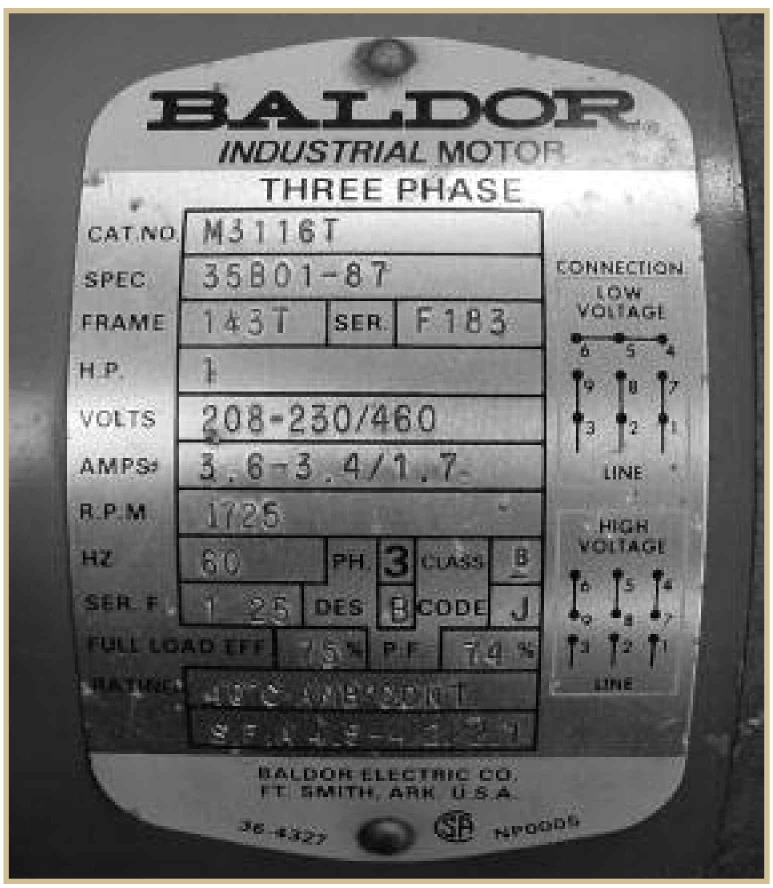



*FIGURE 18—Motors should have a nameplate attached on the outside of the housing to give operation and connection data.*

Compressor flow specifications are given by manufacturers in cubic feet per minute at "standard" conditions. The typical standard atmospheric condition is 14.7 psia, 68°F, and 36% relative humidity. Since compressors can be located at vastly different parts of the world, with different elevations, average temperature, and humidity, compressor performance can vary significantly. Air tools, cylinders, and motors are sized by the amount of air required at the operating pressure. For example, an air wrench might be rated at 3.5 CFM at 90 psig. The compressor must take free air and compress it to the operating pressure, so it obviously must take in many more CFM of free air than it supplies as compressed air.

## Compression Ratio

To determine how much free air must be supplied to the compressor to deliver a quantity of compressed air to the tool, you need to know about compression ratios. *Compression ratios* are important because they give us a way of relating equipment performance to a standard measure of air consumption, whether the device runs at 50 psig or 100 psig. To find the real air consumption of a system that has a variety of equipment connected, we simply add up all of the SCFM requirements, at whatever pressure they happen to operate.

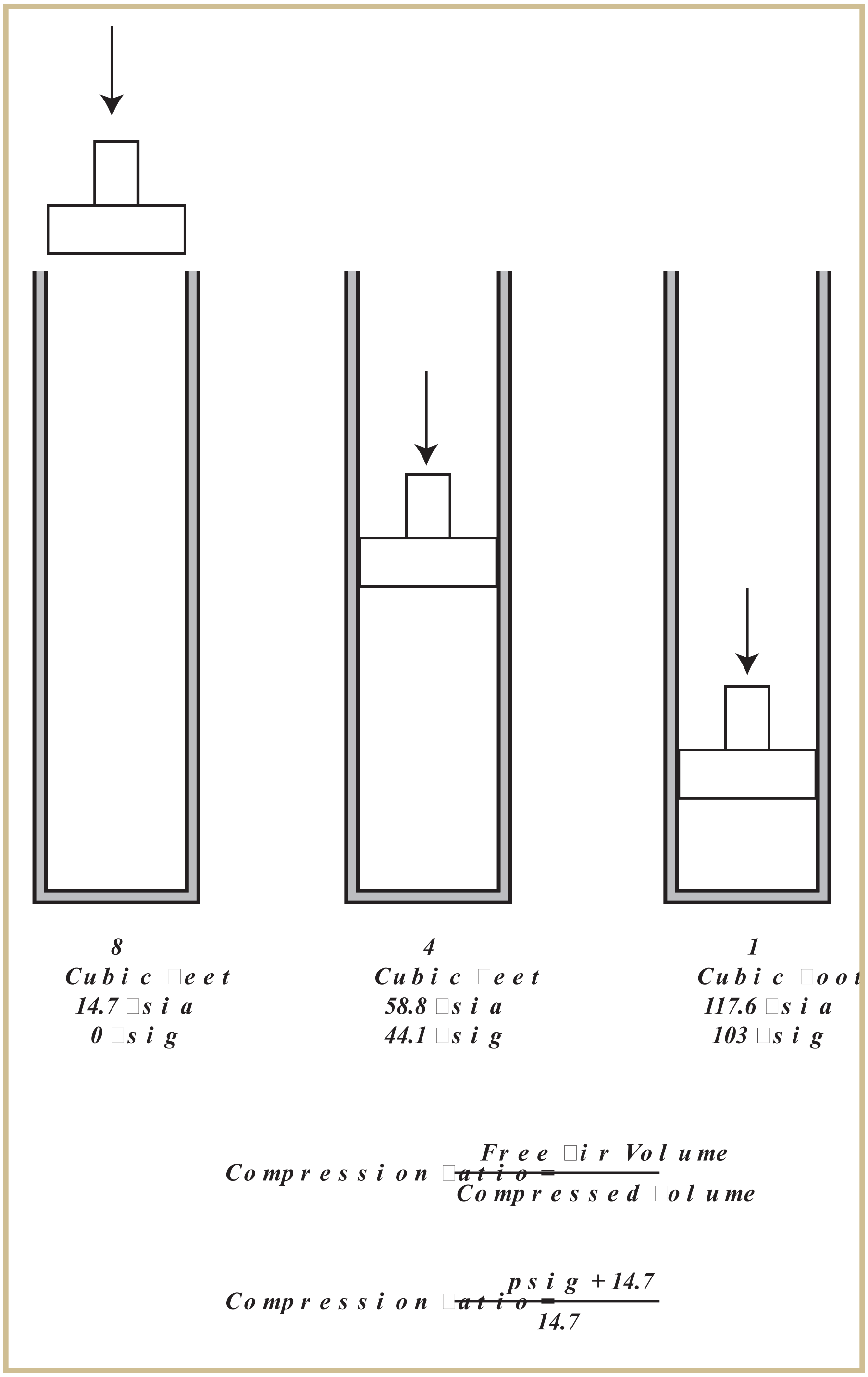
A compression ratio (Figure 19) is defined as the ratio of the initial (or *free air*) volume to a final compressed volume:

$$\text{Compression Ratio (CR)} = \frac{\text{Initial Volume (IV)}}{\text{Compressed Volume (FV)}}$$

For example, if a volume of 8 cubic feet of air is compressed to 1 cubic foot, the compression ratio would be

$$CR = \frac{8\ ft^3}{1\ ft^3} = 8$$

FIGURE 19—The compression ratio is defined as the ratio of the initial volume to the compressed volume. It measures the potential energy stored in the air.




The compression ratio is a unitless number, meaning a proportion of two quantities to one another. A more meaningful way to compute compression ratio is to calculate the ratios of pressures:

$$CR = \frac{\text{Operating Pressure (psia )}}{\text{Ambient Pressure (psia)}}$$

Since most pressures read from gauges are in gauge pressure units of psig, you need to convert gauge pressures to absolute pressures. To calculate the compression ratio using gauge pressures, use the following relationship:

$$CR = \frac{(\text{Operating Pressure, psig} + 14.7\ \text{psia})}{14.7\ \text{psia}}$$

For example, to find the compression ratio of a compressor that has an output pressure of 90 psig, use the equation above as shown:

$$CR = \frac{(90 + 14.7\ \text{psi})}{14.7\ \text{psi} = 7.122}$$

This means that it takes 7.122 cubic feet of air at 0 psig to make a cubic foot of air at 90 psig. The amount of "free air" flow at standard conditions, SCFM, can be calculated by multiplying the number of CFM at the operating pressure by the compression ratio:

$$SCFM = CFM \times CR$$

To see how this works for calculating relative airflows, look at the following example.

***Example:*** What amount of free air must be supplied to the compressor to power an air wrench requiring 4.5 CFM at 80 psig?

*Solution:*

1) Calculate the compression ratio:

$$CR = \frac{(80 + 14.7\ \text{psi})}{14.7} = 6.442$$

2) SCFM = CFM x CR

$$SCFM = 4.5\ CFM \times 6.442 = 28.99\ SCFM$$

This means that to supply an air wrench 4.5 CFM of air at its working pressure of 80 psig, the compressor must take in 28.99 cubic feet of air per minute at 0 psig (or 14.7 psia).

***Example:*** A compressor must supply compressed air to an air wrench that requires 3.0 CFM at 80 psig and a grinder that takes 4.5 CFM at the same pressure. How much free air must the compressor consume (SCFM)?

*Solution:*

1) Calculate the compression ratio:

$$CR = \frac{(80 + 14.7 \text{ psi})}{14.7 \text{ psi}} = 6.442$$

2) Calculate total CFM = 3.0 CFM + 4.5 CFM = 7.5 CFM

3) Calculate SCFM = CR × CFM = 6.442 × 7.5 CFM = 48.32 SCFM

Remember that this SCFM computed may not be the "real" free air used because the standard condition is 14.7 psia, 36% humidity, and 68°F. The actual ambient air conditions may be very different, especially inside a closed room. As mentioned earlier, a compressor's performance can be different from specified if it's located in a nonstandard environment.

## Calculating Compressor Size

As we mentioned before, to determine the necessary size of the compressor, you need to know the required air volume and the allowable duty cycle of the motor. The *duty cycle* (Figure 20) is simply the ratio of the time a motor operates to

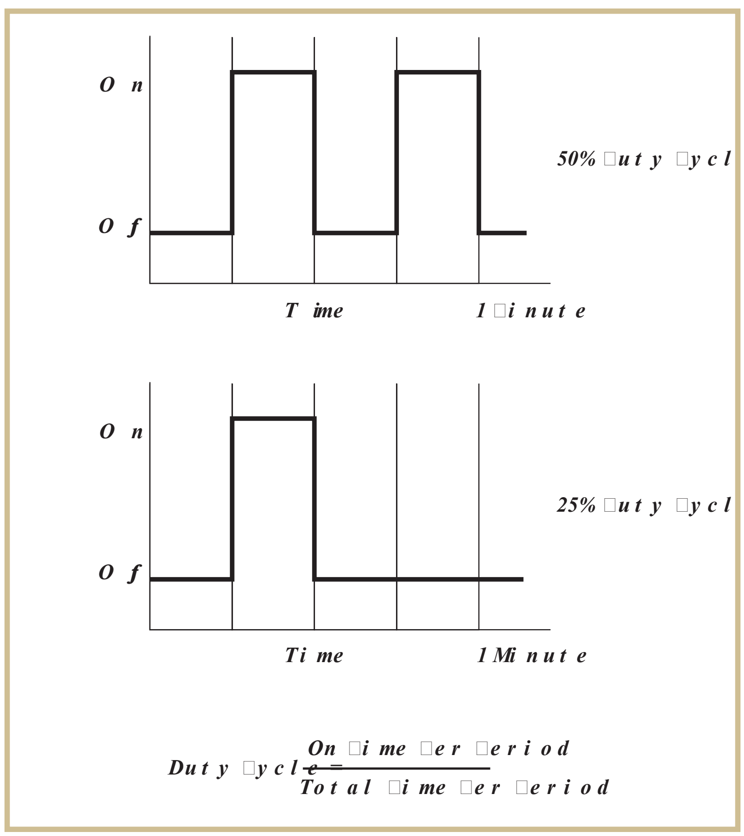



***FIGURE 20—The required duty cycle for a motor is an important specification for compressors and other electrical equipment.***

total time. For example, a motor that's on a total of 30 minutes out of every hour has a duty cycle of 50%. Over a 24-hour period, the same motor would be on a total of 12 hours. Motors are rated for a given horsepower, allowable duty cycle, and temperature.

The required compressor size for a given system requirement can be calculated from the following relationship:

$$\text{System Demand (CFM)} = \frac{(\text{SCFM} \times \text{Duty Cycle})}{\text{Compression Ratio}}$$

This can be rearranged to solve for SCFM, which is what's needed to specify the compressor needed:

$$\text{SCFM} = \frac{\text{CR} \times \text{CFM}}{(\text{Duty Cycle})}$$

***Example:*** What size compressor in SCFM is needed to supply a pneumatic system that consumes 30 CFM at 90 psig? The allowable duty cycle is 75%.

*Solution:*

1) Calculate the compression ratio:

$$\text{CR} = \frac{(90 + 14.7)}{14.7} = 7.122$$

2) Use the above equation to calculate the required SCFM:

$$\text{SCFM} = \frac{7.122 \times 30 \text{ CFM}}{.75} = 284.9 \text{ SCFM}$$

This assumes that the receiver is able to supply air during 25% of the time when the compressor is off.

***Example:*** What's the maximum system demand in CFM at 60 psig that can be satisfied by a compressor able to supply 500 SCFM with a duty cycle of 50%?

*Solution:*

1) Calculate compression ratio:

$$\text{CR} = \frac{(60 + 14.7)}{14.7} = 5.08$$

2) Calculate maximum system demand =

$$\frac{500 \text{ SCFM} \times .50}{5.08} = 49.2 \text{ CFM}$$

The compressor is capable of supplying 49.2 CFM to a system at 60 psig while operating at a duty cycle of 50%.

## Compressor Motor Size

The process of compressing air stores potential energy in the air for use at a later time or location. However, it takes energy to compress the gas, which is in turn supplied by an electric motor. By calculating the required airflow in SCFM and knowing the operating pressure, it's possible to estimate the amount of horsepower necessary to supply a given CFM to a system. Table 1 gives an estimate of the horsepower to compress 1 SCFM of air to the given pressure. Additional SCFM needs a proportionally greater amount. For example, if the system consumption has been calculated to be 30 SCFM at 80 psig, and the compressor is to be a single-stage compressor, the necessary horsepower is 30 SCFM $\times$ 0.160 Hp/SCFM = 4.8 Hp. This is an estimate only, so you should be conservative in preparing specifications for buying compressors.

Because energy is consumed by the motor for compression, it's wasteful to "overcompress" air. As a general rule, you should only compress air to about 10% more than what's required by the load, taking into account any pressure drops in the lines due to other components installed in the lines. To estimate how much horsepower overcompressing wastes, use Table 1 to determine how much horsepower is required to compress 1 SCFM of air to the initial regulator inlet pressure, and then find the horsepower to raise 1 SCFM of air to the regulator output pressure. If you subtract these two numbers and then multiply by the SCFM consumption of the tool (or other equipment connected downstream), you'll have an estimate of the wasted power from overcompression.

| Table 1 | | | |
|---|---|---|---|
| HORSEPOWER FOR COMPRESSING 1 SCFM OF AIR | | | |
| Single-Stage | | Two-Stage | |
| psig | Hp | psig | Hp |
| 5 | 0.021 | 50 | 0.116 |
| 10 | 0.040 | 60 | 0.128 |
| 15 | 0.056 | 70 | 0.138 |
| 20 | 0.067 | 80 | 0.148 |
| 25 | 0.079 | 90 | 0.156 |
| 30 | 0.095 | 100 | 0.164 |
| 35 | 0.099 | 110 | 0.171 |
| 40 | 0.107 | 120 | 0.178 |
| 45 | 0.116 | 130 | 0.185 |
| 50 | 0.123 | 140 | 0.19 |
| 55 | 0.130 | 150 | 0.196 |
| 60 | 0.136 | 160 | 0.201 |
| 65 | 0.143 | 170 | 0.206 |
| 70 | 0.148 | 180 | 0.211 |
| 75 | 0.155 | 190 | 0.216 |
| 80 | 0.160 | 200 | 0.22 |
| 85 | 0.166 | 210 | 0.224 |
| 90 | 0.170 | 220 | 0.228 |
| 95 | 0.175 | 230 | 0.232 |
| 100 | 0.179 | 240 | 0.236 |
| 110 | 0.188 | 250 | 0.239 |
| 120 | 0.196 | 260 | 0.243 |
| 130 | 0.204 | 270 | 0.246 |
| 140 | 0.211 | 280 | 0.25 |
| 150 | 0.218 | 290 | 0.253 |
| 160 | 0.225 | 300 | 0.255 |
| 170 | 0.232 | 350 | 0.269 |
| 180 | 0.239 | 400 | 0.282 |
| 190 | 0.244 | 450 | 0.293 |
| 200 | 0.250 | 500 | 0.303 |

***Example:*** An air motor uses 3.0 SCFM at 40 psig. If the system pressure is 90 psig and a regulator is used to drop the system pressure of 90 psig to 40 psig, how much single-stage compressor horsepower is wasted by overcompression?

*Solution:*

1) First find the compression ratio at the motor:

$$CR = \frac{(40 \text{ psig} + 14.7 \text{ psia})}{14.7 \text{ psia}} = 3.721$$

2) Find the SCFM at 40 psig:

$$SCFM = CFM \times CR = 3.0 \text{ CFM} \times 3.721 = 11.25 \text{ SCFM}$$

3) Find the amount of horsepower to raise 1 SCFM to 90 psig and 40 psig:

From Table 1, 0.170 Hp is required for 90 psig and 0.107 for 40 psig.

4) Subtract the two values:

Hp waste for 1 SCFM = 0.170 – 0.107 = 0.063 Hp

5) Multiply by the Hp wasted per SCFM by the actual SCFM:

$$0.063 \text{ Hp/SCFM} \times 11.25 \text{ SCFM} = 0.709 \text{ Hp}$$

Almost three-fourths Hp of compressor power is wasted to raise the air to a higher-value pressure than is necessary to do the task of the air motor!

## Receiver Size

The *receiver* is a tank where compressed air is stored as it's being delivered from the compressor and being prepared for use in other equipment. The receiver also acts to cool the newly compressed air and collect moisture that condenses as a result of cooling. Receivers are selected and sized to be able to provide a continuous supply of air at a high pressure even when the compressor is off. The receiver also serves to dampen pressure variations in the conductors due to load changes at different parts of the system. As you learned before, receivers are equipped with drains, relief valves, pressure switches, and shutoff valves. Sometimes the receiver is used to mount the air compressor and motor as well, so that it serves as a structural member of the entire assembly.

The receiver is classified as a pressure vessel and therefore is constructed according to standards set by the American Society of Mechanical Engineers (ASME). There are strict requirements for construction and inspection for these pressure vessels, and although you don't need to know the details of the standards, you need to know that receivers may not be repaired or welded by unqualified individuals. In general, repair and fabrication of any pressure vessel must be done by qualified people using proven procedures, and then rigidly inspected for defects before being approved by the inspector.

A common "rule of thumb" often used for sizing a receiver is simply to make it the same size as the free air capacity (in SCFM) of the compressor. Since many receivers are specified in size by gallons, you need to convert cubic feet to gallons: 1 cubic foot = 7.48 gallons. This relation can be expressed as

$$\text{Volume (GAL)} = \frac{(\text{Demand factor K} \times \text{SCFM} \times 7.48)}{\text{CR}}$$

In the above equation, a *demand factor K* is used to size a receiver if the compressor must only operate intermittently (lower duty cycle), so that the receiver must be sized larger to supply the necessary amount of air. A typical K factor is 3 for this intermittent service, where K = 1 should be used for continuous duty.

***Example:*** What should the receiver size be in gallons for a compressor that's needed to deliver 20 SCFM at 90 psig, operating continuously?

*Solution:* Since the compressor is operating continuously, K = 1. Find the compression ratio:

$$\text{CR} = \frac{(90 + 14.7)}{14.7} = 7.122$$

$$\text{Receiver Volume} = \frac{(1 \times 20\ \text{SCFM} \times 7.48)}{7.122} = 21\ \text{gallons}$$

If the receiver were to be sized for intermittent duty, it would be three times larger because of K being set to 3 instead of 1 as above.

Receivers function as a reservoir of air. They can be used to supply air at a higher rate than the compressor capacity for short durations if the compressor is given a chance later to recover and rebuild the air supply in the receiver. For example, a receiver may be able to supply 30 CFM for a short time even though the compressor is only capable of supplying 25 CFM, provided that the compressor is able to build up the air supply in the receiver at a later time. A more rigorous procedure for sizing receivers can be used if you know more about the system characteristics. If you know the maximum and minimum pressures, the airflow in SCFM, and the volume of the receiver, you can calculate how long a receiver can supply air.

$$\text{Time (min)} = \frac{\text{Volume (ft}^3) \times (\text{Max pressure} - \text{Min pressure})}{(14.7 \times \text{NET SCFM})}$$

The pressure values in the above equations are in psig, and the NET SCFM is what the receiver supplies, *not* including the SCFM the compressor supplies. For example, if a compressor is supplying 15 SCFM and the system is using 20 SCFM, the receiver is supplying a net airflow 5 SCFM, which should be the value used in the equation above. You can also rearrange this relationship to solve for other quantities such as volume, pressure, or flow, depending on what you know and what you need to find.

***Example:*** A compressor connected to a 100-gallon receiver supplies 15 SCFM at 120 psig. If the system demand rises to 20 SCFM, how long will it take the pressure to drop to 80 psig?

*Solution:* In this case, the receiver will supply 20 – 15 SCFM, or a net airflow of 5 SCFM, over and above the compressor's ability.

1) The volume in gallons must be converted to cubic feet by dividing 100 gallons by 7.48 $ft^3$ per gallon.

   100 gallon/7.48 $ft^3$/gallon = 13.37 $ft^3$

2) $$\text{Time (min)} = \frac{[13.37 \text{ ft}^3 \times (120 \text{ psig} - 80 \text{ psig})]}{(14.7 \times 5 \text{ SCFM})}$$

   = 7.28 minutes

The receiver will be able to supply the additional 5 SCFM of air for 7.28 minutes until the pressure drops below 80 psig.

***Example:*** What capacity, in gallons, is necessary for a receiver to supply a net airflow of 12 SCFM of air between 140 psig and 90 psig for five minutes?

This problem requires you to solve for the volume in the above equation.

$$\text{Volume} = \frac{\text{T} \times (14.7 \times \text{NET SCFM})}{(\text{PMAX} - \text{PMIN})}$$

1) $$\text{Volume} = \frac{5 \text{ min.} \times (14.7 \times 12 \text{ SCFM})}{(140 - 90 \text{ psig})} = 17.64 \text{ ft}^3$$

2) Convert 17.64 $ft^3$ to gallons:

$17.64 \times 7.48 = 131.95$ gallons

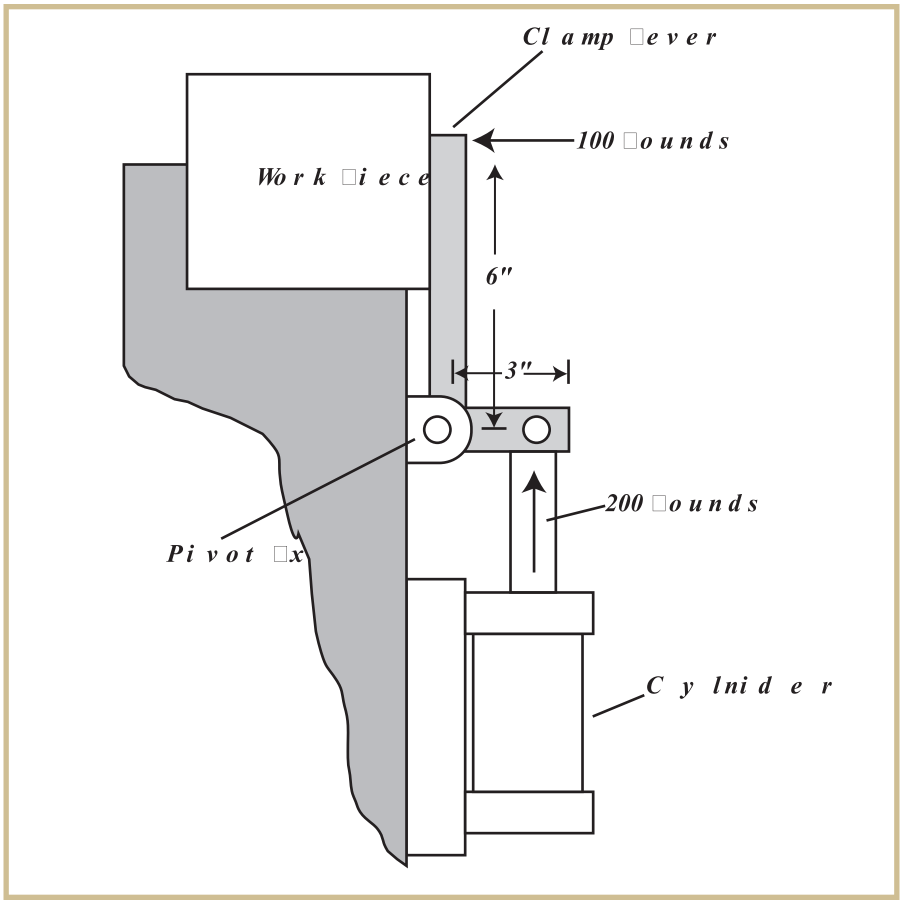
These examples are somewhat of an estimate because we neglect any temperature changes or humidity, whereas in real life they would have a minor effect on the system performance.

## Determining Load Requirements

The most basic force an actuator is required to supply is the force needed to lift a weight. We'll consider how fast the weight is to be lifted later, but for now, to lift a weight at constant speed, we need to have a cylinder that can supply a constant force greater than the weight: If you need to raise a 100-pound load, the cylinder must supply a force greater than 100 pounds. How much more? It depends on the speed and any friction present. Some cylinder manufacturers also specify a *friction pressure,* which is the pressure needed to just get the piston and rod to move and doesn't assist in moving the load.

If the cylinder is simply lifting a weight, finding the force is easy. However, if the cylinder is used with other mechanical components such as levers or gears, you must find out the effective force required. For example, the cylinder in Figure 21 is operating a lever that in turn provides a force used to clamp a load. Because the force developed by the load to rotate the lever against the cylinder is twice the distance from the axis of rotation, the cylinder must generate a force twice as great as the load to move the lever and clamp

*FIGURE 21—Pneumatic cylinders provide forces that can be increased or reduced depending on the mechanical connections. In this case, the force is reduced by a factor of 2:1 because of the mechanical linkage to the actual part.*




the part. If the cylinder were mounted at an angle to the lever arm, and not perpendicular to it, the force from the cylinder would have to be higher yet. In that case, you would have to use trigonometry to determine the value.

Friction is always present to some degree when parts are moving. Friction is a complex phenomenon, not easily analyzed in any but the simplest situations. Frictional forces are generally thought to arise because of microscopic bonds between molecules and atoms of materials in close contact (Figure 22). Friction is less when there's a lubricating film between the two surfaces, keeping the materials separated. However, when two materials are moving past each other, whether sliding or rolling, friction inevitably arises.

There's friction inside the cylinder due to the seals between the piston and rod and cylinder bore, and there's friction in the external mechanism from parts moving against each

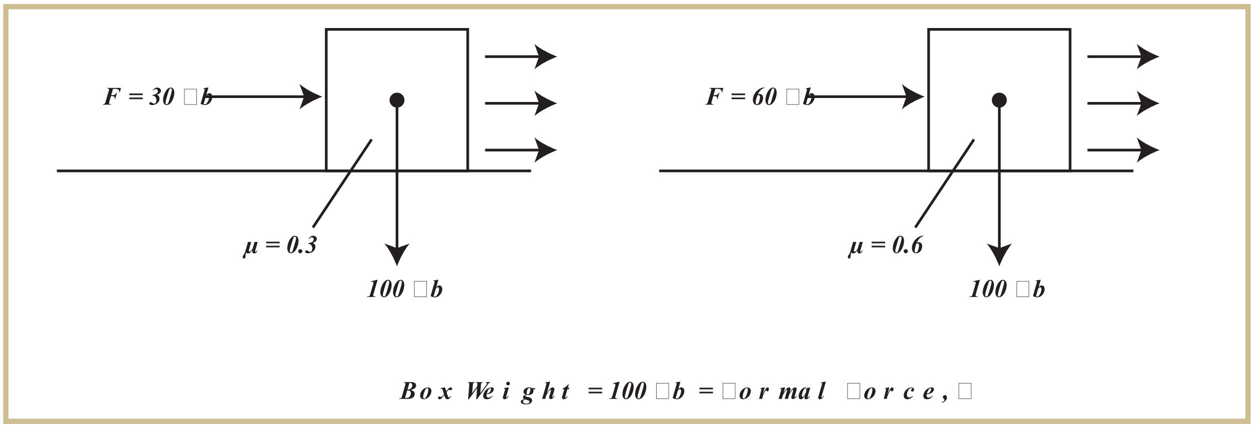



***FIGURE 22—Friction is caused by microscopic contact between surfaces and has an important effect on the amount of force necessary to push a load across a surface.***

other. The simplest case of friction to analyze is when a load such as a box is moved horizontally across a surface. The friction force can be calculated from the equation

$$F_f = \mu \times N$$

$F_f$ is the *friction force* the cylinder must overcome, μ is a coefficient of friction that can be determined experimentally or estimated from table values, and *N* is the *normal force,* which is the force perpendicular to the surface of movement. If the surface is flat, the normal force is simply the weight of the load. The *coefficient of friction* (μ) is a constant that varies between 0 and 1.0; it measures the "stickiness" of the two surfaces. A coefficient of 0 indicates a perfect, no-friction surface, whereas a high coefficient of friction (0.8 or 0.9) indicates a rough or sticky surface with a lot of friction. Coefficients of friction for various combinations of materials sliding together can be found in tables, or often μ can be found through experiment. For two smooth lubricated metals sliding past each other, μ is in the range of .25 to .35. The coefficient of friction for ball bearings, by comparison, is in the range of .001 to .01.

***Example:*** What's the frictional force to overcome if a load of 150 pounds is moved across a surface of wood? The coefficient of friction, μ, is 0.4. What happens if the load is put on metal rollers, such that the coefficient of friction is lowered to .05?

*Solution:* Since the load is sitting on a horizontal surface, the normal force, N, is the weight of the load, 150 lb.

$$F_f = \mu \times N = 0.4 \times 150 \text{ lb} = 60 \text{ lb}$$

This means that any device must produce 60 pounds to move the load horizontally across the wood surface. In the case of the load on rollers, $\mu = 0.05$:

$$F_f = 0.05 \times 150 \text{ lb} = 7.5 \text{ lb}$$

The force necessary to push this load has dropped significantly!

Some additional things to know about friction are that the frictional force always opposes motion, and that it's slightly different for loads at rest and loads that are moving. Although gravity can be of some help in moving the load (Figure 23), it doesn't matter in which direction the load is moving; it'll always take the same force to overcome friction. If a load is at rest and the force is trying to start it moving, you need to use what's called the *static coefficient* of friction. If the load is moving, you need to use the *coefficient of sliding friction,* which is almost always slightly lower than the static $\mu$. This is because when the objects are at rest, the molecules have a chance to settle and allow more molecular bonds to form.

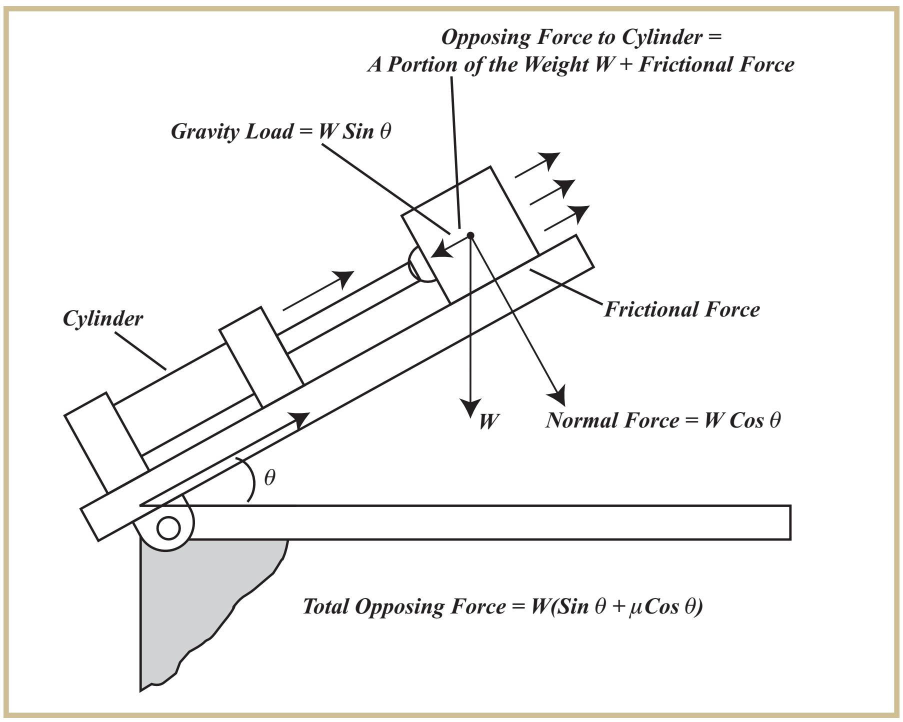



***FIGURE 23—When loads are moved at angles to the horizontal, gravity can aid or hinder movement. But friction always opposes the motion, up or down.***

For sliding surfaces that aren't horizontal, you need to determine the normal force using trigonometry. If a load is moved up or down a slope, as shown in Figure 23, part of the gravitational force pushes the load down the slope, while another part pushes against the surface, causing the normal force. To calculate a normal force for a load on a slope, use the relationship:

$$N = W \times \cos \vartheta$$

In this equation, W is the weight and $\vartheta$ is the angle of the slope, as measured from the horizontal. The cos is the cosine function found on most scientific calculators. The force required to keep the load from sliding down the slope, and therefore the force a cylinder would have to produce to push a load up a slope (plus a little more, obviously), can be calculated from a similar equation:

$$F = W \times \sin \vartheta$$

Again, $\vartheta$ is the slope angle, W is the weight, and *sin* is the sine function on your calculator.

The total force a cylinder needs to move a load up a slope, working against both gravity and friction, is

$$F = W \times \sin \vartheta + \mu \times W \times \cos \vartheta$$

or, simplifying

$$F = W \times (\sin \vartheta + \mu \cos \vartheta)$$

***Example:*** What's the force required from a cylinder to overcome friction and gravity to move a load of 220 lb. up a slope of 35° with a coefficient of friction of 0.22?

*Solution:* Using the above equation,

$$F = 220 \text{ lb} \times (\sin 35° + 0.22 \times \cos 35°) = 220 \text{ lb} \times (0.5736 + 0.22 \times 0.8192) = 220 \text{ lb} \times 0.7538 = 165.8 \text{ lb}$$

A final consideration is that frictional forces don't depend on velocity. They must be considered whenever parts are moving against each other, and this includes parts in the pneumatic devices such as motors and cylinders. Cylinders with rods subjected to side loads are particularly susceptible to developing high frictional forces, so it's important to ensure that actuators are mounted correctly and aligned properly. Improperly functioning pneumatic equipment can often be found to be the result of unexpected friction loads.

Pneumatic systems have advantages over hydraulic and electric systems in many applications requiring speed of operation, repetitive motions, and ease of control. Compressed air is easy to distribute to cylinders and motors used for robotics and other precision manufacturing operations. However, because these pneumatic components must apply forces to objects to move them quickly, determining the real load a cylinder is required to move isn't intuitive. To determine the actual force the cylinder needs to supply involves some applications of the basic laws of motion you learned in your physics courses.

It may help to work through a simple example. Let's say that a cylinder has to lift a load of 10 pounds a vertical distance of 6.0 inches, and that it must do it in 0.250 seconds. While the load of 10 pounds doesn't seem like much, and 6 inches doesn't seem very far, the fact that it must be moved in 0.250 seconds may be of concern when it comes to selecting an actuator. If the valve that operates the cylinder is electrically actuated, there may even be less time than 0.250 seconds because of the time it takes to activate the solenoid. But we'll ignore that for now. We'll also assume that we don't need to slow down the cylinder and load (however, often real-world applications require that the load be slowed near the end of its travel), and the cylinder is stopped simply by running into the physical stops in the system—a "bang-bang" application.

*Newton's laws of motion,* in this case $F = m \times a$, tell us how much force is required to accelerate a load from a rest to a given velocity. In our example we know the load in pounds, we know the distance traveled, and we know the time it's going to take. From this information we can calculate the required force:

Force = mass x acceleration

$$F = m \times a$$

or

$$a = \frac{F}{m}$$

What's the acceleration? *Acceleration* is the change in velocity divided by the time it takes to accomplish the change. In our case, the average velocity will be the total distance, 6.0 inches, divided by the total time. 0.250 seconds:

$$\text{Velocity} = \frac{6.0 \text{ inches}}{.250 \text{ sec}} = 24 \text{ in/sec}$$

If this is the average velocity, and one of the numbers we average is zero (the starting velocity), the other velocity (the peak velocity) is twice the average:

$$\text{Average velocity} = \frac{(\text{Final velocity} - \text{initial velocity})}{2}$$

$$24 \text{ in/sec} = \frac{(\text{Final velocity} - 0 \text{ in/sec})}{2}$$

$$\text{Final velocity} = 48 \text{ in/sec}$$

The acceleration is defined as how rapidly the velocity changes:

$$\text{Acceleration} = \frac{(\text{Final velocity} - \text{initial velocity})}{\text{time}}$$

$$\text{Acceleration} = \frac{(48 \text{ in/sec} - 0 \text{ in/sec})}{0.250 \text{ sec}} = 192 \text{ in/sec}^2$$

The acceleration of gravity is 386.4 in/sec$^2$, so this acceleration of 192 in/sec$^2$ represents an acceleration of 192/386.4 = 0.497 g of acceleration. To find the additional force, multiply by the weight of 10 pounds:

$$\text{Acceleration force} = 10 \text{ lb} \times 0.497 \text{ g} = 4.97 \text{ lb}$$

This “hidden” force represents 50% of the weight alone!

These forces generated by the required acceleration of a mass from rest to a certain velocity are called *inertial forces.* Forces produced by cylinders, motors, and actuators must overcome not only the weight of loads, but also these inertial loads. Inertial loads appear whenever a mass must be moved from rest, or slowed down from an initial speed. To find the total force the cylinder must supply, you would add the two, plus any friction known to be present:

$$\text{Total force} = \text{Weight} + \text{Inertial force} + \text{Friction force}$$

In our example above, the cylinder chosen must supply a total of 10 lb + 4.97 lb = 14.97 lb, and this is ignoring any frictional force that may be present. If we use the rule of thumb that cylinders should be sized for twice the required force (discussed in the next section), then we would select a cylinder rated at 30 lb of force. Had we naively selected one for a 20-lb force, we would have found our cylinder severely undersized for the application.

## Sizing Actuators

As you remember from the previous study unit in this series, the force that a pneumatic cylinder produces is a function of the area of the piston (minus the rod area if it's a double-rod cylinder or if the cylinder is being retracted) times the pressure supplied to the port:

$$\text{Force} = \text{Pressure} \times \text{Area}$$

***Example:*** What force is generated by a cylinder with a 2.5-inch inside diameter bore operating at 60 psi?

$$\text{Area} = \frac{\pi \times (2.5 \text{ in})^2}{4} = 4.907 \text{ in}^2$$

$$\text{Force} = 60 \text{ lb/in}^2 \times 4.907 \text{ in}^2 = 294.5 \text{ lb}$$

Most of the time, however, the situation is that we know what force we want to produce, and then we have to pick a cylinder to provide that force. We can rearrange the formulas for force and area to get a relationship to calculate the cylinder bore (without a rod) for a given air pressure:

$$\text{Cylinder bore (in)} = \sqrt{\frac{4 \times \text{Force (lb)}}{\pi \times \text{Pressure (psi)}}}$$

***Example:*** What minimum cylinder bore is necessary to give 500 pounds of force using an air supply of 80 psi?

$$\text{Cylinder bore} = \sqrt{\frac{4 \times 500 \text{ lb}}{\pi \times 80 \text{ lb/in}^2}} = 2.82 \text{ in}$$

*You should check this result by calculating the area of a cylinder with a 2.82 in bore and multiplying by the pressure. Again, this calculation doesn't include any area "missing" due to the presence of a rod.*

The technician would probably pick the next higher standard size, a $2\frac{7}{8}$ or 3-in diameter, since the cylinders are most often supplied in common sizes. However, you must realize that the minimum size from this calculation doesn't take into account any extra force necessary to overcome inertia of the load, or any speed restrictions due to limitations on airflow. We need to discuss a way to size actuators to deliver enough extra, but not excessive, amounts of force.

Pneumatic systems function by moving air through conductors, valves, and components to accomplish the desired work. Different systems will have different requirements, depending on whether the system is optimized for minimal device size or high productivity. In general, selecting components for optimizing system size, speed, or energy consumption will all give different sizes of cylinders, conductors, and output devices. If an actuator needs to provide a force of 100 pounds with a supply pressure of 90 psi, you'll find that a cylinder with a bore diameter of 1 $^3/_{16}$ will give the required force. However, if the actuator must work rapidly, this amount of output force may not be enough to overcome the inertial load of the mass that's moved, so this minimum actuator size isn't suitable. A 4-in-diameter cylinder operating at 90 psi will provide over 1,100 pounds of output force, which will certainly do the job. However, the cylinder will be much larger than necessary. More important, because the volume of the larger cylinder is so much greater, the required airflow into and out of the cylinder is also much higher. This may actually make the cylinder operate slower than a smaller cylinder! Remember, the intent in sizing many actuators is to optimize productivity of the system, not simply size or cost.

Some designers size the cylinder for twice the load requirement to give the greatest actuation speed without oversizing the cylinder. For example, if you calculate a need for 100 lb, then you would select a cylinder bore that would give 200 lb of force at the given pressure. You probably won't be able to pick the exact bore calculated, but you should be close enough to a standard to give reasonable performance.

***Example:*** A cylinder must supply 150 lb of clamping force for parts of a production-line drilling operation. If 100 psi air is available, what size cylinder should be used?

*Solution:* If you know that 150 lb is required and production speed is an important consideration, size a cylinder to provide 300 lb of force. From the above equation:

$$\text{Cylinder bore} = \sqrt{\frac{4 \times 300 \text{ lb}}{\pi \times 100 \text{ lb/in}^2}} = 1.954 \text{ in}$$

Therefore, a 2-in cylinder is selected, since it's the closest standard fractional size available.

# Air Motor Selection

As you learned in the previous unit, air motors (Figure 24) are rated by their torque, rotational speed, and air consumption. The first step in determining the size of a required air motor is to determine the torque required by the load. Torque is the rotational effort that's required to turn a rotating load. In most cases, the load shaft must turn more than one revolution, as when a motor turns a shaft connected to a gearbox. In other cases, only limited travel is required, such as when a motor turns a lever arm to move it back and forth through a limited rotation.

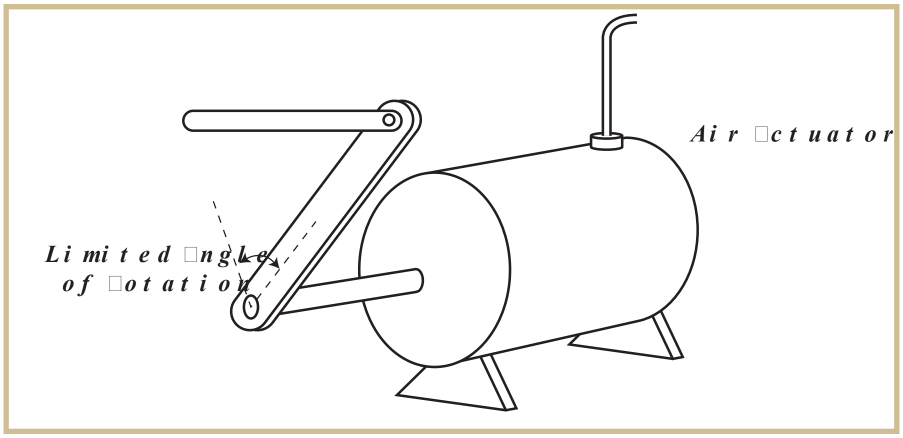


***FIGURE 24—Air motors can be used to turn a shaft, the same as an electric motor. They can also provide limited rotary motion or even change a torque into a linear force.***

*Torque* is the product of a force times a moment arm. And this is the case whether the torque is turning the moment arm or if the force is acting on a moment arm to produce a torque. In other words, a force can be used to produce a torque, or a torque can be used to produce a force (Figure 25).

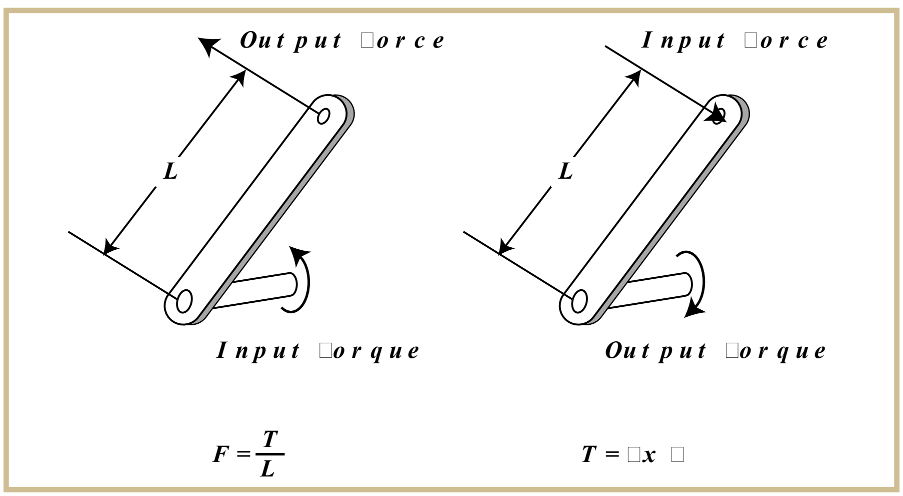



***FIGURE 25—Torque is the product of force acting through a moment arm. A torque can produce a force, or a force can produce a torque.***

Some of the considerations you must make when selecting an air motor include the air pressure at the location of the motor and the variation of this pressure throughout the production day. An air motor size should be based on the minimum air pressure likely to be available through its normal fluctuations. Standard practice is to size the motor to provide the needed torque at two-thirds the available line pressure. The conductor size must also be adequate for the required airflow for the size and power of the motor. Motors that need to reverse must have a four-way valve installed for operator control.

Motor horsepower can be calculated by the relationship:

$$Hp = \frac{(T \times n)}{5252}$$

Hp is the horsepower, T is the torque in lb-ft, and n is the rpm. This equation is the same as the one you used in the previous unit. If you want to use lb-in for your units of torque, the constant “5252” in the above equation becomes 63024, since there are 12 inches per foot.

Manufacturers can provide graphs for motors to aid in the selection of the proper motor size. Air motors that are typically found in factory installations are manufactured in a variety of sizes from fractional sizes to considerable horsepower output. Fractional horsepower motors generally consume on the order of 35 SCFM per horsepower, while larger sizes are a little lower at about 30 SCFM per horsepower. Figure 26 shows typical motor performance graphs, illustrating how air consumption varies with output speed, and how torque varies with speed. Notice that the SCFM consumption varies linearly with speed and increases with the pressure. Also, notice that the charts of speed versus torque show that torque reaches a peak value and then declines as speed increases. As we noted, to ensure adequate size, motors are selected based on providing the required horsepower at 67% of the expected pressure. This ensures that the motor will give good performance despite any reduction of pressure, and extra torque will be available for starting and overloads.

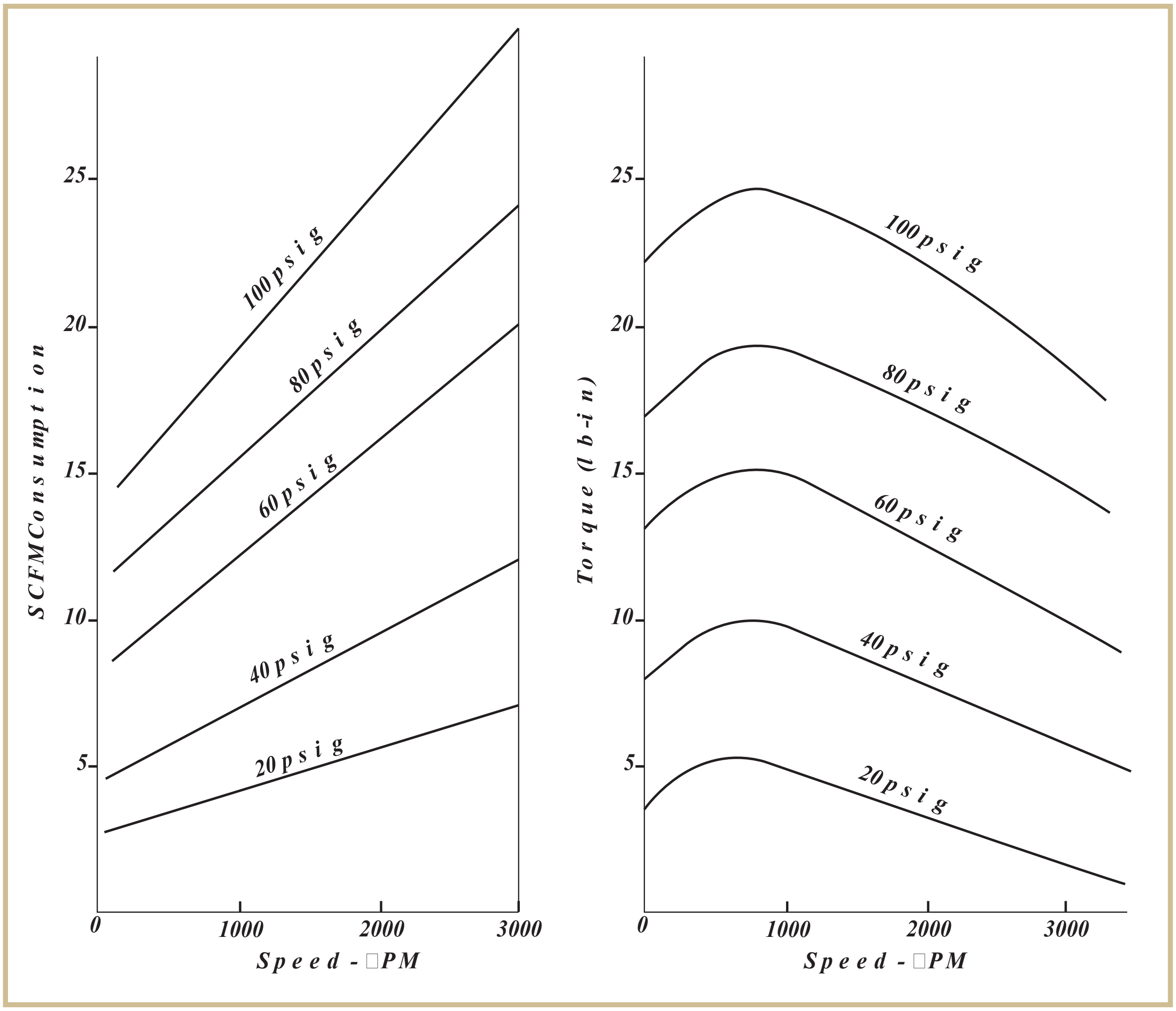



***FIGURE 26—Manufacturers can supply performance graphs for air motors that will allow you to determine power output and air consumption.***

***Example:*** What's the output torque of a $\frac{1}{4}$-Hp motor at 1500 rpm?

*Solution:* Using the torque horsepower equation above, solve for torque, T, since we know the Hp and the rpm:

$$T = \frac{Hp \times 5252}{n} = \frac{0.25 \times 5252}{1500} = 0.875 \text{ lb-ft} = 10.5 \text{ lb-in}$$

***Example:*** For the above motor, find the required pressure needed to develop the necessary torque.

*Solution:* In the right graph of Figure 26, read upward from the horizontal axis at the 1500 rpm point, and over from the 10.5 lb-in point. Read the pressure at the intersection of these two "lines," and interpolate if necessary. The pressure is approximately halfway between the 40 and 60 psig lines on the graph, so the estimated air pressure would be about 50 psig.

***Example:*** For the above motor, what is the free air consumption at the 1500 rpm, 10.7 lb-in point?

*Solution:* In the left chart of Figure 26, read upward from the horizontal axis at the1500 rpm point until you reach the pressure found in the last problem. Read across to the vertical axis to find SCFM. In this case, the 50 psig point at 1500 rpm will intersect the vertical axis at about 11 SCFM.

Note that if this were the required specification, 10.5 lb-in at 1500 rpm, you would anticipate providing a working air pressure of about 50% more than required from your calculations. In this problem, it would be 1.5 × 50 psig, or 75 psig. If you knew you only had, say, 60 psig available, you would have to ensure your motor produced adequate torque and speed at 40 psig, or about two-thirds of the available pressure. Horsepower output of air motors can be throttled back by limiting airflow with a valve.

## Coefficient of Velocity, $C_V$

You've already learned that there are different types of flow—laminar and turbulent—that occur as fluids pass through piping, fittings, and components attached to regulators, filters, or valves. The condition of the flow depends on the velocity of the fluid, the geometry of the flow path, and, to some extent, the temperature and density of the fluids. As the fluid passes through the system, energy is unavoidably lost as the fluid winds its way past obstructions normally found in pneumatic systems. When moving air gives up its energy, there's a pressure drop. Engineers and technicians have standardized a comparison of how well different components conduct air (and other fluids) with a quantity called the *coefficient of velocity,* or sometimes *flow coefficient.* It's abbreviated $C_V$. Component manufacturers will often list $C_V$ values for their products so that the proper sizes can be readily selected.

All fittings and conductors will resist airflow, and the amount of resistance is reflected by the pressure drop across the component as air flows through it. Figure 27 shows how $C_V$ values of a device are measured. A known flow rate, (Q), in SCFM, is directed through the component. The pressure is measured before the component and afterward, so that absolute pressures can be measured and the pressure drop can be calculated. The greater the airflow, the greater the pressure drop. Calculating the necessary $C_V$ for the valves and other equipment is the preferred method of selecting components, since the older method of simply matching port sizes often resulted in under- or oversized valves and conductors.

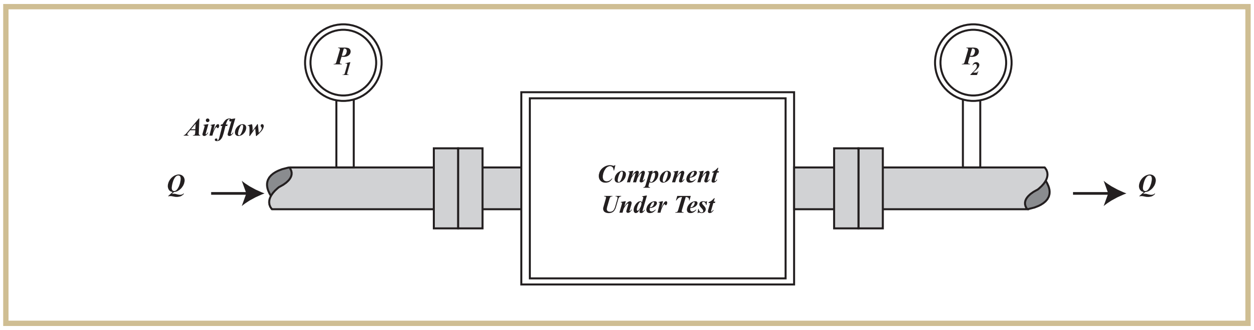



***FIGURE 27—The pressure drop across the pneumatic component with a known airflow allows direct measurement of the coefficient of velocity. This $C_V$ value can be used to predict performance under other operating conditions.***

The National Fluid Power Association (NFPA) publishes an equation to calculate $C_V$ based on airflow, ambient temperature, operating pressure, and pressure drops. The standard ANSI/NFPA T3.21.3 details how the testing is to be done and how the equation should be used. Figure 28 shows the equation and the definition of the variables and constants. You may see other versions of this equation in various references, often with reference to a K-factor. This version is the preferred version of the NFPA since it tries to account for the effect of pressure drop magnitudes on the airflow. An important fact to know is that airflow, Q, doesn't increase if the pressure drop is greater than about 53% of the input pressure. This is because the air has reached the sonic velocity, and further increases in the input pressure won't significantly affect the output flow. Thus, the equation breaks down for ΔP values of greater than 53% of the input pressures. For example, if the input pressure to the device was 100 psia and the output pressure was 50 psia, the ΔP is 50% of $P_{IN}$, so the formula would still be valid (using the third K-value equation listed in Figure 28). However, if the $P_{OUT}$ value was 40 psia, the ΔP is now 60 psia, or 60% of $P_{IN}$, and the equation is no longer valid.

**The $C_V$ Formula**

$$C_V = \frac{Q_{SCFM}}{22.67} \times \sqrt{\frac{T}{(P_{IN} - P_{OUT})K}}$$

$\Delta P = P_{IN} - P_{OUT}$

$K = P_{OUT}$ if ΔP is less than or equal to 10% $P_{IN}$

$K = \frac{(P_{IN} + P_{OUT})}{2}$ if ΔP falls between 10% and 25% $P_{IN}$

$K = P_{IN}$ if ΔP is greater than 25% but less than 53% of $P_{IN}$

Q = Flow in SCFM

T = Temperature, Rankine (R°)

**(A)**

**The $C_v$ equation for ΔP**

$$\Delta P = \left(\frac{Q_{SCFM}}{22.67\ C_V}\right)^2 \times \frac{T}{K}$$

Q = Flow, SCFM

T = Temperature, R°

K = Flow factor

***FIGURE 28—(A) The $C_v$ value can be calculated if airflow and pressure drop are known. NFPA Standard T3.21.3 details the use of the equation and testing. (B) The $C_v$ equation can be rearranged to predict pressure drop with a given flow and operating pressure.***

This equation can be easily set up on a spreadsheet for calculations of various conditions, as shown in Figure 29. A programmable calculator is also a handy method of solving these problems. And if you search the Internet, you'll find several pneumatic companies that have online calculators as well as downloadable shareware programs. The principal caution in using these calculators is to remember to use absolute temperatures (Rankine scale) and pressures (psia). You should also know that *pneumatic prototyping systems* allow for design testing of some pneumatic applications before installation (Figure 30).

FIGURE 29—The NFPA equation for $C_v$ can be easily entered in a spreadsheet for quickly calculating different cases. Results can be printed and stored electronically.

| | A | B | C | D |
|---|---|---|---|---|
| 1 | **Calculating Cv Values** | | | |
| 2 | | | | |
| 3 | Cv is the flow coefficient of a pneumatic component. | | | |
| 4 | This calculation uses the NFPA recommended equation. | | | |
| 5 | | | | |
| 6 | | | | |
| 7 | | | | |
| 8 | Temperature: | 68 | F | |
| 9 | | 528 | R | |
| 10 | | | | |
| 11 | Inlet Pressure | 90 | psig | |
| 12 | | 104.7 | psia | |
| 13 | | | | |
| 14 | Outlet Pressure | 88.72054 | psig | |
| 15 | | 103.4205 | psia | |
| 16 | Pressure Drop: | 1.279457 | psia | |
| 17 | K Factor | 103.4205 | | |
| 18 | | | | |
| 19 | | | | |
| 20 | CFM Flow Rate | 7.02 | | |
| 21 | Compression Ratio, CR: | 7.122 | | |
| 22 | SCFM Flow Rate | 50.0 | | |
| 23 | | | | |
| 24 | Cv Value: | 4.405744 | | |
| 25 | | | | |
| 26 | | | | |

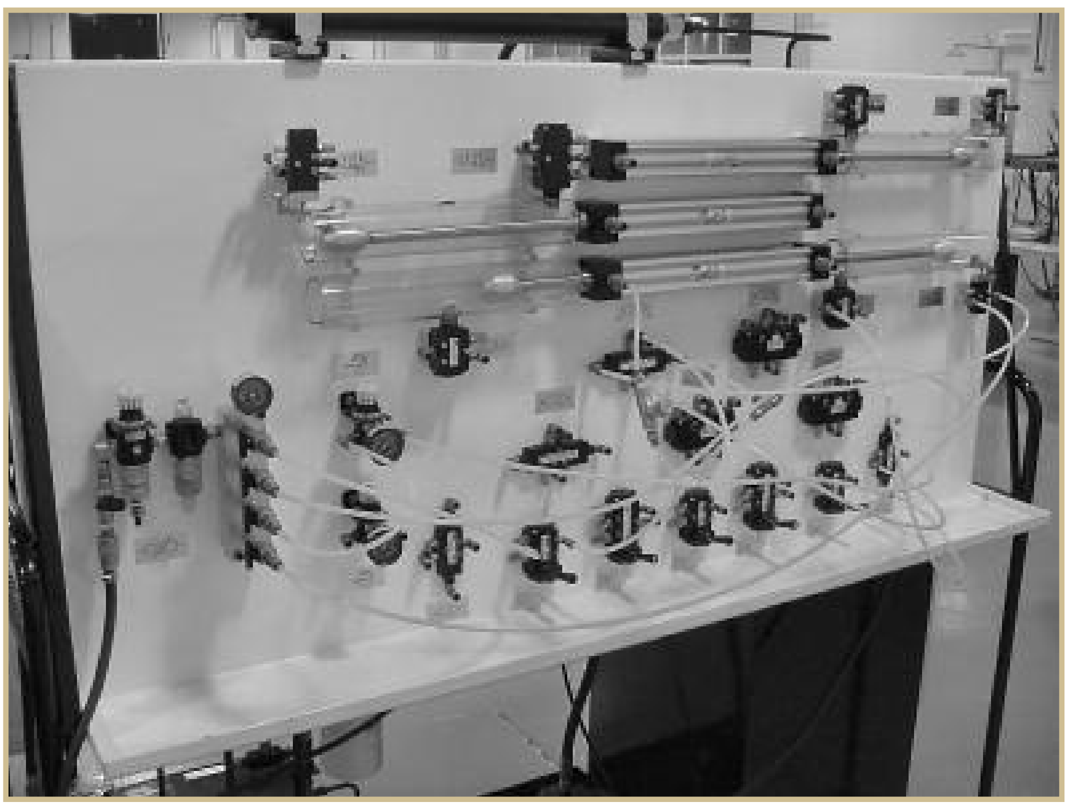


FIGURE 30—Pneumatic prototyping systems allow for design testing of some pneumatic applications before installation.

Since $C_V$ is much like conductance (the opposite of resistance) in electrical circuits, you might suspect that when pneumatic components are connected in series or parallel, they would behave the same as series and parallel resistors. This is somewhat correct, and to calculate the total $C_V$ of several components in parallel, you would simply add them up. Pneumatic components connected in series are treated mathematically the same as resistors in parallel. Figure 31 shows the mathematical relationship of the two conditions.

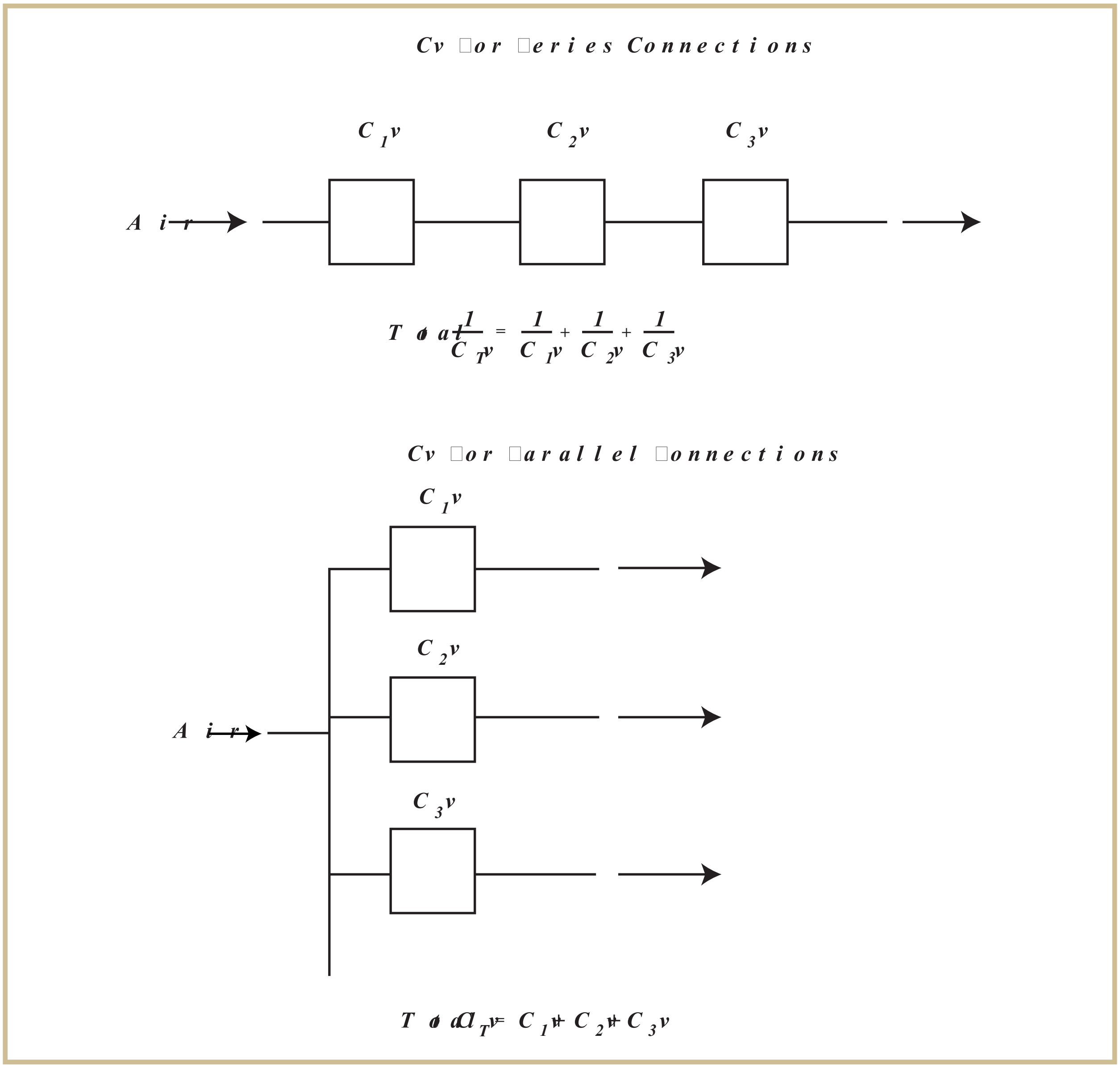



*FIGURE 31—The calculations for $C_v$ with multiple components resemble calculations for electrical resistors.*

## Calculating Cylinder Air Consumption

One of the key elements you need to know to size the compressor and other components for a pneumatic system is the amount of air used by output devices connected to the system. In hydraulic systems, since the fluid is incompressible, you can calculate the volume of fluid consumed per stroke and multiply by the number of strokes per minute. You would then convert the total volume of fluid required to gallons per minute, the usual way of specifying flow requirements.

In pneumatic cylinders, you follow a similar procedure, but the calculation needs to take into account that the air is used at a high pressure. This is another use of the compression ratio you learned about previously. The general procedure for calculating the air consumption of pneumatic cylinders is first to calculate the number of air volume changes that occur during extension and retraction over a specific time period (such as during a minute). The amount of compressed air is then converted to "free air," or air at 14.7 psia.

***Example:*** Calculate the required airflow in SCFM for a cylinder with a 4-in bore and a 10-in stroke that operates at 15 cycles per minute. The air pressure is 90 psi.

*Solution:*

1) Calculate the cylinder volume per stroke:

   $$\text{Area} = \frac{\pi \times 4.0^2}{4} = 12.57\ \text{in}^2$$

   $$\text{Volume} = \text{Area} \times \text{Stroke} = 12.57\ \text{in}^2 \times 10\ \text{in} = 125.7\ \text{in}^3$$

   This is the volume of one-half of a cycle. Since the cylinder also retracts under pressure from the rod side, we can double this volume to get the total volume per stroke. To be exact, the volume of the rod should be subtracted from the volume of the cylinder on the return stroke, but we can neglect this and still get a conservative estimate of the required air volume.

   $$\text{Volume per cycle} = 2 \times 125.7\ \text{in}^3 = 251.4\ \text{in}^3$$

2) Determine volume of 90 psi air that's consumed per minute:

   $$\frac{251.4\ \text{in}^3}{\text{cycle}} \times \frac{15\ \text{cycles}}{\text{min}} = \frac{3771\ \text{in}^3}{\text{min}}\ \text{of 90 psi air}$$

3) Convert the volume in cubic inches to cubic feet:

$$3771 \text{ in}^3/\text{min} \times \left[\frac{1 \text{ ft}^3}{1728 \text{ in}^3}\right] = 2.18 \text{ ft}^3/\text{min}$$

4) Convert air compressed to 90 psi to "free" (uncompressed) air using the compression ratio:

$$\frac{(90 \text{ psi} + 14.7 \text{ psi})}{14.7 \text{ psi}}$$

= 7.12 (times air is compressed when at 90 psi)

5) Determine cubic feet of free air used per minute. 2.18 $\text{ft}^3$/min (CFM) × 7.12 compression ratio = 15.53 $\text{ft}^3$/min of free air used.

Therefore, the air consumption rate of a 4-in bore, 10-in stroke cylinder operating 15 complete cycles per minute at 90 psi is 15.53 SCFM (standard cubic feet per minute) of free air. "Standard" means at a temperature of 68°F, 38% relative humidity, and sea level pressure of 14.7 psia.

## Control Valve Operation and Selection

Pneumatic valves start and stop mechanical sequences, they direct the flow of compressed air, they control the rate of flow into and out of motors and actuators, and they regulate the pressure of parts of the system. Directional control valves may be used as part of the signal (or logic) system, or they may be used to provide the main flow to a cylinder or actuator. Control valves can be activated by means of pilot air, electrical solenoids, mechanical levers, springs, and many combinations of these methods. It isn't uncommon, for example, to have a valve controlled by mechanical and electrical means, as we discussed earlier. In another unit, we'll discuss more sophisticated means of controlling valves, using computers and PLC devices.

A valve has two or three distinct positions. There's a neutral position, which is the position the valve returns to when the actuation method has been removed, and there are usually one or two working positions. Valves are very often returned to neutral positions by springs, but some valves without springs simply remain in their current position when power is removed. An important safety consideration when selecting valves is what will happen when electric power is removed from the system or when air pressure is relieved. Removal of either air pressure or electric power may leave valves and cylinders in a position that could cause injury or damage when power or air pressure is restored. This is often the reason that the system schematics seems more complicated than necessary to accomplish its function: Some of the additional components may be present to restore the system to a known starting point when power is removed for some reason.

In older systems, the valves and conductors were often selected simply by matching port sizes of the cylinder or motor. This often led to inefficient operation because oversize valves and conductors are more expensive and often require more air volume to be moved into and out of cylinders, thus degrading performance. The most critical factor in selection of control valves is sizing the valve for the required airflow at the maximum air consumption rate. As you've learned, this is done by calculating a coefficient of velocity, $C_V$, which is a measure of how well air flows through the valve. Most valve manufacturers recommend a pressure drop of between 2 and 10 psi across the exhaust port. To properly size a valve, you must determine the flow required by the pneumatic load. Knowing the flow rate (and converting to SCFM if necessary), and assuming a nominal pressure drop, you can then find the $C_V$ for the required valve. You aren't likely to find a valve with the exact $C_V$ you need, but you can select one that's close.

Both the extension and retraction flow rates for cylinders must be calculated, and the air line volumes must be included for a true representation of the system characteristics. Calculating a flow rate in SCFM without including the air line volume in your calculations can leave you with a system that doesn't perform as expected. The lines to and from the cylinder may be small in diameter. But if they're long, they'll have significant air volumes that must be moved, and they also may have significant pressure drops. How you calculate air line $C_V$ values will be discussed in a later section, but you need to know that all components have a $C_V$ that affects the system.

***Example:*** The exhaust line from a cylinder must remove 12 SCFM that passes through a control valve to atmosphere. If the pressure drop is 7 psia, what's the $C_V$ for the valve? The temperature of the air is 68°F.

*Solution:* Use the $C_V$ formula from Figure 28.

1) Convert the temperature to Rankine:
   TR = TF + 460° = 68° + 460° = 528°R

2) In this case, $P_2$ is ambient air pressure, or 14.7 psia. The pressure drop is 7.0 psia, so we know the $P_1$ is equal to 14.7 + 7 = 21.7 psia. This means that $\Delta P$ is $\frac{7.0}{21.7}$, or 32.3% of $P_1$.

3) Find K:

   $K = P_{IN}$, from the NFPA equation in Figure 28.

4) Inserting the appropriate values for K, $\Delta P$, and Q, solve for $C_V$:

$$C_V = \frac{12\ \text{SCFM}}{22.67} \times \sqrt{\frac{528}{(21.7 - 14.7) \times 21.7}}$$

This valve has a $C_V$ value of 0.987 for flow under these conditions. Note that if assumed you could use $P_2$ as the K factor (as you often see in other forms of the equation), the calculated $C_V$ would be 1.20, about 21% higher.

***Example:*** What's the approximate pressure drop across a valve that has a $C_V$ of 1.15 with a flow of 15 SCFM at a temperature of 75°F? The input pressure is 100 psi.

*Solution:*

1) Calculate the absolute temperature:
   TR = TF + 460° = 75° + 460° = 535°R

2) Calculate absolute pressure = 100 psig + 17.4 psia = 114.7 psia

3) In this case, use $K = P_1$ because we don't know what $P_2$ will be.

4) Rearrange the $C_V$ equation to solve for $\Delta P$:

$$\Delta P = \frac{T}{K} \times \frac{Q}{(22.67 \times C_V)^2}$$

$$\Delta P = \frac{535°R}{114.7psia} \times \frac{(15\ SCFM)}{(22.67 \times 1.15)^2}$$

$$\Delta P = 1.544\ psi$$

If you try different values for K, you'll see that the pressure can vary quite a lot and not change the value of ΔP very much. For example, if you get 104.7 as the K value (based on a 10 psi pressure drop), you would still calculate a pressure drop of only 1.69 psi.

## Conditioning Equipment

As you learned in the previous unit, pneumatic equipment must have air that's free of moisture and contaminants, at the correct pressure for efficient operation, and lubricated to avoid friction and wear in the moving parts of the mechanism. These requirements occur at so many locations throughout the system that filters, regulators, and lubricators can often be bought as integral units (Figure 32). The devices are known as *FRLs,* filter-regulator-lubricators. You still must be aware of how these individual components are sized, however. Manufacturers supply data charts for different models of FRLs that have different flow rates, pressure ranges, or flow capabilities. Many of these charts are available on the Internet, which makes it easy for a pneumatic technician to access up-to-date information.

Moisture must be removed from pneumatic lines because of its potential to corrode lines, damage tools and equipment, and react with oil to form varnish or sludge on the inside of components. The bulk of moisture removal takes place at or near the receiver, sometimes with sophisticated dryers. You learned about these in a previous unit about air compressors. For every 1000 cubic feet of air that's saturated (100% relative humidity) at 80°F, there will be about 1.6 lbs of moisture. Compression to 90 psig at the same temperature will cause about 1.4 lbs of water to condense in the receiver or other locations, necessitating removal before it can cause problems with the equipment. We'll discuss pneumatic line installation methods that require provisions for removing moisture in the

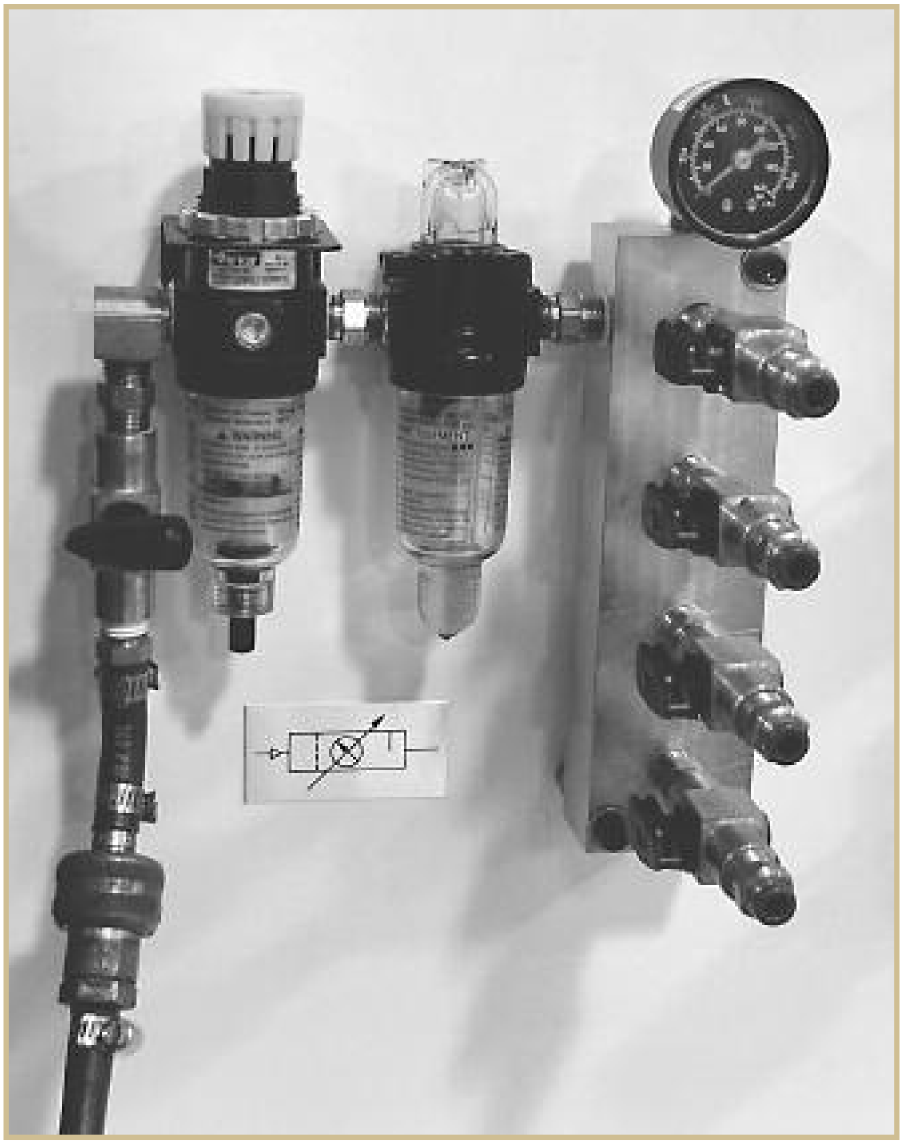


***FIGURE 32—Combination units of filter, regulator, and lubricator are common and may be bought as a complete assembly.***

next section, but you must be aware of the need to remove as much moisture as possible before it travels through the conductors. Again, different types of dryers have different moisture removal capabilities, and manufacturers publish data sheets that you can access to determine the type and size of the drying equipment you may need. Also, painting applications require great care to remove moisture and contamination that may be present in the air. As you can see in Figure 33, a dryer is the last component before the paint gun is attached.

*FIGURE 33—Painting applications require great care to remove moisture and contamination that may be present in the air. Here, a dryer is the last component before the paint gun is attached.*

Filter manufacturers publish performance curves that specify pressure drop versus flow rates. You should consult these charts to select a filter. Larger filters will produce smaller pressure drops and longer operating life but will be more expensive and require more room to install. A typical pressure drop through a filter will range from 1 to 5 psi. Once a pneumatic output device is selected and the most efficient operating pressure is determined, air must be supplied to equipment at the correct pressure regardless of flow and upstream pressure variations. Figure 34 shows a graph of pressure drop versus airflow for a typical filter. These curves would be supplied to match a specific filter by the manufacturer. Some filters are available with *service indicators,* which are markers showing excessive pressure drop. If the filter is functioning normally, a green marker appears; if there's excessive pressure drop, a red marker indicates a need for servicing.

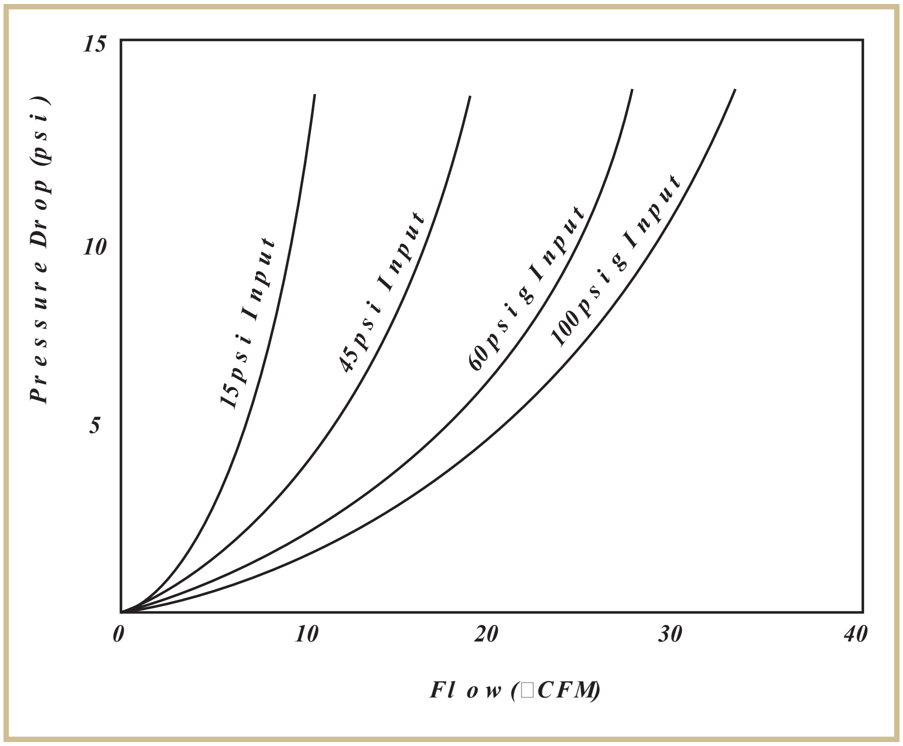



***FIGURE 34—The pressure drop across a filter of a particular size depends on the airflow through it.***

*Pressure regulators* are special valves that reduce the upstream pressure to the correct equipment pressure. They must be protected by the filter, which is always placed upstream from the regulator. Different regulator styles and sizes have different sensitivities (the ability to set specific pressures from a range of operating pressures) and different responses to load and supply pressure variations. Figure 35 shows how the regulated pressure varies as a function of the input pressure for a typical small regulator. Note what is called the *hysteresis* of the graph. This occurs when the relationship of input to the output pressure differs depending on whether input pressure is increasing or decreasing. Large-body valves generally are better for sensitivity and cause less drop than small-body regulators, but they're larger and more expensive to install. Figure 36 shows an example of manufacturers' graphs for pressure drop versus flow rate, which you must consult to determine suitable regulators for specific applications.

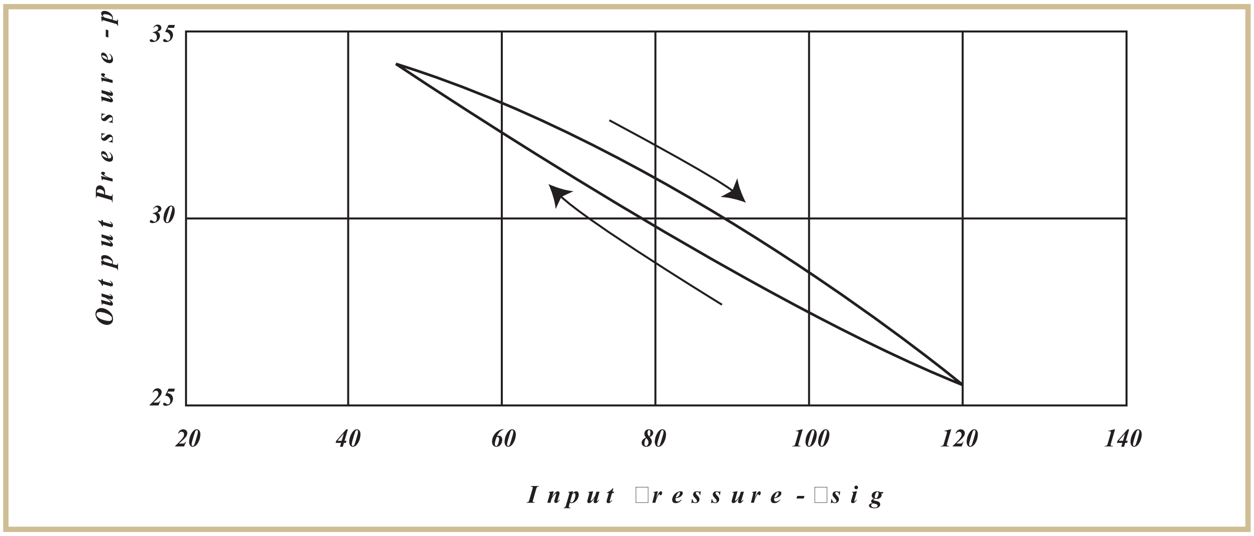
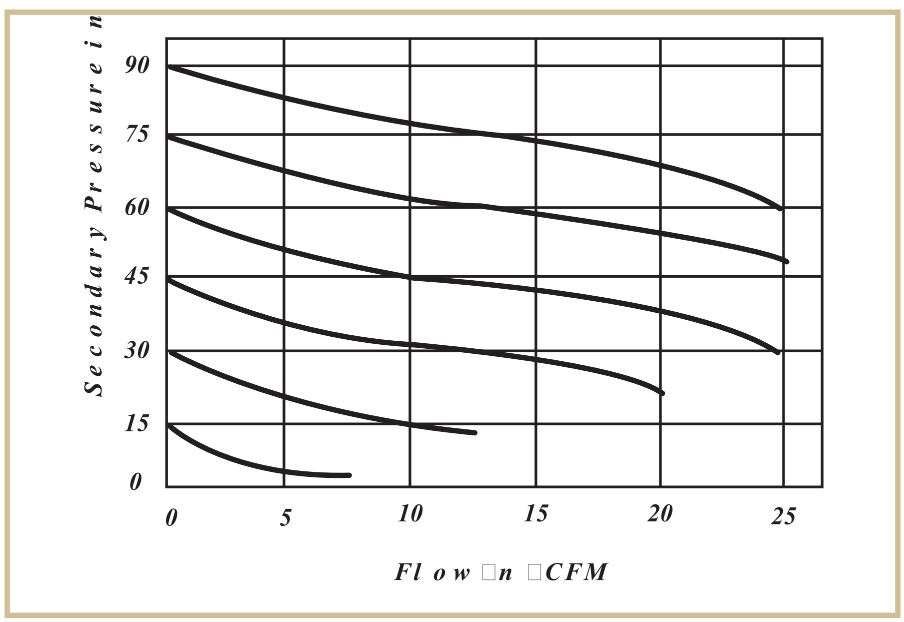


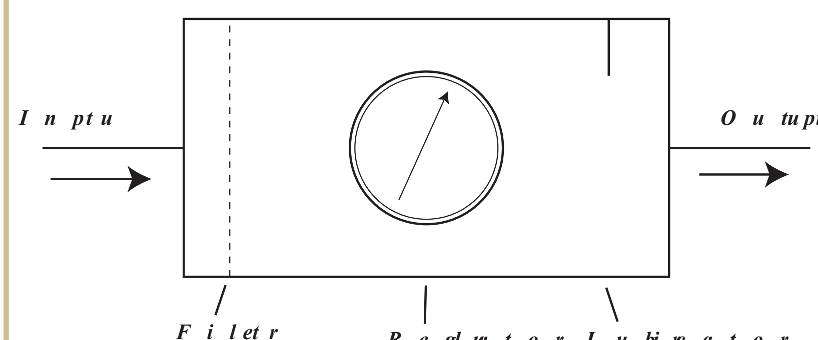

***FIGURE 35—The relationship between input and output pressure through a regulator varies depending on whether the input pressure is increasing or decreasing. This is called hysteresis.***

***FIGURE 36—The ability to set an output pressure will vary as the airflow through the regulator changes.***



Lubricators are installed after the regulators to supply a constant lubrication source for downstream equipment. An acceptable lubricator pressure drop is between 3 and 7 psi, and the pressure drop will increase quickly as the flow rate rises. Remember that many lubricators need a minimum flow rate to operate correctly. Some types of lubricators have internal compensation to accommodate airflow variations by bypassing excess airflows around the lubricating section. Many manufacturers supply individual filters, regulators, and lubricators, as well as integrated FRLs (Figure 37). You should contact the manufacturers' data sheets for specific technical information, including service and repair information where necessary.


(□)




(□)

***FIGURE 37—(A) Lubricator bowls must be checked daily for proper lubricant levels and feed rates. The glass or plastic bowls must remain clear or else should be replaced. (B) Filter assemblies, regulator, and lubricator, known as FRLs, are designated on schematics by this symbol.***

# Conductor Sizing and Installation

Air compressors in manufacturing facilities are generally placed away from the various locations where the energy is used by tools, and they're often isolated in separate rooms because of noise, safety, and vibration of the compressor. The system receiver and primary conditioning equipment will also be located in this room. The primary conditioning consists of a filter, cooler, receiver, dryer, and lubricator. From this room, air is conducted to the needed factory locations by conductors of pipe, tubing, or hose. The principal consideration in the selection and design of conductors is to minimize the pressure drop between the receiver and the point of use. Standard practice is to avoid pressure drops of greater than 10% of the initial pressure. Secondary considerations are selecting materials for the working environment and pressure level, and handling moisture and water removal from the lines.

## Piping Layout

The layout of the piping system is critical in minimizing the pressure drop from source to load. Some general layout types include a single pipe, a distribution trunk with branches, and a looped system. Figure 38 shows examples of these possible types. The type used most often is the loop system, because at any point on the line there are actually two sources of compressed air. If heavy demand from another part of the system arises, two paths of compressed air will minimize pressure drops and fluctuations as airflow increases and decreases. Also, where conductor lines are long, receivers should be placed near the point of air consumption so that short periods of high demand don't cause unacceptable pressure drops in other parts of the line.

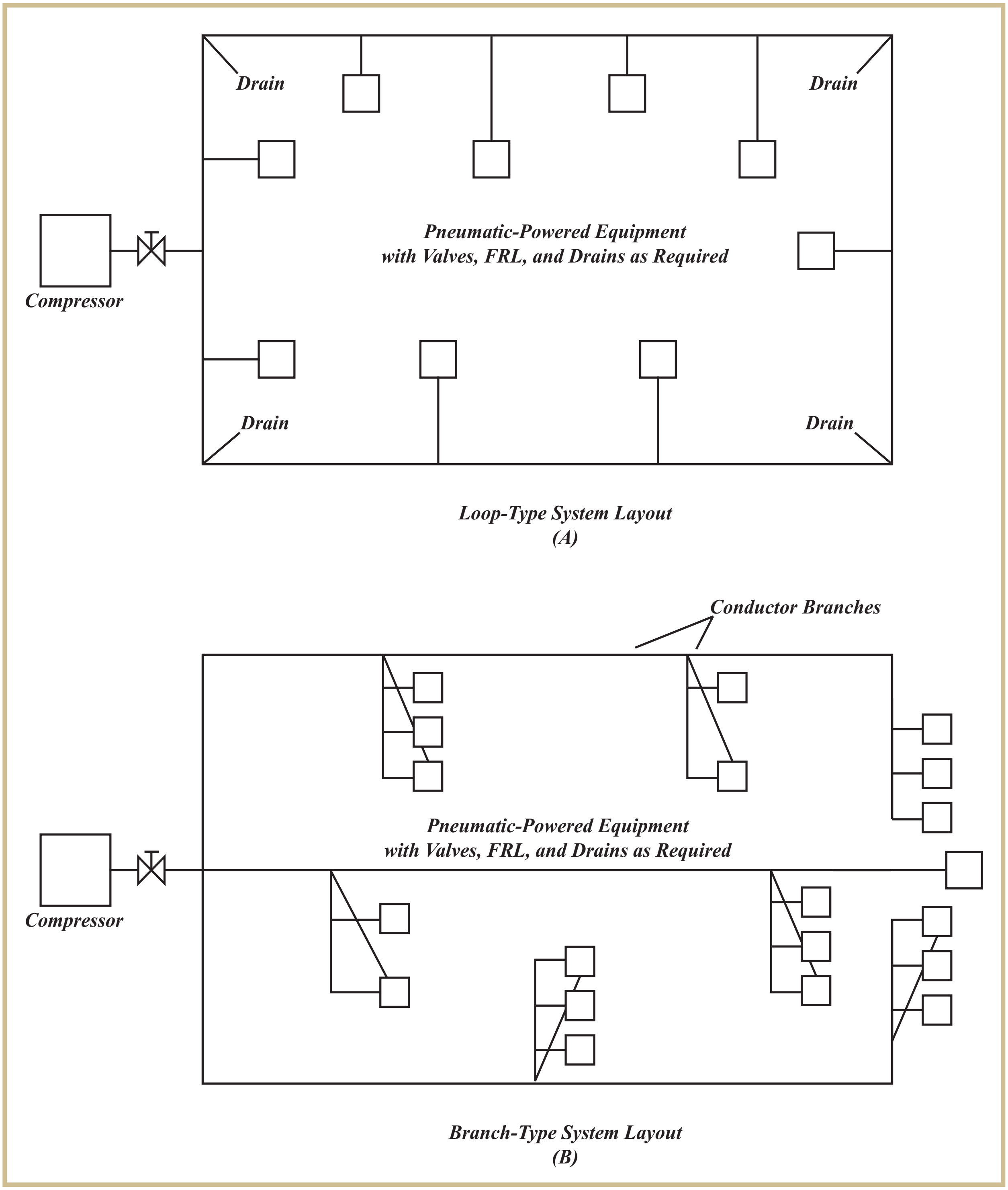



*FIGURE 38—The best pneumatic system layout has a loop system that allows air to be supplied to a load from two directions.*

Good piping layout involves a number of considerations. Piping runs should avoid sharp bends to minimize pressure drops. Fittings should be used where necessary for maintenance. But the fewer the number of fittings, the less chance there is of leakage, which is one of the primary losses in pneumatic systems. Pipes and tubing should be firmly supported to avoid vibration problems, because physical connections with threads will leak eventually when subjected to even minor vibrations.

Since some amount of moisture is always present in compressed air, piping systems must accommodate water-removal methods. All straight runs of pipe or tubing should be installed with a 1% to 2% slope to allow water to be trapped and drained from low points in the system. You can calculate the amount of drop required for a length of pipe by the following relationship:

$$\text{Line Drop (inches)} = \text{Line Run (feet)} \times \text{Grade (1 to 2 \%)} \times 0.12$$

***Example:*** What should the drop in inches be for a pneumatic pipe 30 feet long if the specifications call for a 1.5% slope in installed pneumatic piping?

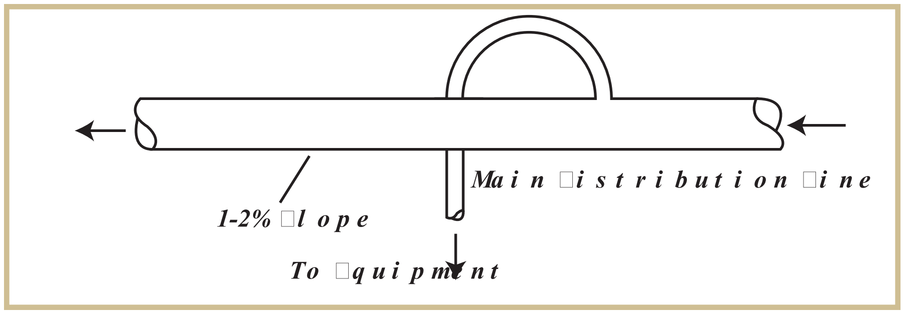
*Solution:* Using the above equation,

$$\text{Line drop} = 30\text{ ft} \times 1.5 \times 0.12 = 5.4\text{ in}$$

A rule of thumb you can use to quickly estimate the required drop is that a 1% to 2% slope is 1.2 to 2.4 inches of drop in a 10-foot section of pipe. So for every 10 feet of horizontal run, you should plan to have the pipe or tube drop about 2 inches. In the above example, you can see that for a 30-foot pipe, the estimated drop would be about 6 inches, close enough to our calculated value of 5.4 inches.

Because of moisture, tees in the line should be positioned with their vertical leg pointing up. This forces moisture in the line to continue on to a lower portion of the line and a drain, rather than reaching the equipment served by the main distribution line. A drain should be installed at the bottom of a tee-off, with air service taken from a connection 6 to 8 inches above the drain. Figure 39 shows diagrams of various tap and branch configurations, and Figure 40 shows the configuration of moisture drains that should be placed at the lower ends of conductors.

FIGURE 39—Branches in pneumatic lines should come off the top of a pipe to avoid allowing water or moisture to continue to other parts of the line.



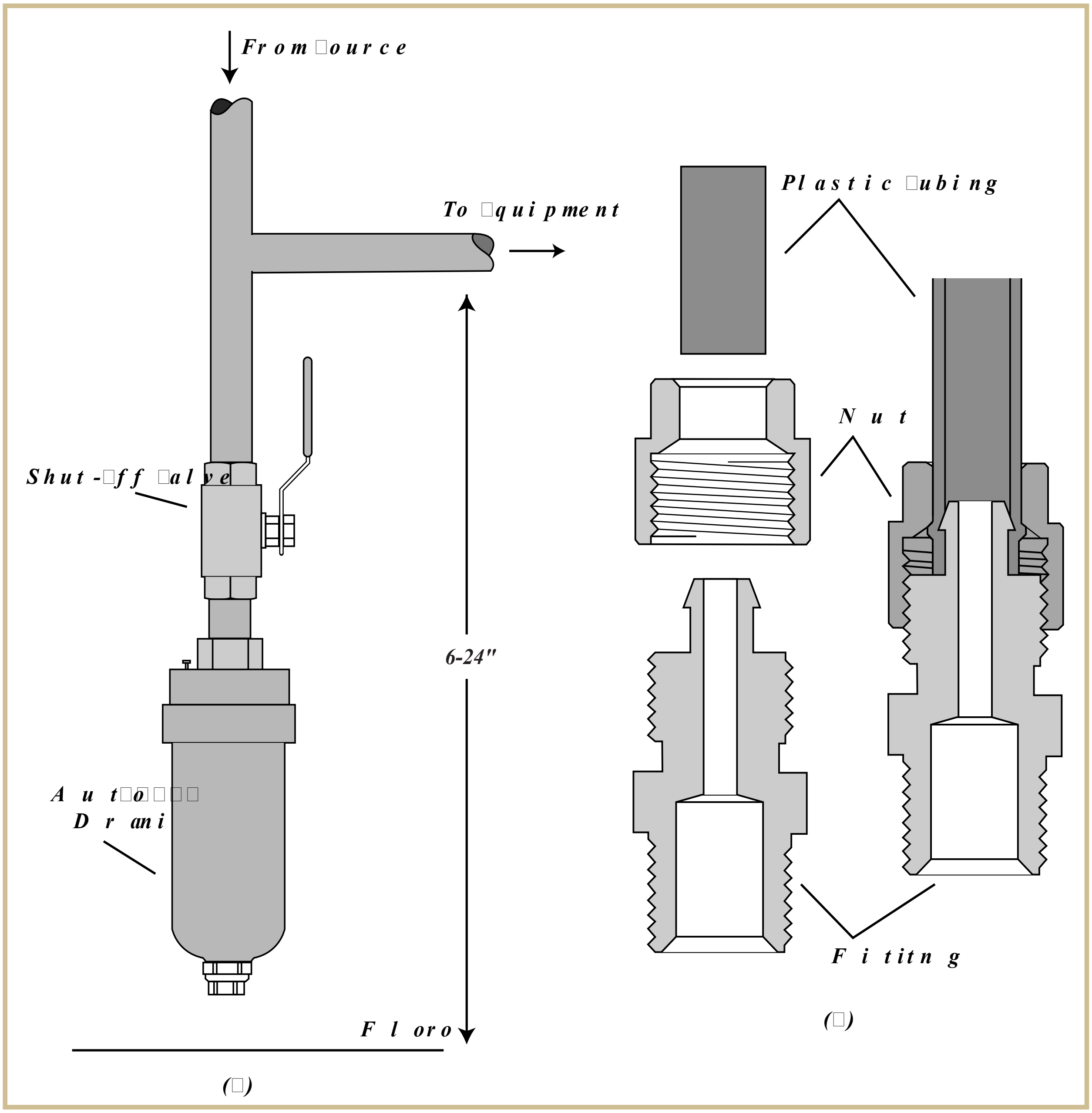




FIGURE 40—(A) Drains at the end of the sloped supply lines can be manual or automatic, but must be periodically opened to remove condensed water. (B) One system of plastic pneumatic tubing connectors has a nut that traps the plastic tubing to a plastic or metal fitting and ensures a leak-free seal.

## Piping Materials

In hydraulic systems, pressure can be very high, making conductor-material selection critical. Since pneumatic systems usually operate at much lower pressures—typically around 90–100 psi—material selection is less crucial. More important than pressure considerations are environmental factors. Materials that are common in pneumatic systems include

- Galvanized and cast iron
- Copper and aluminum tubing
- High-strength steel pipe
- Plastic, nylon, or rubber hose (solid or reinforced)
- Brass tubing

Distribution pipes from the compressor room are often made from steel pipe that's electrical resistance welded (ERW), while the branches may be copper, steel, or brass tubing. Equipment is often attached by flexible tubing or hose, such as where pneumatic wrenches are used on a production line. Flexible hose is installed when relative movement between two parts of the system is required, or when parts of the system must be isolated from vibration sources.

The pressure in pneumatic systems is usually not high, commonly less than 150 psi, and materials selected for pneumatic lines aren't chosen specifically with regard to pressure capacity. However, with moisture as a constant ingredient in compressed air, corrosion problems must be considered by the technicians servicing the system.

Plastics such as PVC and ABS are becoming more popular, because the conductor lengths are assembled with glue. Glued joints offer significantly less chance of leaks than threaded pipes and are much quicker to assemble. Steel pipe usually comes in long (20-feet) lengths that are cut to size and threaded. They're then joined with unions or other fittings. Threading the pipe requires special tools and has the possibility of leaving metal debris inside the lines after assembly. Plastic pipes are quickly cut without special tools and are glued together quickly in relatively foolproof glued joints, thus saving considerable assembly time. Unions still must be inserted occasionally, however, because of maintenance requirements. The biggest disadvantage of PVC, and the reason it's often not recommended, is that PVC tends to shatter when subjected to excessive pressure, with the possibility of many sharp projectiles causing injury. The ABS plastic ruptures when it fails but doesn't shatter, and thus is somewhat more attractive for pneumatic applications. The pressure rating of both types decreases with increased temperatures. Because of the possibility of material mix-ups, ABS materials are manufactured and supplied in metric sizes, while PVC is supplied in inch sizes. Another consideration for plastic conductors is that they expand more as temperature increases, thus necessitating careful consideration in piping layouts.

A popular alternative to carbon steel pipe and plastic is hard-drawn copper tubing. Although it's slightly more expensive that steel pipe, it's easier to install and maintain compared to steel. Copper tubing is lighter than steel tubing, so it's somewhat easier to handle, and it's easily joined by soldering or brazing, thus avoiding the problems of threading and potential leaks. And finally, copper tubing is corrosion-resistant, doesn't shatter like PVC, and is easy to cut into for system expansion if necessary.

Flexible plastic tubing is becoming more popular for some applications because the conductors are easily fabricated and connected, especially for complex conductor paths and multiple connections. "Push-on" fittings make this conductor material easy to use. The tubing is cut square with a cutting tool, and a nut is placed on the tube. The tubing is then pushed onto the fitting and the nut tightened over the fitting end, trapping the plastic tubing between the two parts.

## Pressure Drop in Conductors

As you learned in the section about friction, frictional forces are generated whenever two materials are moving past each other. In the last unit, you learned that the type of airflow (laminar or turbulent) had significant effects on the pressure drop in a conductor, fitting, or pneumatic component. The pressure drop is a result of friction of moving air against itself and the conductor walls, because energy is being removed from the system and changed into heat. The pressure will drop when energy is removed.

As you may expect, a pressure drop occurs when air flows through conductors. Many studies have been done to measure pressure drop in various sizes and types of conductors, and many tables are published that can give you fairly accurate estimates. When air passes through fittings such as reducers, elbows, tees, and connectors, there are additional pressure drops. The usual way to estimate the effect of these is to find the equivalent length in a reference table. In other words, a table may tell you that an elbow fitting of a certain pipe size is the equivalent of adding a six-foot section of straight pipe. Other sources will tell you to count each fitting as the equivalent of a certain length of pipe or tube. You then add all of the equivalent lengths together and, from the table, estimate the pressure drop due to a specific length of pipe or tubing.

As with valves or any other component through which air flows, pipe and tubing have a $C_V$ that can be used to calculate pressure drops for certain flow rates. One method of calculating the $C_V$ for tubing is to use the relationship:

$$C_V = 42.3 \times A_t \times \sqrt{\left(\frac{d_t}{(f \times l)}\right)}$$

In the above equation, $A_t$ is the cross-sectional area of the tubing, $d_t$ is the inside diameter of the tubing, f is a friction factor – 0.02 for flexible tubing and 0.03 for rigid steel pipe, and l is the length of tubing in inches. Calculating $C_V$ and pressure drop is done the same way as for a control valve. If the air line has 90° fittings attached, you should add an equivalent length correction factor to the line of $L_{eq} = 48 \times d_f$ for each fitting (where $d_f$ is the fitting's inside diameter). For example, if an air line with an inside diameter of $\frac{1}{4}$ inch has two 90° fitting attached at the ends, each fitting will have an equivalent length of $L_{eq} = 48 \times 0.250 = 12$ in. So you would add 24 inches to the line length before calculating the $C_V$.

***Example:*** What's the $C_V$ value for a 48-inch length of flexible tubing that's 1/4-inch inside diameter?

*Solution:*

1) The diameter of the tubing is 1/4 inch, so the area is $A = \pi \times \frac{(0.25)^2}{4} = 0.049 \text{ in}^2$.
2) The friction factor is 0.02, and the length is 48 inches.
3) Inserting these values into the above equation:

$$C_V = 42.3 \times (0.049 \text{ in}^2) \sqrt{\left(\frac{0.250 \text{ in}}{(0.02 \times 48 \text{ in.})}\right)}$$

$$C_V = 1.059$$

This value can be used in the $C_V$ equation you used for valves to determine pressure drops at various flow rates.

***Example:*** What's the pressure drop of the above tube when it's used to conduct 12 SCFM at 90 psig? The air temperature is 68°F (528°R).

*Solution:*

1) Convert 90 psig to psia: $P_1$ = 90 psig + 14.7 psia = 104.7 psia
2) Rearrange the $C_V$ equation to solve for pressure drop, as shown in Figure 28, and insert the known values. In this case, $P_1$ and $P_2$ will be very close, and the value of the equation won't be greatly affected by using the 104.7 psia as the K factor.

$$\Delta P = \left(\frac{Q}{22.67 \times C_V}\right)^2 \times \frac{T}{K}$$

$$\Delta P = \left(\frac{12 \text{ SCFM}}{(22.67 \times 1.059)}\right)^2 \times \frac{528°\text{R}}{104.7}$$

$$\Delta P = 1.26 \text{ psi}$$

Setting up these equations in a spreadsheet is recommended. You can calculate flow rates, $C_V$s, or pressure drops very quickly for a variety of conditions. And you can go back to recheck if the conditions change. With a spreadsheet, you can use a process for the calculation that will allow you to use the estimated downstream pressure $P_2$ instead of assuming $P_1$ for the K factor. In this case, you get a slightly different $\Delta P$ of 1.276—still very close to our estimate.

A rule of thumb calculation for fittings is to use the following expression for the approximate $C_V$:

$$C_V = 18 \times (d_f)^2$$

Here, $d_f$ is the inside diameter of the fitting.

***Example:*** What's the $C_V$ for a $^1/_4$-inch NPT fitting that has an inside diameter of 0.280?

*Solution:* From above, $C_V = 18 \times (0.280 \text{ in.})^2 = 1.411$

This is the $C_V$ value that you would use in computing the pressure drop of this fitting if used in a pneumatic system.

Our modern computing capabilities have made calculations easy, and there are many software programs available that you can use to calculate these characteristics. Spreadsheets are one of the most useful tools you can use to learn to do technical calculations. In the past, however, because of the difficulties of calculating quickly, engineers often prepared tables that were useful for system design and troubleshooting. The Compressed Air Institute has developed many tables that are useful for pneumatic technicians.

Table 2 is a list of *air loss factors* that can be used to calculate pressure drop. To use the table, find the factor listed at the intersection of the appropriate SCFM and NPT pipe size. Calculate the compression ratio: CR = (psig +14.7)/14.7. Divide this into the factor. Multiply this number by the length in feet of the pipe, and divide by 1000. To summarize:

$$\Delta P = \left(\frac{\text{Factor}}{\text{CR}}\right) \times \frac{\text{Length (ft.)}}{1000}$$

***Example:*** What's the approximate pressure drop for 60 feet of $^3/_4$-NPT pipe carrying 50 SCFM at 90 psig?

*Solution:*

1) The compression ratio is $\text{CR} = \frac{(90 + 14.7)}{14.7} = 7.122$.
2) The table factor is 196.
3) $\Delta P = \left(\frac{196}{7.122}\right) \times \frac{60 \text{ ft}}{1000} = 1.65 \text{ psi}$

**Table 2**

**AIRFLOW LOSS FACTOR THROUGH PIPES**

| | PIPE SIZE-NPT | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **SCFM** | ½ | ¾ | 1 | 1 ¼ | 1 ½ | 1 ¾ | 2 | 2 ½ | 3 ½ | 4 | 4 ½ | 5 |
| 5 | 12.7 | 1.2 | .5 | - | - | - | - | - | - | - | - | - |
| 10 | 50.7 | 7.8 | 2.2 | .5 | - | - | - | - | - | - | - | - |
| 15 | 114 | 17.6 | 4.9 | 1.1 | - | - | - | - | - | - | - | - |
| 20 | 202 | 30.4 | 8.7 | 2.0 | - | - | - | - | - | - | - | - |
| 25 | 316 | 50.0 | 13.6 | 3.2 | 1.4 | .7 | - | - | - | - | - | - |
| 30 | 456 | 70.4 | 19.6 | 4.5 | 2.0 | 1.1 | - | - | - | - | - | - |
| 35 | 621 | 95.9 | 26.6 | 6.2 | 2.7 | 1.4 | - | - | - | - | - | - |
| 40 | 811 | 125 | 34.8 | 8.1 | 3.6 | 1.9 | - | - | - | - | - | - |
| 45 | - | 159 | 44.0 | 10.2 | 4.5 | 2.4 | 1.2 | - | - | - | - | - |
| 50 | - | 196 | 54.4 | 12.6 | 5.6 | 2.9 | 1.5 | - | - | - | - | - |
| 60 | - | 282 | 78.3 | 18.2 | 8.0 | 4.2 | 2.2 | - | - | - | - | - |
| 70 | - | 385 | 106 | 24.7 | 10.9 | 5.7 | 2.9 | 1.1 | - | - | - | - |
| 80 | - | 503 | 139 | 3203 | 14.3 | 7.5 | 3.8 | 1.5 | - | - | - | - |
| 90 | - | 646 | 176 | 40.9 | 18.1 | 9.5 | 4.8 | 1.9 | - | - | - | - |
| 100 | - | 785 | 217 | 50.5 | 22.3 | 11.7 | 6.0 | 2.3 | - | - | - | - |
| 110 | - | 950 | 263 | 61.1 | 27.0 | 14.1 | 7.2 | 2.8 | - | - | - | - |
| 120 | - | - | 318 | 72.7 | 32.2 | 16.8 | 8.6 | 3.3 | - | - | - | - |
| 130 | - | - | 369 | 85.3 | 37.8 | 19.7 | 10.1 | 3.9 | - | - | - | - |
| 140 | - | - | 426 | 98.8 | 43.8 | 22.9 | 11.7 | 1.4 | - | - | - | - |
| 150 | - | - | 490 | 113 | 50.3 | 26.3 | 13.4 | 5.2 | - | - | - | - |
| 160 | - | - | 570 | 129 | 57.2 | 29.9 | 15.3 | 5.9 | - | - | - | - |
| 170 | - | - | 628 | 146 | 64.6 | 33.7 | 17.6 | 6.7 | - | - | - | - |
| 180 | - | - | 705 | 163 | 72.6 | 37.9 | 19.4 | 7.5 | - | - | - | - |
| 190 | - | - | 785 | 177 | 80.7 | 42.2 | 21.5 | 8.4 | - | - | - | - |
| 200 | - | - | 870 | 202 | 89.4 | 46.7 | 23.9 | 9.3 | - | - | - | - |
| 220 | - | - | - | 244 | 108 | 56.5 | 28.9 | 11.3 | - | - | - | - |
| 240 | - | - | - | 291 | 128 | 67.3 | 34.4 | 13.4 | - | - | - | - |
| 260 | - | - | - | 341 | 151 | 79.0 | 40.3 | 15.7 | - | - | - | - |
| 280 | - | - | - | 395 | 175 | 91.6 | 46.8 | 18.2 | - | - | - | - |
| 300 | - | - | - | 454 | 201 | 105 | 53.7 | 20.9 | - | - | - | - |
| 320 | | - | - | - | - | - | 61.1 | 23.8 | - | - | - | - |
| 340 | - | - | - | - | - | - | 69.0 | 26.8 | 2.0 | - | - | - |
| 360 | - | - | - | - | - | - | 77.3 | 30.1 | 2.2 | - | - | - |
| 380 | - | - | - | - | - | - | 86.1 | 33.5 | 2.5 | - | - | - |
| 400 | - | - | - | - | - | - | 94.7 | 37.1 | 2.7 | - | - | - |

*(Continued)*

*Table 2—Continued*

| | PIPE SIZE-NPT | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **SCFM** | ½ | ¾ | 1 | 1 ¼ | 1 ½ | 1 ¾ | 2 | 2 ½ | 3 ½ | 4 | 4 ½ | 5 |
| 420 | - | - | - | - | - | - | 105 | 40.9 | 3.1 | - | - | - |
| 440 | - | - | - | - | - | - | 116 | 44.9 | 3.4 | - | - | - |
| 460 | - | - | - | - | - | - | 126 | 48.8 | 3.7 | 2.0 | - | - |
| 480 | - | - | - | - | - | - | 138 | 53.4 | 4.0 | 2.2 | - | - |
| 500 | - | - | - | - | - | - | 150 | 58.0 | 4.3 | 2.4 | - | - |
| 525 | - | - | - | - | - | - | 165 | 64.2 | 4.8 | 2.6 | - | - |
| 550 | - | - | - | - | - | - | 182 | 70.2 | 5.2 | 2.9 | - | - |
| 575 | - | - | - | - | - | - | 197 | 76.7 | 5.7 | 3.1 | - | - |
| 600 | - | - | - | - | - | - | 215 | 83.5 | 6.2 | 3.4 | - | - |
| 625 | - | - | - | - | - | - | 233 | 92.7 | 6.8 | 3.7 | - | - |
| 650 | - | - | - | - | - | - | 253 | 98.0 | 7.3 | 4.0 | 2.2 | - |
| 675 | - | - | - | - | - | - | 272 | 106 | 7.9 | 4.3 | 2.4 | - |
| 700 | - | - | - | - | - | - | 294 | 114 | 8.5 | 4.6 | 2.6 | - |
| 750 | - | - | - | - | - | - | 337 | 131 | 9.7 | 5.3 | 2.9 | - |
| 800 | - | - | - | - | - | - | 382 | 148 | 11.1 | 6.1 | 3.3 | - |
| 850 | - | - | - | - | - | - | 433 | 168 | 12.5 | 6.8 | 3.8 | - |
| 900 | - | - | - | - | - | - | 486 | 188 | 14.0 | 7.7 | 4.2 | - |
| 950 | - | - | - | - | - | - | 541 | 209 | 15.7 | 8.6 | 4.7 | - |
| 1000 | - | - | - | - | - | - | 600 | 232 | 17.3 | 9.5 | 5.2 | 1.9 |
| 1050 | - | - | - | - | - | - | 658 | 256 | 19.1 | 10.4 | 5.8 | 2.1 |
| 1100 | - | - | - | - | - | - | 723 | 281 | 21.0 | 11.5 | 6.3 | 2.4 |
| 1150 | - | - | - | - | - | - | 790 | 307 | 22.9 | 12.5 | 6.9 | 2.6 |
| 1200 | - | - | - | - | - | - | 850 | 344 | 25.0 | 13.7 | 7.5 | 2.8 |
| 1300 | - | - | - | - | - | - | - | 392 | 29.3 | 16.0 | 8.8 | 3.3 |
| 1400 | - | - | - | - | - | - | - | - | 33.9 | 18.6 | 10.2 | 3.8 |

If we compare this tabular result with what we calculate (using a 0.824-inch ID for $^3/_4$-NPT pipe), we would find a calculated $C_V$ of 4.406 and a calculated pressure drop of 1.28 psi. They're comparable, and it would be difficult to detect a performance difference of the difference between a 1.65 psi and 1.28 psi drop in pressure.

Table 3 shows the pressure drop across a standard 25-foot-length air hose of various diameters at various flow rates. Pressure drop across longer or shorter hoses is linearly proportional. Again, the table data is comparable to calculated values using the equations provided. Table 4 shows loss factors in terms of equivalent lengths of pipe for different types of fittings you may encounter in air lines. After finding the equivalent length of a fitting, you would add that length to the length of the air line before calculating $C_V$ or pressure drop.

**Table 3**

**PRESSURE DROP PER 25 FEET OF AIR HOSE**

| SIZE-ID | SCFM | 50 psi | 60 psi | 70 psi | 80 psi | 90 psi | 100 psi |
|---|---|---|---|---|---|---|---|
| ½ inch | 20 | 1.8 | 1.3 | 1.0 | 0.9 | 0.8 | 0.7 |
| | 30 | 5.0 | 4.0 | 3.4 | 2.8 | 2.4 | 2.3 |
| | 40 | 10.1 | 8.4 | 7.0 | 6.0 | 5.4 | 4.8 |
| | 50 | 18.1 | 14.8 | 12.4 | 10.8 | 9.5 | 8.4 |
| | 60 | - | 23.4 | 20.0 | 17.4 | 14.8 | 13.3 |
| | 70 | - | - | 28.4 | 25.2 | 22.0 | 19.3 |
| | 80 | - | - | - | 34.6 | 30.5 | 27.2 |
| ¾ inch | 20 | 0.4 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 |
| | 30 | 0.8 | 0.6 | 0.5 | 0.5 | 0.4 | 0.4 |
| | 40 | 1.5 | 1.2 | 0.9 | 0.8 | 0.7 | 0.6 |
| | 50 | 2.4 | 1.9 | 1.5 | 1.3 | 1.1 | 1.0 |
| | 60 | 3.5 | 2.8 | 2.3 | 1.9 | 1.6 | 1.4 |
| | 70 | 4.4 | 3.8 | 3.2 | 2.8 | 2.3 | 2.0 |
| | 80 | 6.5 | 5.2 | 4.2 | 3.6 | 3.1 | 2.7 |
| | 90 | 8.5 | 6.8 | 5.5 | 4.7 | 4.0 | 3.5 |
| | 100 | 11.4 | 8.6 | 7.0 | 5.8 | 5.0 | 4.4 |
| | 110 | 14.2 | 11.2 | 8.8 | 7.2 | 6.2 | 5.4 |
| 1 inch | 30 | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 |
| | 40 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 |
| | 50 | 0.5 | 0.4 | 0.4 | 0.3 | 0.3 | 0.2 |
| | 60 | 0.8 | 0.6 | 0.5 | 0.5 | 0.4 | 0.4 |
| | 70 | 1.1 | 0.8 | 0.7 | 0.7 | 0.6 | 0.5 |
| | 80 | 1.5 | 1.2 | 1.0 | 0.8 | 0.7 | 0.6 |
| | 90 | 2.0 | 1.0 | 1.3 | 1.1 | 0.9 | 0.8 |
| | 100 | 2.6 | 2.0 | 1.6 | 1.4 | 1.2 | 1.0 |
| | 110 | 3.5 | 2.6 | 2.0 | 1.7 | 1.4 | 1.2 |

| Table 4 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **PRESSURE LOSS FACTOR THROUGH FITTINGS** | | | | | | | | |
| **Pipe Size NPT** | **Standard "L"** | **Long Radius "L"** | **Medium Radius "L"** | **Angle Valve** | **Gate Valve** | **Globe Valve** | **Close Return Bend** | **Tee Thru Side** |
| ½ | 0.84 | 0.41 | 0.52 | 1.1 | 0.31 | 2.5 | 1.3 | 1.7 |
| ¾ | 1.2 | 0.57 | 0.73 | 1.6 | 0.44 | 3.5 | 1.8 | 2.3 |
| 1 | 1.6 | 0.77 | 0.98 | 2.1 | 0.57 | 4.7 | 2.3 | 3.1 |
| 1 ¼ | 2.2 | 1.1 | 1.4 | 2.9 | 0.82 | 6.5 | 3.3 | 4.4 |
| 1 ½ | 2.6 | 1.3 | 1.6 | 3.5 | 0.98 | 7.8 | 3.9 | 5.2 |
| 2 | 3.6 | 1.7 | 2.2 | 4.8 | 1.3 | 10.6 | 5.3 | 7.1 |
| 2 ½ | 4.4 | 2.2 | 2.8 | 5.9 | 1.6 | 13.1 | 6.6 | 8.7 |
| 3 | 5.7 | 2.8 | 3.6 | 7.7 | 2.1 | 17.1 | 8.5 | 11.4 |
| 4 | 7.9 | 3.9 | 5.0 | 10.7 | 3.0 | 23.7 | 11.8 | 15.8 |
| 5 | 10.4 | 5.1 | 6.5 | 13.9 | 3.9 | 31 | 15.5 | 20.7 |

Now take a few moments to review what you've just learned by completing *Self-Check 2.*

# Self-Check 2

1. Operating characteristics of the electric motor can usually be found on the _______.
2. The flow capacity of a compressor is expressed in ______ under a standard operating conditions of 14.7 psia, 68 degrees F and 36% relative humidity.
3. A gauge pressure of 90 psig would result in a compression ratio of _______.
4. A flow of 5.0 CFM at an operating pressure of 60 psig is actually a flow of _______ SCFM.
5. To avoid wasting energy by overcompression, a compressor should be asked to raise the pressure to only about _______ above what is needed by the equipment.
6. Short periods of high demand can be met by sizing the _______ with extra capacity.
7. The _______ affects how much total force it will take to push a load across a floor.
8. For the most efficient operation of cylinders designed for speed of movement, you should size a cylinder _______ the required load needed for the application.
9. Motor horsepower is a function of _______ and _______.
10. The _______ of a pneumatic component is calculated by measuring the pressure drop across the component for a known airflow.
11. To calculate cylinder air consumption, you need to know _______, _______, and the _______.
12. After the actuation method of a valve has been removed, it returns to the _______ position.
13. Most valve manufacturers recommend a pressure drop of _______ psi across the exhaust port at the required flow rate.
14. The most effective system layout for pneumatic conductors is in a/an _______ configuration.
15. Tight bends and fittings cause _______ flow, which results in higher _______ values and pressure drops.

# SAFETY PROCEDURES FOR PNEUMATIC EQUIPMENT

Safety concerns for people working with pneumatic equipment are similar to those for hydraulic and electrical equipment. You must make sure that people working on or near the system are protected from inadvertent injuries, and that involves understanding where and how such injuries could take place. In the following discussion, you'll find that many of the precautions are common-sense procedures. Nevertheless, they bear repeating to ensure that you're aware of safety at all times while servicing, repairing, or installing pneumatic equipment.

The first proper safety practice to use when working on pneumatic systems is to *follow approved lockout/tagout procedures* for your facility when repairing or troubleshooting the equipment. *You should first de-energize all moving equipment by removing air supplies and electrical power to control systems and valves.* As with electrical equipment that has been de-energized for repairs, you should place a locked barrier to prevent others from starting the equipment while you or others are working on it. The brightly colored tag should list your name and details of the repair to notify others about the reason the service is off. Some facilities have a system with multiple locks: Not only do you lock the equipment, but a supervisor or other administrator must also lock the device, requiring that more than one person be present to restore power.

Before any equipment is restarted, you should make sure all safety guards are in place and operating correctly. If any equipment is able to run in two directions, you should make sure that when started, it will turn or move in the right direction. A three-phase AC motor is particularly susceptible to being started in a "backward" condition, since switching two wires will make it turn in the opposite direction. Sometimes power supplied to the AC device must be checked for phase, because in older facilities care wasn't taken to label the phase of individual wires as they were distributed across the buildings.

Pneumatic systems are in many ways safer to repair and maintain than electrical systems. With electrical equipment, there's always danger from shock, and hydraulic systems use hazardous liquids under high pressure. However, pneumatic systems offer some hazards of their own, and you should follow these guidelines for your personal safety where they apply:

- For receivers, *use only approved containers* that are clearly marked for their intended use and pressure capacity. Never exceed that capacity under any condition. Weld repairs or modifications to these containers must be done by qualified welders, with approved procedures, so it's unlikely your facility will be able to repair these containers on site. The best policy is simply not to weld or modify any pressure vessel.

- *Don't use any frayed or damaged hoses or tubing.* All fittings connected to these hoses should be in good working condition and properly secured to the hose. Hose and tubing should be designed for use with compressed air.

- *Shutoff valves should be placed strategically in the system lines* so that maintenance can be performed without depressurizing the entire system. These valves should be able to be locked in the *off* position so that air can't be restored while someone is working on the machinery.

- *High-volume air hoses that could possibly open to the atmosphere should have a pneumatic fuse installed.* A pneumatic fuse will cause the air supply to be blocked if the flow exceeds a specified amount, similar to an electrical fuse. A pneumatic fuse is able to prevent a broken air line from whipping, avoiding injury to nearby personnel.

- *Always use eye protection around pneumatic tools and equipment.*

- Never disconnect air lines that are pressurized; remove pressure from the line by using a shutoff valve to that part of the system or turn off the compressor and receiver altogether.

- Use compressed air for cleaning with *extreme* caution, and take special care to ensure that dirt isn't blown at other people or toward equipment that may be affected by dirt. Don't exceed 30 psig for cleaning purposes, and never clean dirt from your clothes with compressed air.

- Never apply compressed air to your skin or point a hose at another person. Serious internal injuries have resulted from horseplay or accidents, even with low pressures.

- Avoid breathing oil mists from lubricators or other equipment.

- Make sure noise-reducing mufflers are installed where necessary. Wear hearing protection around machinery to avoid hearing loss. Studies have shown that exposure to even moderately high machinery noise will cause hearing loss over time. This generally appears as a loss of high-frequency perception, which in turn causes an inability to hear voices well.

- Maintain a high level of cleanliness for all work areas and equipment. It's easier to detect problems in a clean work environment.

- If you must work on a live pneumatic or electrical circuit, make sure you have accurate schematics and a thorough understanding of electrical and pneumatic systems to be able to troubleshoot a working system. It's often good to work in pairs so that two sets of eyes can reveal dangerous situations.

- When you're troubleshooting equipment, other safety considerations arise. These are discussed in detail in the next section because of the nature of the procedures involved.

## Troubleshooting Pneumatic Systems

Pneumatic systems offer many advantages over other types of systems due to the ease of installation and maintenance of even complex systems. If pneumatic systems are installed properly and maintained on a regular basis, they should give reliable service for many years. For a system that has operated successfully for long periods of time, sudden failures are usually due to specific, traceable causes. The cost of lost production makes it imperative that the machines are diagnosed and repaired as quickly as possible.

One of the greatest causes of failures in pneumatic systems is the presence of dirt or contamination in the air. Many of the problems you'll encounter can be avoided by keeping the primary and secondary conditioning equipment—filters and lubricators—in top shape. Dirt causes abrasions in moving metal parts and causes seals to develop cracks. Dirt may also prevent movement of valves and cylinders. In all of our discussions of troubleshooting pneumatic systems, keep in mind that the root cause of many problems you'll encounter could be dirt that has found its way into the system. As we discussed before, a good policy is to maintain high cleanliness in all areas where repairs take place and where pneumatic equipment is installed.

Troubleshooting systems can be broadly divided into two areas. You may be trying to diagnose inadequate performance of a new system. Or you may be troubleshooting a system that has been known to be installed correctly, and has been operating successfully in the recent past. Each of these situations will dictate your approach to finding the problem. In both cases, however, you'll need schematic diagrams for the system that reflect the intended connections of the conductors and the equipment. You may also want to have pictorial diagrams showing exactly where the components are located. You'll also want to make sure you understand exactly what the system is intended to do, either by talking to the people who operate the equipment or from written descriptions of the systems.

## New or Modified Systems

Troubleshooting a new system that has never been operated (or a system that has been modified to enable new processes) is more difficult in many ways because its proper design hasn't been proven. You'll want to have access to a list of components, as well as their individual specifications, so that you can verify that their available performance is correct for the application. New systems often incorporate new control methods such as programmable logic controls (PLC) or even computer control via programming and network communications.

As pneumatic systems become more automated, especially those controlled by computers and those electrically operated, you'll need to understand much more about networks, controls, and electrical systems to be able to fully diagnose a faulty system. This means that you may have to work closely with electrical engineers or technicians to understand the proper operation of all parts of the system. As the electrical system becomes more complex, there's a greater possibility of electrical problems related to interference with other electrical equipment, such as motors and relays. Motors that are turned off and on, switches that are opened and closed, and relays that are energized and de-energized all generate voltage spikes on electrical power lines. Any equipment connected to them may be subject to interference that will cause faulty electrical operation. In addition to line voltage disruptions, this electrical machinery also can radiate—through the air—electrical signals strong enough to interfere with sensitive electronic controls. Many electrical and electronic components and wiring must be shielded with metal to prevent this type of radiated interference. Improper shielding and grounding can be difficult to find and solve, to say the least. Thus, when the wiring is installed, be sure to use proper and recommended procedures for cabling and attachments. You should consult the manufacturers' literature for the controls to make sure you're installing it correctly.

To determine if the problem lies with the mechanical components, some of the diagnostic procedures you should perform include the following:

- Make sure that all electrical connections are properly made with good connections and adequate wire size. With electrical schematics, make sure the proper voltages are present at the proper time to operate electrically actuated valves, switches, and sensors. When plastic tubing and hose are used, make sure equipment is adequately grounded. Many "strange" problems are the result of poor electrical grounds.

- Analyze intended motions to determine if any forces have been overlooked when sizing cylinders, motors, or tools. Make sure static loads due to levers, clamps, and weights are accounted for, and that dynamic loads due to forces applied over time are calculated and included in the sizing process of cylinders, motors, control valves, and conductors. Make sure reasonable delay times (the time when pressure is first applied until it reaches full pressure) are incorporated into load calculations, and that delay times for solenoid actuation are also considered.

- Make sure cylinders and mechanical components are aligned and mounted correctly. Excessive side loads will cause larger frictional loads that may cause poor or reduced performance.
- Verify that cylinders, motors, conductors, receivers, and valves are all sized correctly for the given load. This involves first finding required forces, air pressures, and flow rates for the moving equipment, and working backward to make sure the components are sized to provide the proper flow. You must make sure you've included the effects of fittings, components such as connectors and shutoff valves, conductor size and length, bends in conductor paths, and pressure drops through conditioning equipment.
- Make sure the mechanical components such as valves and cylinders operate in the correct sequence. A good troubleshooting technique is to step through a cycle to make sure that all equipment operates correctly at a low speed. If it does, the electrical and mechanical control sequence has been verified and problems that remain are likely due to dynamic effects with airflow and/or loads (inertia and friction).

## Troubleshooting Existing Systems

Troubleshooting an existing system is, in a sense, easier than diagnosing faults in a system that has never been proven to operate successfully. The problem is to analyze the current performance to find reasons why it has changed from good performance to poor or unacceptable performance. In this section, we'll consider how to find and solve problems with systems that have been known to operate correctly in the past. How rapidly that performance has changed also indicates what the problems may be with the system.

If the pneumatic system performance has degraded slowly over time from a period of good performance to poor performance, that points to a problem of equipment deterioration from wear, improper maintenance, or a slow change in conditions not anticipated in the original design and installation. Some areas of concern to check where system performance has shown long-term degradation include:

Wear of cylinders, actuators, and motors; wear of bearings, guides, or machine ways; and internal wear of valves and seals. Wear can be caused by

- Normal expected wear due to relative motion of parts
- Excessive loads on cylinder shafts and motor shafts due to misalignments
- Rod wear due to side loads caused by inadequate rod diameter or excessive stroke
- Seal or dust cover failure due to dirt or contamination
- Lubrication failure due to faulty or inoperative lubricator, or improper lubricant type
- Corrosive wear due to moisture or incompatible lubricants
- Abrasive wear due to system contamination with dirt due to faulty or inoperative filter system

Inadequate airflow that may be the result of

- Decreased compressor capacity from wear and/or faulty primary conditioning equipment, including filters, dryers, moisture traps, relief valves, and pressure controls
- Excessive moisture in the system due to faulty or inoperative moisture traps, drains or dryers, or improper installation of conductors and take-offs

- Air leakage due to loosening of fittings; faulty connectors; faulty seals on cylinders and valves; and faulty or inoperative pressure regulators

- Buildup of corrosion products (rust) or varnish on the inside of conductors and fittings

- Control valves that don't operate correctly due to wear, sludge, inadequate lubrication, weak electrical signals, and low pilot pressure

- Addition of more air-consuming components over time, which results in gradual lack of performance. The additional equipment was simply not planned for, and compressor, receiver, and existing conductors aren't adequate to supply current demand for air.

- Improperly adjusted, faulty, or inoperative flow-control valves

Change in system loads that may be the result of

- Changes in weights/mass due to different products or processes

- Increased friction

- Change in ambient conditions of temperature and humidity

In a case of gradual deterioration, you should look at whether the system performance as a whole has degraded, or if parts of the system are working well while other sections aren't. The broader the scope of the lack of performance, the more likely the problem will lie with components that affect the entire system, such as compressor, receiver, and primary conditioning equipment. Remember, as we noted before, that the single greatest source of pneumatic failures is dirt and contamination. Another significant factor is air leakage, which often increases over time due to loosened fittings from vibration, or from holes or cracks that develop in hoses and tubing; quick connects that become stuck or broken and aren't replaced; and "small" failures in drains and traps that aren't noticed or serviced on a regular basis. As you learned in the units on compressors, air leakage is a significant factor in the cost of supplying energy to the facility.

In the case of a system whose performance has suddenly become worse, the first thing you should do is ask if anything has been done to the system, such as a repair or maintenance procedure, an addition of equipment, or a change in the process. You need to check all of the items listed above, but you need to isolate the problem to a particular component or section of the system. In many cases, it'll be necessary for you to work on live systems, with protective devices disabled. In these cases you must be absolutely sure to keep clear of any moving mechanisms that, if they were to move suddenly, could cause serious injuries.

Some dangers that you may encounter include jammed actuators or other nonfunctioning equipment. If you attempt to repair the equipment, several dangers become immediately present. Actuators that are "unjammed" may move quickly before you have a chance to react, because the nonpressurized side of the cylinder may be exhausted and not offer any resistance to the applied pressure on the pressurized side. Moving around energized equipment may bring you close to energized limit switches. If you accidentally bump a limit switch (or other control switch), the mechanism may move suddenly. Actuators stopped in mid-stroke may still be pressurized on one or both sides. Anything that causes the pressure to be relieved, such as movement of any associated valve, could cause the cylinder to move without warning. Sudden exhaust of cylinders may also cause eye injuries from fast-moving debris or ear injuries from noise.

A simplified troubleshooting procedure can be listed as follows:

- Isolate the device that isn't operating correctly. Determine what motion or action isn't occurring.

- Inspect the condition of the control valve inputs and outputs. Are the signals that actuate the valve present and correct: electric signals to a solenoid; pilot air pressure to control ports; mechanical linkage from levers or springs? Did the valve move to the proper position as a result of these inputs?

- If the answer is "yes" to all the previous questions, then the fault is between the valve and the actuator. Tubes could be bent, disconnected, plugged, or otherwise damaged.
- If the answer to the previous questions is "no," then you must follow the incorrect signal back to its source to find out why. If the output is incorrect (the valve didn't move correctly), the trouble is internal to the valve.

This is a simple procedure that you can use to begin troubleshooting faults in a pneumatic system. Not every problem will fall neatly into a procedure such as this one, but you must begin to think logically about what the system is supposed to do, and you must thoroughly understand the operation of the circuits.

## Maintenance Requirements

Pneumatic systems are relatively easy to maintain compared with electric or hydraulic systems. They have the potential to give years of trouble-free service, if they're serviced and maintained on a regular schedule. One of the key factors to an efficient and effective pneumatic system is to establish a preventative maintenance schedule that's faithfully followed. In the next sections we'll discuss some of the particular requirements to consider as you maintain these systems.

### Compressors

You learned about air compressor maintenance previously, so we'll only highlight some of the more important points about these critical components. As with other components, cleanliness is a must. With clean equipment, problem areas become readily apparent, so one of the most important procedures in servicing compressors is to maintain their external cleanliness. Compressed air is hot immediately after it comes out of the compressor (and between stages), so you should make sure that all cooling elements such as fins or water jackets are clean and properly mounted. Fan shrouds or other parts that direct cooling airflow should be installed correctly and be free of dirt deposits. Water-cooled compressors should have ample supplies of cooling water, as indicated on flow gauges or other sensors.

Oil in compressors should be changed at regular intervals according to the manufacturers' recommendation. Make sure the proper weight and grade of oil is used.

Safety valves should be tested regularly because a failure could cause a severe explosion and possible injury. There are many safety valves at multiple points in the compressed air delivery systems, and they should be listed and checked on a firm schedule. Valves that isolate the compressor from the rest of the system should be checked for proper operation and leakage.

Another test for compressors is to ensure that the pressure switch functions correctly. Compressors are designed for specific duty cycles, and stuck electrical relays or pressure switches may cause the compressor to cycle at undesirable times or pressures.

## Air Lines and Fittings

A primary maintenance procedure for air lines is removal of moisture. Air lines should be fitted with traps and drains at strategic points in the system (such as at the end of sloped piping), and the moisture should be drained on a daily basis.

On a periodic basis, all lines and fittings should be examined for mounting, physical integrity, presence of corrosion or wear, and system leaks. The presence and size of leaks can be determined by pressurizing the system, with the compressor and all tools and equipment off, and by measuring the pressure drop at the output of the receiver. As you learned in a previous section, the airflow can be calculated from the amount of pressure drop over time. Leaks can be found from the noise that escaping air produces, if the amount is great enough. Smaller leaks may be undetectable without special equipment. Fittings can be retightened or replaced; sections of hose or tubing can be replaced; valves can be repacked; and seals can be replaced.

## Receivers

Moisture is always present in compressed air, and the receiver is the first place it can collect in significant volumes. Receivers should be drained of collected water on a regular basis. If the drain system is automatic, it should be checked for proper operation at regular intervals. Cold temperatures will aggravate the moisture problems and add the possibility of freezing water, which could clog the drains or valves. Relief valves should be checked periodically.

The receiver is a specialized pressure vessel regulated according to ASME rules, and many businesses may require them to be pressure-tested on a regular schedule. This is usually done with *hydrostatic testing*—pressurizing the tank with water and noting any leaks. Ultrasonic testing can reveal the thickness changes that may result from internal corrosion, especially on older receivers. Note again that no welds or other repairs should be done to the receiver.

## Conditioning Equipment

Primary and secondary conditioning components will require similar maintenance procedures. Intake filters should be cleaned or replaced on a regular basis (perhaps daily), depending on their type. Wet filters, those wetted with oil that trap dirt particles, need to be washed with a detergent cleaner and have oil reapplied. Screens and cartridges in FRLs (Figure 41) should be cleaned and replaced as recommended by

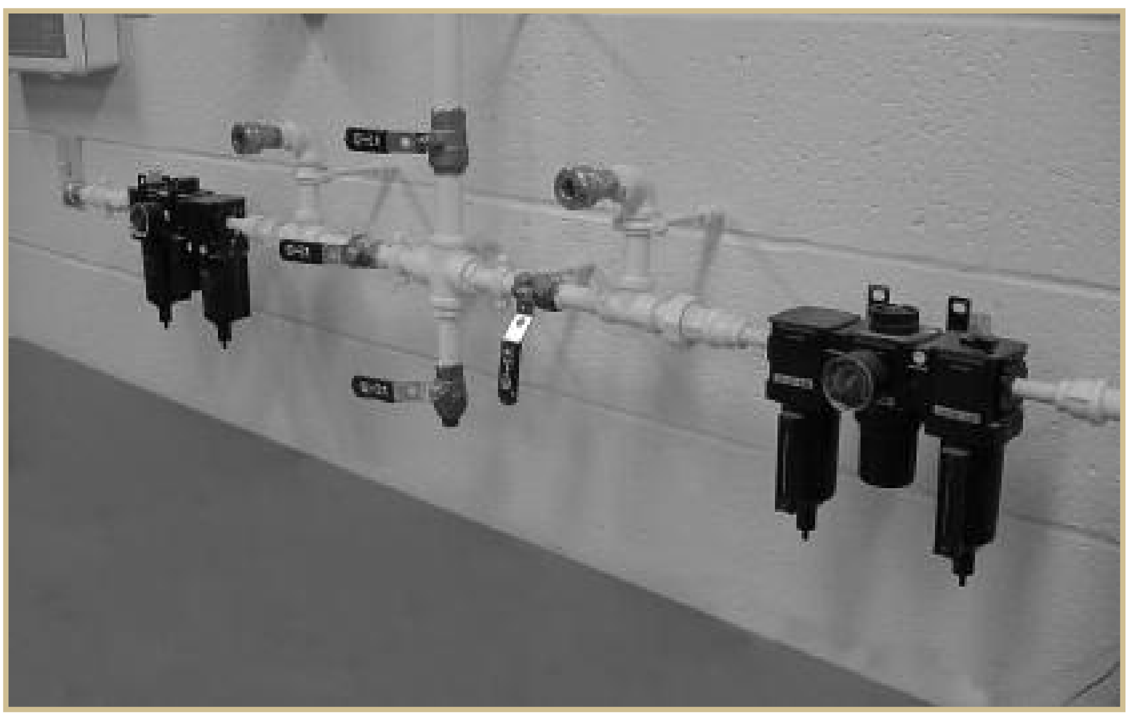


***FIGURE 41—FRLs are often placed directly in front of the air line connection for pneumatic equipment.***

the manufacturer for specific conditions. Excessive pressure drops noted on gauges may indicate a need for maintenance, but regular service is more effective.

Pneumatic components such as lubricators and traps with plastic bowls should be carefully inspected to ensure the bowl isn't cracked or "crazed" from cleaning with solvents. The sun's ultraviolet light also causes some types of plastic to deteriorate. Internal movement of fluids may cause the plastic bowls to become opaque instead of clear, as they're intended to be. Bowls should be replaced at any indication of damage.

Lubricators need to be filled on a regular basis, usually at least weekly, with the proper lubricant for tools connected to the downstream side of the FRL. Excess moisture should be removed from these devices as necessary (checked at least daily). If the drain is automatic, the circuit and relays that operate the drain should be tested. This applies to any other components with automatic drains. The FRL unit should be disassembled and cleaned approximately every six months. This semiannual maintenance should include cleaning or replacing the filter, cleaning the filter and lubricant bowl, calibrating the pressure gauge, cleaning oil passages, and replacing gaskets and seals as necessary.

## Cylinders and Motors

Air cylinder and motor maintenance is more complex due to the presence of moving parts. These devices should be checked for leaks on at least a weekly basis, particularly around seals, boots, and gaskets. Mechanically, you should inspect mounting components such as pins and threaded connections for tightness. Tubing connections, silencers, and fittings should be checked on a monthly or semiannual schedule, along with any necessary mechanical alignments. Signs of insufficient cylinder force and speed can be checked weekly, with any corrosion or wear on the rod noted. Misalignments and excessive side loads are usually responsible for rod wear, although lack of lubrication is another possible cause.

Motor inspection and repairs should involve checking the mountings and connections, as well as motor speed and torque. You should also observe for any excess vibration. Motor overhauls and general repairs will include replacing bearings and seals and cleaning air passages and flow controls.

### Valves

As with cylinders and motors, valves contain moving parts that make service more critical. FRLs that protect control valves should be carefully examined for proper function: filter quality, pressure regulation, and proper lubrication rates, as noted before. Valves with electrical connections must be examined at least on a semiannual basis for proper activation, including full engagement of solenoids, delay time, and return-spring function. Valves require lubrication to prevent wear, and inadequate oil supply will cause excessive internal wear of metallic spools and seals. Overhaul of valves will include repair or replacement of spools and seals; cleaning air passages; removing residues; and adjusting any internal mechanical connections. Manufacturers can supply repair procedures with diagrams and caution notes for each different valve model, and these should be maintained in a centrally located office file. Many maintenance procedures and diagrams of equipment are now available on the Internet and can be downloaded easily. In addition, e-mail now makes it possible to correspond with manufacturer's service technicians and access service manuals very quickly.

## Leak Detection

You should understand that air leakage can be a significant energy cost for businesses using compressed air for power. Leak detection is therefore an important part of a technician's responsibility. Unfortunately, leaks are often difficult to find because one of the most common methods is to listen for the noise of leaking air, and it's often not possible to hear the noise in areas where other equipment operates.

One method of finding leaks uses some facts you already know about receivers. If the compressor is shut off, and equipment that uses the air is shut off or isolated from the lines, you can detect and estimate the amount of leakage from the rate at which the pressure in the receiver drops. From this, it may be possible to determine the extent of leaks and estimate energy costs. Finding leaks this way, however, doesn't isolate their location. To actually find leaks, you must examine all of the air lines and fittings.

Leaks are often found at *junctions,* places where fittings or connectors are attached. They may also be found where hoses join with tubing or piping, or at joints placed in lines for servicing or future expansion. Pipes and tubing expand and contract with temperature, and fittings may work loose from vibration. In rare cases, pipe may corrode from the inside to the point where pinholes develop in lines, which allow leakage. Regular service performed by a technician will involve the close examination of all pneumatic piping and tubing. This may be easy for lines that run near the floor, but many times the pipes are in awkward locations for close inspection, such as overhead in ceilings or roof trusses.

***FIGURE 42—Modern leak detectors use ultrasonic transducers to listen for air leaking from lines and fittings at frequencies too high for normal hearing. These are reasonably priced instruments that can pay high dividends in finding and eliminating leaks.*** (Provided by Superior Signal, Co., Inc.)

A modern piece of equipment that helps technicians is the ultrasonic leak detector (Figure 42). When air leaks from a small hole, it may not make a noise loud enough for you to hear, even when you place your ear very close to the leak. This is because much of the vibration energy caused by the leaking air occurs above the normal range of hearing. To help find air leaks, especially in locations that are difficult to reach, ultrasonic detectors can be used. These instruments may be aimed at pipes and fittings from some distance away to detect high-pitched sounds of leaking air. They have electronic filters that remove low-frequency sounds and concentrate the energy from high-frequency sounds. Once a suspected leak area is found, you can examine it closely.

An old-fashioned but effective method of finding leaks is to "paint" the surface of the fitting or pipe with a soap solution. You may have seen this as a way to check a tire bead for leaks. Even small leaks will show up as a collection of tiny bubbles. The disadvantage of this approach is that it requires a relatively good idea of where a leak is located, and then you must spend time examining suspect areas, which can be tedious and time consuming.

Leaks in fittings can sometimes be repaired by retightening the nuts. Sometimes you must disassemble the fitting and replace parts such as ferrules, or pipe threads that may be coated with Teflon or pipe sealant (where these are allowed). As we discussed before, one of the principal advantages of plastic pipe such as PVC or ABS is that it can be made leak-free with properly glued connections. However, if the pipe later has to be disassembled, the pipe must be cut and additional fittings inserted.

Another way to detect system leaks is to collect and maintain data over a period of time and compare air consumption rates from present and prior levels. Modern electronic flow meters have data-logging capabilities that can record air consumption at regular intervals and give sophisticated reports. While this doesn't pinpoint leaks, it will warn technicians of increased air consumptions due to fittings or equipment failures.

## Air Audits

An emerging tool for cutting costs in facilities that use compressed air is an *air audit.* These audits can be performed by either internal personnel or external contractors, but the purpose is to analyze and examine the pneumatic system to improve efficiency and reduce costs due to waste. While pneumatic systems have distinct advantages, efficiency isn't one of them. For example, for an air motor to deliver one horsepower at 90 psig, it takes about 30 SCFM. This translates to about 6 to 7 Hp at the output of the compressor and 7 to 8 Hp of electrical energy. This means that less than 15% of the input energy is available at the equipment location. If a compressed air system is running 24 hours a day and 365 days a year (8760 hours), at $0.05 a kilowatt hour, this means it will take about $50,000 for every 100 HP of compressor capacity.

An air audit is intended to address both the usage and implementation of the compressed air system. Air audits can identify areas where air energy can be used more effectively and where it shouldn't be used due to higher costs than alternative methods. For example, an air drying process may be much less effective in terms of cost than an electric drying system because of the cost of air consumption. Several different categories of audits are conducted by trained personnel. Leak audits locate and mark leaks for subsequent repair. Supply audits monitor pressures at various locations in the system and monitor compressor output and equipment consumptions. A comprehensive audit will include leak and supply audits but also include analysis of compressed air usage and application, analysis of alternative techniques, and cost/benefit analysis of existing or projected applications.

Now take a few moments to review what you've just learned by completing *Self-Check 3.*

# Self-Check 3

1. The first step before working on pneumatic equipment is to ________ all equipment and electrical power.

2. A/an ________ prevents whipping hoses that would otherwise result from broken fittings.

3. Necessary troubleshooting tools include ________ and ________ schematics.

4. One of the primary causes of pneumatic system failures is ________.

5. Many unusual electrical problems in a factory are caused by ________ from lighting, motors, or other electrical equipment.

6. Wear marks of cylinder rods may be caused from excessive ________.

7. Vibration of conductors often leads to ________, a significant part of energy loss in pneumatic systems.

8. Compressor maintenance should include checking the ________ that sets the duty cycle of the compressor.

9. Improper alignment of ________ can lead to increased friction and wear.

10. A/an ________ audit monitors air production and consumption rates.

**Check your answers with those on page 94.**

## *NOTES*

# Answers

## Self-Check 1

1. maintenance
2. computer
3. regulators
4. pilot
5. entry or source
6. 1, P
7. deactuated
8. flow-control valves

## Self-Check 2

1. nameplate
2. cu. ft./min. (CFM)
3. 7.122
4. 25.41
5. 10%
6. receiver
7. coefficient of friction
8. twice
9. torque, speed or rpm
10. coefficient of velocity ($C_V$)
11. operating pressure, cylinder volume, number of cycles per minute
12. neutral
13. 2 to 10
14. loop
15. turbulent, $C_v$

## *Self-Check 3*

1. de-energize
2. pneumatic fuse
3. pneumatic, electrical
4. dirt or contamination
5. interference
6. side loads
7. leakage
8. pressure switch
9. cylinders and motors
10. supply

# A WORD ABOUT UNITS

We've used the U.S. Customary System (USCS) in our discussions of pneumatic systems. As we deal with more and more international businesses, you'll undoubtedly run across other systems of units, and even mixed units. For your calculation to turn out correctly, you must make sure all units are compatible with the expressions used. One of the common pressure units used in both U.S. and SI systems is the bar. Remember that 1 bar is slightly less than the atmospheric pressure of 14.7 psia. It doesn't matter what pressure unit you use as long as you understand what is being calculated. For example, you could calculate a compression ratio for a system operating at a pressure of 6.5 bar (gauge) by putting all pressure in bar:

$$CR = \frac{(6.5 + 1)}{1} = 7.5$$

You can see an advantage right away in using the units of bar: the constant addition and division of "14.7 psi" isn't needed. You simply add "1" to the bar (gauge), and you have the compression ratio.

Another application is in calculating $C_V$. An example equation for the coefficient of flow can be found in some textbooks as

$$Q = 6.844 \times C_V \times \sqrt{(\Delta P \times ((PS + 1) - \Delta P))}$$

PS = inlet pressure, bar (gauge)

In this equation, all pressure values are in bar (gauge), and the flow rate Q is in liters/min of free air delivered (f.a.d.). You can use this equation the same as the one we discussed; however, you must be sure not to mix units or constants in these equations.

Finally, most dimensional information for pneumatic systems in the SI system of units will use millimeters (mm). Cylinder bores are in mm, as are pipe and tubing IDs. It helps if you remember that 25 mm is about (but not exactly) 1 inch. Volumes will be in liters or cubic meters. You shouldn't be afraid to use these units, as they'll become more common in the future. It will take practice, but you'll find that you'll understand manufacturers' information more readily if you're familiar with all unit systems.

# *NOTES*

Examination

## Pneumatics, Part 2

**EXAMINATION NUMBER:**

**28609900**

**Whichever method you use in submitting your exam answers to the school, you must use the number above.**

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**Questions 1–20: Select the one best answer to each question.**

1. A continuous-duty compressor supplies 35 SCFM to a pneumatic system at 80 psig. What is the minimum size receiver that should be used?

   **A.** 6.4 gallon
   **B.** 35.0 gallon
   **C.** 40.7 gallon
   **D.** 80 gallon

2. Pneumatic components that control movements of motors and cylinders are

   **A.** FRLs.
   **B.** valves.
   **C.** regulators.
   **D.** fittings.

3. Which of the following is *not* an advantage of pneumatic systems?
   **A.** Efficient energy conversion
   **B.** Easy to service and maintain
   **C.** High output forces at zero speed
   **D.** Spark-free operation for combustible environments

4. A pneumatic circuit diagram shows
   **A.** where components are physically located.
   **B.** the output forces of the pneumatic application.
   **C.** the way components are connected.
   **D.** all of the components connected to the pneumatic lines.

5. Gradual pneumatic system degradation of performance could indicate
   **A.** increased wear or leakage somewhere in the system.
   **B.** increased resistance caused by failed control wiring.
   **C.** improper exhaust valves installed on cylinders.
   **D.** not enough oil in the lubricators.

6. A double-acting cylinder with a 3.0-inch bore operates at 75 psig. It has a stroke of 12 inches and completes 10 complete extend-and-retract strokes per minute. What is the required airflow to this cylinder? You can ignore the rod diameter for the retract stroke.
   **A.** 0.939 SCFM
   **B.** 2.87 SCFM
   **C.** 5.73 SCFM
   **D.** 17.19 SCFM

7. Speed limitation of cylinders is done
   **A.** usually with shuttle valves connected to the rod side of the cylinder.
   **B.** with flow-control valves connected to the input ports.
   **C.** by limiting the operation speed of the control valves.
   **D.** with flow-control valves in the air output lines.

8. The duty cycle of an electric motor
   **A.** is the ratio of the on-time to the total time of a given duration.
   **B.** is the ratio of on-time to off-time for a specific duration.
   **C.** determines the horsepower output of the motor.
   **D.** isn't usually considered when sizing compressor requirements.

9. A volume of 7.5 $ft^3$ of air is compressed to 2.2 $ft^3$. The compression ratio is
   **A.** 4.1.
   **B.** 2.2.
   **C.** 3.4.
   **D.** 0.29.

10. An air volume of 25 SCFM is supplied to an air motor at 60 psig. The CFM used at this pressure is

**A.** 0.202.
**B.** 4.92.
**C.** 5.08.
**D.** 127.04.

11. A pneumatic pipe that's 60 feet long should have a slope with a drop of about ________ inches from one end to the other.

**A.** 1.2
**B.** 6.0
**C.** 7.5
**D.** 18.0

12. If allowable motor duty cycle is 80%, what size compressor in SCFM is required to supply a pneumatic system that consumes 60 CFM at 75 psig?

**A.** 516
**B.** 542
**C.** 814
**D.** 458

13. Approximately what motor Hp will be required for a two-stage compressor for a 250 SCFM pneumatic system that operates at 100 psig?

**A.** 44.75
**B.** 41.0
**C.** 25.0
**D.** 100

14. The $C_V$ equation recommended by the NFPA

**A.** isn't valid for metric units.
**B.** shouldn't be used if the correct fitting sizes are known.
**C.** requires accurate knowledge of tubing size.
**D.** is invalid for pressure drops greater that 53% of $P_{in}$.

15. The compressor is turned off to a pneumatic system, and the 100-gallon receiver pressure drops from 120 psig to 90 psig in 3.5 minutes due to a leak in the system. What is the approximate size of the leak?

**A.** 6.7 SCFM
**B.** 7.8 SCFM
**C.** 8.2 SCFM
**D.** 26.2 SCFM

16. What is the force required from an actuator to move a 28-pound bracket across a metal table if the coefficient of sliding friction is 0.28?

**A.** 5.6 lb
**B.** 7.8 lb
**C.** 28 lb
**D.** 100 lb

17. A pneumatic cylinder must lift a 14-pound weight a distance of 6 inches. The inertial load is calculated to be 10.5 pounds. What approximate minimum force should be specified for the cylinder in this application?

**A.** 11 lb
**B.** 15 lb
**C.** 25 lb
**D.** 50 lb

18. What would be the minimum bore size for a cylinder if it needed to develop 550 pounds of force and operate from a pressure of 110 psig?

**A.** 2.52 in
**B.** 2.75 in
**C.** 2.98 in
**D.** 3.15 in

19. What torque is produced by a 2.5 Hp air motor that operates at 1800 rpm with 80 psig air pressure?

**A.** 9.0 lb-in
**B.** 32 .0 lb-in
**C.** 87.5 lb-in
**D.** 720 lb-in

20. On pneumatic schematics, cylinders often have marking strokes at the rod ends. These marking strokes show

**A.** the length of the rod travel.
**B.** the location of mechanically actuated switches or valves.
**C.** the sequence of cylinder operation.
**D.** how the associated cylinder is operated.