
An Introduction to Industrial Compressed Air Systems

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SECTION 1: INTRODUCTION TO COMPRESSED AIR SYSTEMS

This section of the sourcebook is intended for readers who want to gain an understanding of the basics of industrial compressed air systems. A glossary of basic terminology is included in [Appendix A](#) for users unfamiliar with the terms used in this chapter.

Compressed air is widely used throughout manufacturing industries and is often considered the “fourth utility” at many facilities. Almost every industrial plant, from a small machine shop to an immense pulp and paper mill, has some type of compressed air system. In many cases, the compressed air system is so vital that the facility cannot operate without it. Plant air compressor systems can vary in size from a small unit of 5 horsepower (hp) to huge systems with more than 50,000 hp.

In many industrial facilities, air compressors use more electricity than any other type of equipment. Inefficiencies in compressed air systems can be significant. Energy savings from system improvements can be substantial, resulting in thousands, or even hundreds of thousands of dollars of potential annual savings, depending on use. A properly managed compressed air system can save energy, reduce maintenance, decrease downtime, increase production throughput, and improve product quality.

Compressed air systems consist of a supply side and a demand side. The supply side includes compressors and air treatment (dryers and filters). The demand side includes distribution and end-use equipment. A properly managed supply side will result in clean, appropriately dried, stable air being delivered at the appropriate pressure in a dependable, cost-effective manner. A properly managed demand side minimizes wasted air and uses compressed air for appropriate applications. Improving and maintaining peak compressed air system performance requires addressing both the supply and demand sides of the system and how the two interact.

Components of an Industrial Compressed Air System

A compressor is a machine that is used to increase the pressure of a gas. The earliest compressors were bellows, used by blacksmiths to intensify the heat in their furnaces. The first industrial compressors were simple, reciprocating piston-driven machines powered by a water wheel.

A modern industrial compressed air system is composed of several major sub-systems. Major sub-systems include the compressor, prime mover, controls, treatment equipment and accessories, and the distribution system. The compressor is the mechanical device that takes in ambient air and increases its pressure. The prime mover powers the compressor. Controls serve to regulate the amount of compressed air being produced. The treatment equipment removes contaminants from the compressed air, and accessories keep the system operating properly. Distribution systems are analogous to wiring in the electrical world—they transport compressed air to where it is needed. Compressed air storage can also serve to improve system performance and efficiency. Figure 1.1 shows a representative industrial compressed air system and its components.

Compressor Types

Many modern industrial air compressors are sold “packaged” with the compressor, drive motor, and many of the accessories mounted on a frame for ease of installation. Provision for movement by forklift is common. Larger packages may require the use of an overhead crane. An enclosure may be included for sound attenuation and aesthetics.

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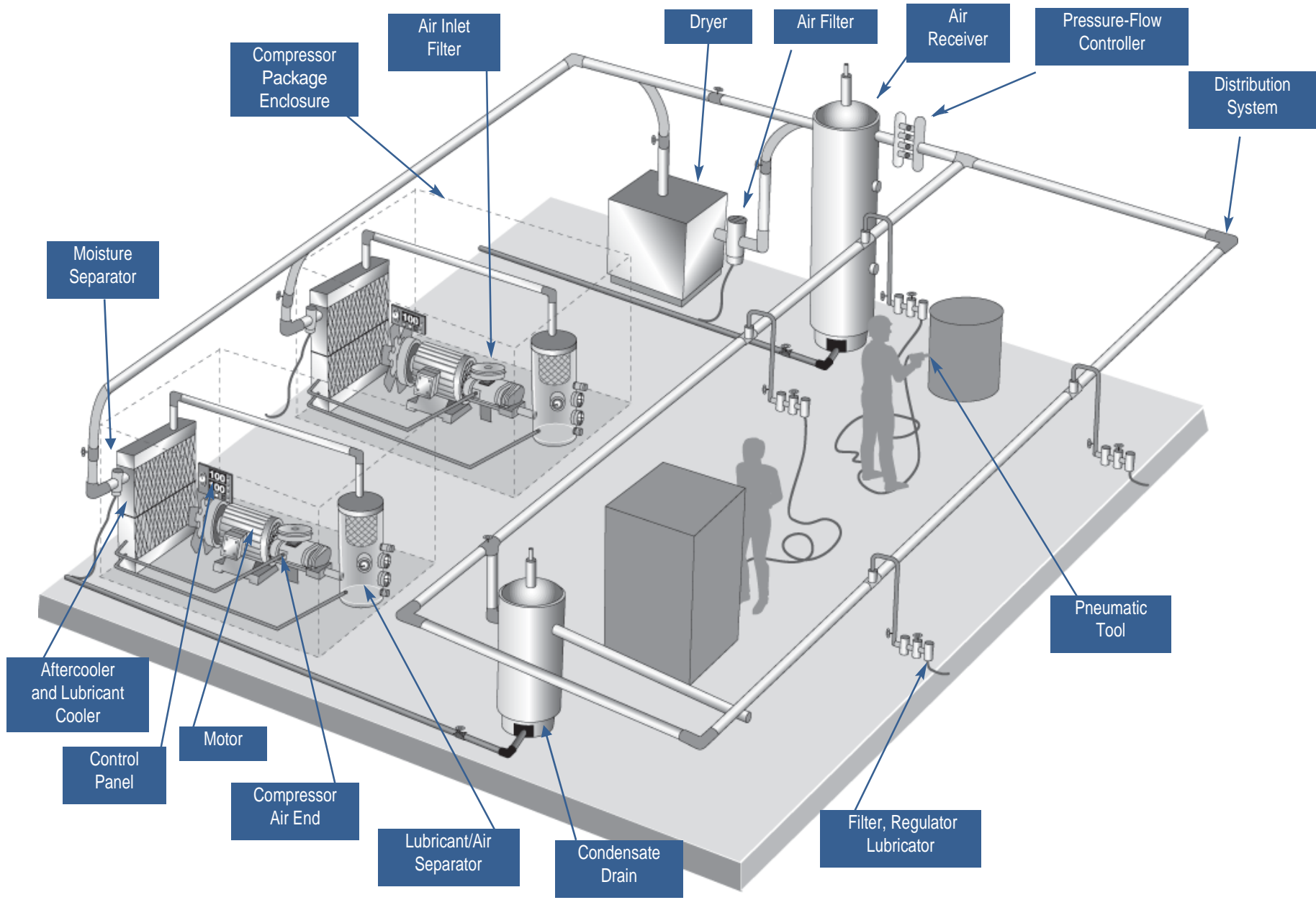


Figure 1.1 Components of a Typical Industrial Compressed Air System

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As shown in Figure 1.2, there are two basic compressor types: positive-displacement and dynamic. In the positive-displacement type, a given quantity of air or gas is trapped in a compression chamber and the volume which it occupies is mechanically reduced, causing a corresponding rise in pressure prior to discharge. At constant speed, the air flow remains essentially constant with variations in discharge pressure. Dynamic compressors impart velocity energy to continuously flowing air or gas by means of impellers rotating at very high speeds. The velocity energy is changed into pressure energy both by the impellers and the discharge volutes or diffusers. In the centrifugal-type dynamic compressors, the shape of the impeller blades determines the relationship between air flow and the pressure (or head) generated.

Positive Displacement Compressors

These compressors are available in two types: reciprocating and rotary. Reciprocating compressors work like bicycle pumps with the exception that an electric motor replaces the human energy source. A piston, driven through a crankshaft and connecting rod by an electric motor, reduces the volume in the cylinder occupied by the air or gas, compressing it to a higher pressure. Single-acting compressors have a compression stroke in only one direction, while double-acting units provide a compression stroke as the piston moves in each direction. Large, industrial reciprocating air compressors are double-acting and water-cooled. Multi-stage, double-acting compressors are the most efficient compressors available, and are typically larger, noisier, and more costly than comparable rotary units. Reciprocating compressors are available in sizes from less than 1 hp to more than 600 hp.

Rotary compressors have gained popularity and are now the “workhorse” of American industry. They are most commonly used in sizes from about 10 to 500 hp. The most common type of rotary compressor is the helical-twin, screw-type (also known as rotary screw or helical-lobe). Male and female rotors mesh, trapping air, and reducing the volume of the air along the rotors to the air discharge point. Rotary screw compressors have low initial cost, compact size, low weight, and are easy to maintain. Rotary screw compressors may be air- or water-cooled. Less common rotary compressors include sliding-vane, liquid-ring, and scroll-type.

Single-Acting, Reciprocating Air Compressors

This type of compressor is characterized by its “automotive” type piston driven through a connecting rod from the crankshaft. Compression takes place on the top side of the piston on each revolution of the crankshaft. Single-acting, reciprocating air compressors are generally air-cooled. These may be single-stage, usually rated at discharge pressures from 25 to 125 pounds per square inch gauge (psig), or two-stage, usually rated at discharge pressures from 125 psig to 175 psig or higher.

The most common air compressor in the fractional and single-digit hp sizes is the air-cooled, reciprocating air compressor. Single-acting reciprocating compressors above 30 hp are much less common. Two-stage and multi-stage designs include inter-stage air-cooling to reduce air temperatures to the second stage for improved efficiency and durability.

Pistons used in single-acting compressors are of the “automotive” or “full skirt” design, the underside of the piston being exposed to the crankcase. Lubricated versions have a combination of compression and lubricant-control piston rings, which seal the compression chamber, control the lubricant to the compression chamber, and act (in some designs) as support for piston movement on the cylinder walls.

Lubricant-free, or non-lube designs, do not allow lubricant in the compression chamber and use pistons of self-lubricating materials or use heat resistant, non-metallic guides and piston rings that are self-lubricating. Some designs incorporate a distance piece or crosshead to isolate the crankcase from the compression chamber.

Lubricant-less (or oil-less) designs have piston arrangements similar to lubricant-free versions, but do not have lubricant in the crankcase. Generally these have greased pre-packed crankshafts and connecting rod bearings.

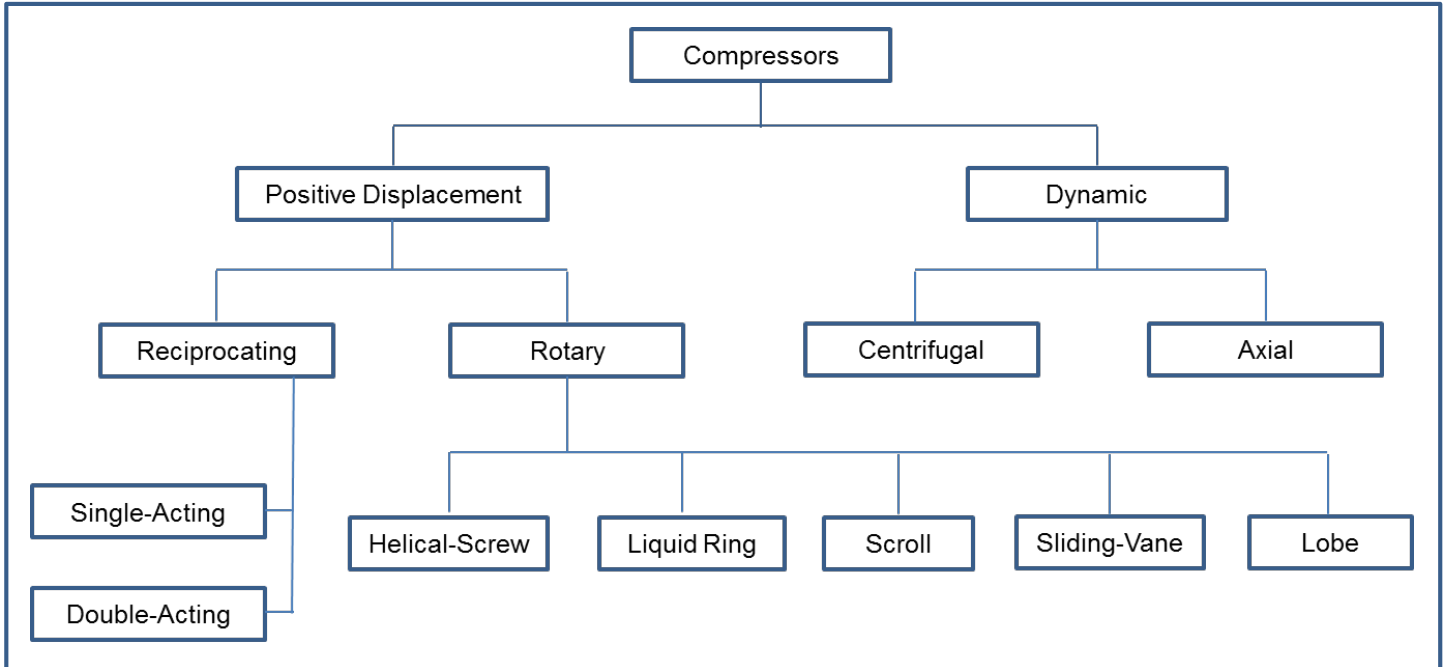


Figure 1.2 Compressor Family Tree

Cooling. Single-acting air compressors have different arrangements for removing the heat of compression. Air-cooled versions have external finning for heat dissipation on the cylinder, cylinder head, and in some cases, the external heat exchanger. Air is drawn or blown across the fins and the compressor crankcase by a fan, which may be the spokes of the drive pulley/flywheel.

Liquid-cooled compressors have jacketed cylinders, heads and heat exchangers, through which liquid coolant is circulated to dissipate the heat of compression. Water, or an ethylene glycol mixture to prevent freezing, may be employed.

Drives. The most common drive arrangement is a belt drive from an electric motor. The compressor sheave also acts as a flywheel to limit torque pulsations and its spokes often are used for cooling air circulation. Belt drives allow a great degree of flexibility in obtaining the desired speed of rotation.

Flange-mounted, or direct-coupled motor drives provide compactness and minimum drive maintenance. Belts and couplings must be properly shielded for safety and to meet Occupational Safety & Health Administration (OSHA) requirements.

Double-Acting, Reciprocating Air Compressors

Double-acting reciprocating compressors use both sides of the piston for air compression, almost doubling the capacity for a given cylinder size. A piston rod is attached to the piston at one end and to a crosshead at the other end. The crosshead ensures that the piston travels concentrically within the cylinder. These compressors may be single- or multi-stage, depending on discharge pressure and hp size. These are generally available in larger horsepower sizes.

Cooling. Double-acting air compressors generally have cooling water jackets around the cylinder body and in the cylinder head. This, combined with their relatively slow speed of operation and water-cooled intercooling, results in excellent compression efficiency.

Lubrication. Cylinder lubrication is generally by means of a pressure or vacuum-feed cylinder lubricator, with a feed rate of several drops per minute, depending on cylinder size and piston speed and as specified by the manufacturer. Lubricant-free versions also are available with polytetrafluorethylene (PTFE) or similar materials for pistons, riders, and compression rings. A distance piece is provided between the crankcase and the cylinder(s) to ensure that no part of the piston rod,

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which enters the lubricated crankcase, can enter the lubricant-free cylinder area.

Balance. Single- and two-cylinder compressors of this type generally require a substantial foundation due to unbalanced reciprocating forces.

Drives. Below 200 hp, belt drives and flange-mounted induction motors are normally used. For motors larger than 300 hp, flange-mounted, synchronous motors are sometimes used with a 1.0 power factor or 0.8 leading power factor to provide power factor correction to offset other induction-type electrical loads.

Lubricant-Injected Rotary Screw Compressors

The lubricant-injected rotary screw compressor powered by an electric motor has become a dominant type of industrial compressor for a wide variety of applications.

Compression Principle. The lubricant-injected, rotary-screw compressor consists of two intermeshing rotors in a machined housing (Rotor Housing) having an inlet port at one end and a discharge port at the other. The male rotor has lobes formed helically along its length while the female rotor has corresponding helical grooves or flutes. The number of helical lobes and grooves may vary in otherwise similar designs.

Air flowing in through the inlet port fills the spaces between the lobes on each rotor. Rotation then causes the air to be trapped between the lobes and the rotor housing as the inter-lobe spaces pass beyond the inlet port. As rotation continues, a lobe on one rotor rolls into a groove on the other rotor and the point of intermeshing moves progressively along the axial length of the rotors. This reduces the space occupied by the air, resulting in increased pressure. Compression continues until the inter-lobe spaces are exposed to the discharge port when the compressed air is discharged.

Lubricant is injected into the compression chamber during compression and serves three basic functions: 1) lubrication for the intermeshing rotors and associated bearings; 2) removal of the heat caused by compression; and 3) seals the clearances between the meshing rotors and between rotors and rotor housing.

Lubrication. The generic term “lubricant” has been used instead of oil. The lubricant may be a hydrocarbon product, but most compressors now use cleaner and longer life synthetic lubricants, including diesters, polyglycols, polyalphaolefins, polyol esters, and silicone-based lubricants. These newer products are suitable for a wider range of temperatures.

A mixture of compressed air and injected lubricant leaves the air end and is passed to a sump/separator where the lubricant is removed from the compressed air. Directional and velocity changes are used to separate most of the liquid. The remaining aerosols in the compressed air, then are separated by means of an air/lubricant separator or a coalescing filter, resulting in only a few parts per million (ppm) of lubricant carry-over (usually in the range of 2 to 5 ppm). A minimum pressure device, often combined with a discharge check valve, prevents excessive velocities through the separator element until a normal system pressure is achieved at start-up. Most lubricant-injected rotary screw compressor packages use the air pressure in the lubricant sump/separator, after the discharge of the air end, to circulate the lubricant through a filter and cooler prior to reinjection to the compression chamber. Some designs may use a lubricant pump.

Multi-stage compressors. Multi-stage compressors have different manufacturing designs. Multiple stages are used either for improved efficiency at a given pressure or to achieve higher pressures.

Cooling. The temperature of the lubricant injected into the compression chamber is generally controlled directly or indirectly to a minimum temperature by controlling the discharge temperature. A thermostatic bypass valve allows some or all of the lubricant being circulated to bypass the lubricant cooler to maintain the desired temperature over a wide range of ambient temperatures.

Generally, suitable lubricant temperature and viscosity are required for proper lubrication, sealing, and to avoid condensation in the lubricant sump. It also is necessary to avoid excessive temperatures, which could result in a breakdown of the lubricant and reduced life.

In addition to lubricant cooling, an aftercooler is used to cool the discharged air and a moisture separator with an automatic drain trap removes the condensate. In the

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majority of applications, air-cooled, radiator-type lubricants and air coolers are employed and provide the opportunity for heat recovery from the compression process for facility heating. In water-cooled designs, water-cooled heat exchangers with water control valves also are available on most rotary screw compressor packages.

Single-stage, lubricant-injected, rotary screw compressor packages are available from 3 to 900 hp, or 8 to 5000 cubic feet per minute (cfm), with discharge pressures from 50 to 250 psig. Two-stage versions can reduce specific power and some can achieve discharge pressures up to 500 psig. Lubricant-injected, rotary screw vacuum pumps also are available from 80 to 3,100 inlet cfm and vacuum to 29.7 inches Hg. Lubricant-injected, rotary-vane compressors are a less common type of rotary compressor and are available in a limited size range.

Air/Lubricant Separators. The air/lubricant separator in a lubricant-cooled, rotary screw compressor generally starts with a 2 to 3 psid pressure drop at full-load when new. Higher pressure differentials cause the compressor motor to consume more energy and possibly exceed the service factor. Maintenance manuals usually suggest changing them when there is a 10 to 12 psid pressure drop across the separator. In many cases it may make sense to make an earlier separator replacement, especially if electricity prices are high.

Lubricant-Free Rotary Screw Compressors

The principle of compression in lubricant-free rotary screw compressors is similar to that of the lubricant-injected rotary screw compressors but, without lubricant being introduced into the compression chamber. Two distinct types are available: the dry type and the water-injected type.

In the dry type, the intermeshing rotors are not allowed to touch and their relative positions are maintained by means of lubricated timing gears external to the compression chamber. Since there is no injected fluid to remove the heat of compression, most designs use two stages of compression with an intercooler between the stages and an aftercooler after the second stage. The lack of a sealing fluid also requires higher rotation speeds than for the lubricant-injected type. Dry-type,

lubricant-free rotary screw compressors have a range from 25 to 4,000 hp or 90 to 20,000 cfm. Single-stage units operate up to 50 psig, while two-stage can generally achieve up to 150 psig.

In the water-injected type, similar timing gear construction may sometimes be used, but water is injected into the compression chamber to act as a seal in internal clearances and to remove the heat of compression. This may allow pressures in the 100 to 150 psig range to be accomplished with only one stage. The injected water, together with condensed moisture from the atmosphere, is removed from the discharged compressed air by a conventional moisture separation device. Similar to the lubricant-injected type, lubricant-free rotary screw compressors generally are packaged with all necessary accessories.

Lubrication. Lubricant-free rotary screw compressors utilize lubricant for bearings and gears, which are isolated from the compression chamber. The lubricant also may be used for stator jacket cooling in air-cooled units. Typically, a lubricant pump is directly driven from a shaft in the gearbox, assuring lubricant flow immediately at start-up and during run-down in the event of power failure. A lubricant filter, typically with 10 micron rating, protects bearings, gears, and the lubricant pump from damage.

Cooling. The cooling system for the dry-type, lubricant-free rotary screw compressor normally consists of an air cooler after each stage and a lubricant cooler. These may be water-cooled or air-cooled, radiator-type. Some older two-stage designs also employ an additional heat exchanger to cool a small portion of the compressed air for recycling to the compressor inlet during the unloaded period.

Dynamic Compressors

Dynamic compressors can be categorized as centrifugal or axial. The centrifugal-type is the most common and is widely used for industrial compressed air. Each impeller, rotating at high speed, imparts radial flow to the air or gas, which then passes through a volute or diffuser. Some large manufacturing plants use centrifugal compressors for both base loading and trimming, while in other facilities, plants use other compressor types to accommodate demand load swings

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while the dynamic centrifugal compressors handle the base load.

Axial compressors consist of a rotor with multiple rows of blades and a matching rotor housing with rows of stationary vanes. The rotating blades impart energy to the air, primarily in an axial plane. The stationary vanes then act as a diffuser to convert the residual kinetic energy into potential energy by increasing the pressure. This type of compressor is restricted to very high flow capacities. Mixed flow compressors have impellers and rotors which combine the characteristics of both axial and centrifugal compressors.

Centrifugal Air Compressors

A centrifugal air compressor has a continuously flowing air stream which has kinetic energy, imparted to it by an impeller, or impellers, which rotate at speeds that can exceed 50,000 revolutions per minute (rpm).

Approximately one half of the energy is developed in the impeller with the other half achieved by converting the velocity energy to pressure energy as the air velocity is reduced in a diffuser and volute.

The most common centrifugal air compressor is one with two to four stages for pressures in the 100 to 150 psig range. A water-cooled intercooler and separator between each stage returns the air temperature to approximately ambient temperature and removes condensed moisture before entering the next stage. An aftercooler cools the air from the final stage and a moisture separator with an automatic drain removes the moisture prior to air delivery to distribution. Air-cooled centrifugal compressors are available within a limited size range.

The inherent characteristic of centrifugal air compressors is that as system pressure decreases, the compressor's flow capacity increases. The steepness of the pressure head/capacity curve is dependent upon the design of the impellers and diffusers.

Most standard industrial centrifugal air compressor packages are designed for an ambient temperature of 95°F and near sea level barometer pressure. The dynamic nature of the centrifugal compressor results in the pressure head generated by each impeller increasing as the air density increases. The compressor mass flow and actual cubic feet per minute capacity at a

given discharge pressure increases as the ambient temperature decreases, provided the motor can support the increased power requirements.

Typically, a capacity control system is provided with the compressor to maintain the desired capacity and to operate within the motor horsepower limits. The control system regulates the air flow by means of an inlet throttle valve or inlet guide vanes. The minimal throttle point is established to prevent flow reversal thru an impeller/diffuser stage, which is also known as surge. Control systems either unload the compressor or blow off the excess air to atmosphere to avoid surge, which could result in excessive vibration and potential damage to the compressor. Given adequate storage, some manufacturers will operate the compressor controls in a load/unload mode at lower flow conditions.

Centrifugal air compressors range from around 200 to more than 100,000 cfm, but the more common air compressors are from 1,200 to 5,000 cfm and with discharge pressures up to 125 psig. These may have several impellers in line on a single shaft or with separate impellers integrally geared.

Centrifugal air compressors provide lubricant-free air delivery as there is no lubricant in the compression chambers. Lubrication for speed increasing gears and the special high-speed shaft bearings is kept away from the compression chambers by means of shaft seals, which may also have air purge and vent connections.

Centrifugal air compressors are high-speed rotating machines and as such, shaft vibration monitoring is mandated to record operational trends and protect the equipment. Automatic control of the compressors is typical and has been greatly improved by the use of microprocessors, which monitor the pressure, capacity, temperature characteristics and main-drive motor current draw. It is important that the manufacturer's recommended maintenance procedures be followed and that certain maintenance procedures be carried out by qualified staff. This is particularly true of attempts to remove an impeller from its shaft, since special procedures and tools may be involved.

Lubrication and Lubrication Systems. Centrifugal compressors use a pressure lubrication system for bearings and drive gears. The main lubricant pump may

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be driven from the gearbox input shaft with an electric motor-driven auxiliary lubricant pump for pre-lubrication prior to start-up and for post-lubrication during a cool down period. A water-cooled lubricant cooler is also included.

Because of the high rotation speeds, some designs use a high-pressure lubricant supply to the special bearings involved. The manufacturer's recommended lubricant should be used and changed at the specified intervals.

Compressor Prime Movers

The prime mover is the main power source providing energy to drive the compressor. The prime mover must provide enough torque and power to start the compressor, accelerate it to full speed, and keep the unit operating under various design conditions. This power can be provided by any one of the following sources: electric motors, diesel or natural gas engines, steam turbines and combustion turbines. Electric motors are by far the most common type of prime mover.

Electric motors are a widely available and economical means of providing reliable and efficient power to compressors. Most compressors use standard, polyphase induction motors. In many cases, either a standard- or a premium-efficient motor can be specified when purchasing a compressor or replacement motor. The incremental cost of the premium efficient motor is typically recovered in a very short time from the resulting energy savings. When replacing a standard motor with a premium-efficient version, careful attention should be paid to performance parameters, such as full-load speed and torque. A replacement motor with performance as close as possible to the original motor should be used. Most new motors are suitable for inverter duty applications.

Diesel or natural gas engines are common compressor power sources in the oil and gas industries. Considerations such as convenience, cost, and the availability of liquid fuel and natural gas play a role in selecting an engine to power a compressor. Although the majority of industrial compressed air systems use electric motors for prime movers, in recent years there has been renewed interest in using non-electric drives, such as reciprocating engines powered by natural gas, particularly in regions with high electricity rates.

Standby or emergency compressors may also be engine-driven to allow operation in the event of a loss of electrical power. Maintenance costs for engine-driven systems are significantly higher than those that use electric motors.

The oldest method of driving compressors is through the use of a steam engine or turbine. In general, however, it is not economical to use a steam engine or turbine unless the steam is inexpensively and readily available within the plant for use as a power source.

Compressed Air System Controls

Compressed air system controls serve to regulate the pressure by matching compressor supply with system demand. Proper compressor control is essential to efficient operation and high performance. Because compressor systems are typically sized to meet a system's maximum demand, a control system is almost always needed to reduce the output of the compressor during times of lower demand. Compressor controls are typically included in the compressor package, and many manufacturers offer more than one type of control technology. Systems with multiple compressors use more sophisticated controls (network or system master controls) to orchestrate compressor operation and air delivery to the system.

Network controls use the on-board compressor controls' microprocessors linked together to form a chain of communication that makes decisions to stop/start, load/unload, modulate, vary displacement, and vary speed. Usually, one compressor assumes the lead with the others being subordinate to the commands from this compressor.

System master controls coordinate all of the functions necessary to optimize compressed air as a utility. System master controls have many functional capabilities, including the ability to monitor and control all components in the system, as well as trending data, to enhance maintenance functions and minimize costs of operation. Other types of controllers, such as pressure/flow controllers, may also improve the performance of some systems.

The type of control system specified for a given system is largely determined by the types of compressors being used and the facility's demand profile. If a system has a

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single compressor with a very steady demand, a simple control system may be appropriate. On the other hand, a complex system with multiple compressors, varying demand, and many types of end uses will require a more sophisticated control strategy. In any case, careful consideration should be given to compressor system control selection because it can be the most important single factor affecting system performance and efficiency. For information about efficiency and compressor controls, see the fact sheet titled *Compressed Air System Controls* in Section 2.

Accessories

Accessories are the various types of equipment used to treat compressed air by removing contaminants such as dirt, lubricant, and water; to keep compressed air systems running smoothly; and to deliver the proper pressure and quantity of air throughout the system. Accessories include remote aftercoolers, filters, separators, dryers, heat recovery equipment, lubricators, pressure regulators, air receivers, and condensate drain traps.

Air Inlet Filters. An air inlet filter protects the compressor from atmospheric airborne particles. Further filtration is typically needed to protect equipment downstream of the compressor.

Compressor Cooling. Air or gas compression generates heat. As a result, industrial air compressors that operate continuously generate substantial amounts of heat. Compressor units are cooled with air, water, and/or lubricant. Single-acting reciprocating compressors are typically air-cooled using a fan, which is an integral part of the belt-drive flywheel. Cooling air blows across finned surfaces on the outside of the compressor cylinder's cooling fins. Larger, water-cooled, double-acting reciprocating air compressors have built-in cooling water jackets around the cylinders and in the cylinder heads. The temperature of the inlet water and the design and cleanliness of the cooler can affect overall system performance and efficiency. Centrifugal compressors are generally water-cooled.

Lubricant-injected rotary compressors use the injected lubricant to remove most of the heat of compression. In air-cooled compressors, a radiator-type lubricant cooler is used to cool the lubricant before it is reinjected. The cooling fan may be driven from the main motor-drive

shaft or by a small auxiliary electric motor. In plants where good quality water is available, shell and tube heat exchangers generally are used. Sometimes this heat can be recovered and used for other purposes.

Intercooling. Most multi-stage compressors use intercoolers, which are heat exchangers that remove the heat of compression between the stages of compression. Intercooling affects the overall efficiency of the machine.

Aftercoolers. As mechanical energy is applied to a gas for compression, the temperature of the gas increases. Aftercoolers are installed after the final stage of compression to reduce the air temperature. As the air temperature is reduced, water vapor in the air is condensed, separated, collected, and drained from the system. With cooler water temperatures, most of the condensate from a compressor with intercooling is removed in the intercooler(s), and the remainder in the aftercooler. Almost all industrial systems, except those that supply heated process air require aftercooling. In some systems, aftercoolers are an integral part of the compressor package, while in other systems the aftercooler is a separate piece of equipment. Some systems have both.

Moisture Separators. Moisture separators are devices that remove liquids entrained in the air or gas. A separator generally is installed following each intercooler or aftercooler to remove the condensed moisture. This involves changes in direction and velocity and may include impingement baffles. Lubricant-injected rotary compressors have an air/lubricant coalescing separator immediately after the compressor discharge to separate the injected lubricant before it is cooled and recirculated to the compressor. This separation must take place before cooling to prevent condensed moisture from being entrained in the lubricant.

Dryers. When air leaves an aftercooler and moisture separator, it is typically saturated. Any further radiant cooling as it passes through the distribution piping, which may be exposed to colder temperatures, will cause further condensation of moisture with detrimental effects, such as corrosion and contamination of point-of-use processes. This problem can be avoided by the proper use of compressed air dryers.

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Atmospheric air contains moisture. The higher the air temperature, the more moisture the air is capable of holding. The term “relative humidity” is commonly used to describe the moisture content. When the air contains all the moisture possible under the prevailing conditions, it is called “saturated.” Air at 80 percent relative humidity would contain 80 percent of the maximum possible moisture content.

When air is cooled, it will reach a temperature at which the amount of moisture present can no longer be contained in a vapor state and some of the moisture will condense and drop out. The temperature at which the moisture condenses is called the dew point. In general, reducing the temperature of saturated compressed air by 20°F will reduce the moisture content by approximately 50 percent.

When air is compressed and occupies a smaller volume, it can no longer contain all of the moisture possible at atmospheric conditions. Again, some of the moisture will drop out as liquid condensate. The result of both of these situations is a difference between the dew point at atmospheric conditions and the dew point at higher pressures. Drying compressed air beyond the required pressure dew point will result in unnecessary energy and costs.

Different types of compressed air dryers have different operating characteristics and degrees of dew point suppression. Dryer ratings usually are based on standard dryer inlet conditions, commonly referred to as “the three 100s.” That is, 100 psig, 100°F (inlet compressed air temperature), and 100°F ambient temperature. Deviations from these conditions will affect the capacity of a dryer. An increase in inlet temperature or a decrease in inlet pressure will reduce the dryer’s rated capacity. Most manufacturers provide correction factors for this.

The most common types of dryers are discussed below.

- The refrigerant dryer is the most commonly used dryer in the industry, having relatively low initial and operating costs. Refrigerant-type air dryers (cycling and non-cycling) are not recommended for operation in sub-freezing ambient temperatures. The moisture in the compressed air can freeze and damage the dryer. Most refrigerated dryers are

equipped with a pre-cooler/reheater that reheats the dried compressed air with an air-to-air heat exchanger using the hot incoming air. This lowers the temperature of the incoming air before it passes through the refrigerant or thermal mass-to-air heat exchanger, reducing the heat load on the refrigerant system. Reheating the dried air prevents condensation on the outside of the compressed air piping in warm humid environments. The refrigerated dryer lowers the dew point of the air to the approximate temperature of the air exiting the refrigerant evaporator. To avoid freezing, the evaporator temperature should not go below 32°F. Allowing for separator efficiency, a pressure dew point of between 35 and 40°F can usually be obtained.

- Cycling dryers cool compressed air indirectly through a thermal storage medium (heat sink, thermal mass, chilled media, etc.) while non-cycling dryers directly cool compressed air in a refrigerant to air heat exchanger. Refrigerant-type cycling dryers are controlled with one or two thermostats to shut off the refrigerant compressor, saving energy when it is not needed, and a thermal storage medium (sometimes referred to as heat sink, chilled media or thermal mass) prevents rapid cycling of the refrigerant compressor(s). Powdered metal, glycol and water, sand, steel, and aluminum have all been used as this thermal storage medium. The ideal characteristics of this medium would be high specific heat (effective storage), high coefficient of heat transfer (easy transfer of stored cooling), corrosion protected, and low cost. The quantity of medium required is determined by the temperature band of the controlling thermostat(s) and the refrigerant capacity to be stored.
- Refrigerant-type, non-cycling dryers cool the air in a refrigerant-to-air heat exchanger. The cooling effect is from the evaporation of a liquid refrigerant causing moisture in the air to condense. The moisture then is removed and drained by a separator and drain. The temperature of the air leaving the refrigerant evaporator is controlled by a hot gas bypass valve
- Regenerative-desiccant-type dryers use a porous desiccant that adsorbs the moisture by collecting it in its myriad pores, allowing large quantities of water to be retained by a relatively small quantity

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of desiccant. Desiccant types include silica gel, activated alumina, and molecular sieves. Use only the type specified by the manufacturer. In some cases, more than one desiccant type can be used for special drying applications. In most of these cases, a larger particle size (1/4 inch or more) is used as a buffer zone at the inlet, while a smaller particle size desiccant (1/8 to 1/4 inch) is used for final drying. Where very low dewpoints are required, molecular sieve desiccant is added as the final drying agent.

Normally, the desiccant is contained in two separate towers. Compressed air to be dried flows through one tower, while the desiccant in the other is being regenerated. Regeneration is accomplished by reducing the pressure in the tower and passing previously dried purge air through the desiccant bed. The purge air may also be heated, either within the dryer or externally, to reduce the amount of purge air required. Purge air may also be supplied by a blower. Dryers of this type normally have a built-in regeneration cycle, which can be based upon time, dew point, or a combination of the two.

- Deliquescent-type dryers use a drying medium that absorbs, rather than adsorbs, the moisture in the compressed air. This means that the desiccant medium is used up as it changes from solid to liquid and cannot be regenerated. The most common deliquescent chemicals for compressed air drying are salts of sodium, potassium, calcium, and those with a urea base. Various compounds of these have been developed and sold under a variety of trade names.
- Heat-of-compression dryers are regenerative-desiccant dryers that use the heat generated during compression to accomplish desiccant regeneration, so they can be considered as heat reactivated. There are two types: the single-vessel and the twin-tower.

The single-vessel, heat-of-compression dryer provides continuous drying with no cycling or switching of towers. This is accomplished with a rotating desiccant drum in a single pressure vessel divided into two separate air streams. One air stream is a portion of the hot air taken directly from the air compressor at its discharge, prior to the aftercooler, and is the source of heated purge

air for regeneration of the desiccant bed. The second air stream is the remainder of the air discharged from the air compressor after it passes through the air aftercooler. This air passes through the drying section of the dryer's rotating desiccant bed, where it is dried. The hot air, after being used for regeneration, passes through a regeneration cooler before being combined with the main air stream by means of an ejector nozzle before entering the dryer.

The twin-tower, heat-of-compression dryer operation is similar to other twin-tower, heat-activated, regenerative-desiccant dryers. The difference is that the desiccant in the saturated tower is regenerated by means of the heat of compression in all of the hot air leaving the discharge of the air compressor. The total air flow then passes through the air aftercooler before entering the drying tower. Towers are cycled as for other regenerative-desiccant dryers.

The heat-of-compression dryers require air from the compressor at a sufficiently high temperature to accomplish regeneration. For this reason, it is used almost exclusively with centrifugal or lubricant-free rotary screw compressors.

- Membrane technology dryers have advanced considerably in recent years. Membranes commonly are used for gas separation, such as in nitrogen production for food storage and other applications. The structure of the membrane allows molecules of certain gases (such as oxygen) to pass through (permeate) a semi-permeable membrane faster than others (such as nitrogen), leaving a concentration of the desired gas (nitrogen) at the outlet of the generator. When used as a dryer in a compressed air system, specially designed membranes allow water vapor (a gas) to pass through the membrane pores faster than the other gases (air) reducing the amount of water vapor in the air stream at the outlet of the membrane dryer, suppressing the dew point. The dew point achieved is usually 40°F, but lower dew points to -40°F can be achieved at the expense of additional purge air loss.

Compressed Air Filters. Depending on the level of air purity required, different levels of filtration and types of filters are used. These include particulate filters to remove solid particles, coalescing filters to remove

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lubricant and moisture, and adsorbent filters for tastes and odors. A particulate filter is recommended after a desiccant-type dryer to remove desiccant “fines.” A coalescing-type filter is recommended before a desiccant-type dryer to prevent fouling of the desiccant bed. Additional filtration may also be needed to meet requirements for specific end uses.

Compressed air filters downstream of the air compressor are generally required for the removal of contaminants, such as particulates, condensate, and lubricant. Filtration only to the level required by each compressed air application will minimize pressure drop and resultant energy consumption. Elements should also be replaced, as indicated by pressure differential, to minimize pressure drop and energy consumption, and should be checked at least annually.

Heat Recovery. As noted earlier, compressing air generates heat. In fact, industrial-sized air compressors generate a substantial amount of heat that can be recovered and put to useful work. More than 80 percent of the electrical energy going to a compressor becomes available heat. Heat can be recovered and used for producing hot water or hot air. See the fact sheet in Section 2 titled *Heat Recovery and Compressed Air Systems* for more information on this energy-saving opportunity.

Lubrication. In lubricant-injected rotary screw compressors, lubricants are designed to cool, seal, and lubricate moving parts for enhanced performance and longer wear. Important considerations for compressor lubricants include proper application and compatibility with downstream equipment, including piping, hoses, and seals. A lubricator may be installed near a point-of-use to lubricate items such as pneumatic tools. The lubricator may be combined with a filter and a pressure regulator to make up what is commonly called a FRL (filter-regulator-lubricator). The lubricant should be that specified by the point-of-use equipment manufacturer.

Pressure/Flow Controllers. Pressure/flow controllers are system pressure controls used in conjunction with the individual compressor or system controls described previously. Their primary function is to regulate system pressure more precisely than multiple individual compressor controls and Master system controllers. A pressure/flow controller does not directly control a compressor, and it is generally not included as part of a

compressor package. A pressure/flow controller is a device that serves to separate the supply side of a compressed air system from the demand side. Properly sized storage receiver capacity is needed for adequate pressure/flow control. Not all systems would benefit from this type of controller.

Air Receivers. Receivers are used to provide compressed air storage capacity to meet peak demand events and help control system pressure by controlling the rate of pressure change in a system. Receivers are especially effective for systems with widely varying compressed air flow requirements. Where peaks are intermittent, a large air receiver may allow a smaller air compressor to be used and can allow the capacity control system to operate more effectively and improve system efficiency. An air receiver after a reciprocating air compressor can provide dampening of pressure pulsations, radiant cooling, and collection of condensate. Demand-side control will optimize the benefit of the air receiver storage volume by stabilizing system header pressure and “flattening” the load peaks. Properly sized air receivers also play a crucial role in orchestrating system controls, providing the time needed to start, or avoid starting, standby air compressors. Of course proper application and design is required to optimize the utilization of air receivers.

Traps. Traps (sometimes called drains) allow the removal of moisture from the compressed air system. Automatic condensate traps are used to conserve energy by preventing the loss of air through open petcocks and valves. Poorly maintained traps can waste a lot of compressed air.

There are four methods to drain condensate.

1. **Manual.** Operators will manually open valves to discharge condensate. However, this is not automatic, and unfortunately, too often, manual valves are left open to drain condensate from moisture separators, intercoolers, refrigerated dryers, and filters, allowing compressed air to continually escape into the atmosphere.
2. **Level-operated mechanical traps.** Float-type traps do not waste air when operating properly, but they often require a great deal of maintenance and are prone to blockage from sediment in the condensate. Inverted bucket

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traps may require less maintenance but will waste compressed air if the condensate rate is inadequate to maintain the liquid level (or prime) in the trap.

3. **Electrically operated solenoid valves.** The solenoid-operated drain valve has a timing device that can be set to open for a specified time and at preset adjustable intervals. There are two issues with using these valves.
 - The period during which the valve is open may not be long enough for adequate drainage of accumulated condensate.
 - The valve will operate even if little or no condensate is present, resulting in the loss of valuable compressed air. Level-operated and electrically operated solenoid valves should have strainers installed to reduce contaminants, which block the inlet and discharge ports of these automatic devices. Motorized ball valves are also used with programmable timers. However, while fairly reliable, these valves can be even more wasteful as the duration of the valve opening is dependent on the valve actuator and is not adjustable.
4. **Zero air-loss traps with reservoirs.** There are various types of zero air-loss traps.
 - A float or level sensor operates an electric solenoid or ball valve and maintains the condensate level in the reservoir below the high-level point.
 - A float activates a pneumatic signal to an air cylinder to open a ball valve through a linkage to expel the condensate in the reservoir to the low-level point.

Be sure to drain and clean the reservoir often to prevent the accumulation of contaminants, which could foul the mechanisms of these traps.

The potential for freezing must be considered and provision made for heated drains where necessary. The relatively common practice of leaving a manual drain valve cracked open should not be tolerated because it wastes costly compressed air.

Contaminated condensate requires removal of lubricant before the condensate is discharged to a sewer system. It is recommended that the local sewage authority be

consulted for allowable contamination levels. Condensate treatment should meet local codes.

Air Distribution Systems. The air distribution system links the various components of the compressed air system to deliver air to the points-of-use with minimal pressure loss. The specific configuration of a distribution system depends on the needs of the individual plant, but frequently consists of an extended network of main lines, branch lines, valves, and air hoses. The length of the network should be kept to a minimum to reduce pressure drop. Air distribution piping should be large enough in diameter to minimize pressure drop. A loop system is generally recommended, with all piping sloped to accessible drop legs and drain points.

When designing an air distribution system layout, it is best to place the air compressor and its related accessories where temperature inside the plant is the lowest (but not below freezing). A projection of future demands and tie-ins to the existing distribution system should also be considered. Air leaks are an important issue with distribution system and are addressed in the fact sheet in Section 2 titled *Compressed Air System Leaks*. It is important to note that the majority of system leakage will be at the point of use and not in the distribution piping.

Headers should have a slight slope to allow drainage of condensate and drop legs from the bottom side of the header should be provided to allow collection and drainage of the condensate. The direction of the slope should be away from the compressor.

Piping from each compressor to the header, and the header to points-of-use should connect to the top or side of the header to avoid being filled with condensate. Drainage-drop legs from the bottom of the header should be installed to collect the condensate.

Uses of Compressed Air

Industrial facilities use compressed air for a multitude of operations. Almost every industrial facility has at least two compressors, and in a medium-sized plant there may be hundreds of different uses of compressed air.

Uses include powering pneumatic tools, packaging and automation equipment, and conveyors. Pneumatic tools

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tend to be smaller, lighter, and more maneuverable than electric motor-driven tools. They also deliver smooth power and are not damaged by overloading. Air-powered tools have the capability for infinitely variable speed and torque control, and can reach a desired speed and torque very quickly. In addition, they are often selected for safety reasons because they do not produce sparks and have low heat build-up. Although they have many advantages, pneumatic tools are much less energy-efficient than electric tools. It generally costs 7 to 8 times more energy for pneumatic tools to produce the same mechanical output as electric tools.

Many manufacturing industries also use compressed air and gas for combustion and process operations such as oxidation, fractionation, cryogenics, refrigeration, filtration, dehydration, and aeration. Table 1.1 lists some major manufacturing industries and the tools, conveying, and process operations requiring compressed air. For some of these applications, however, other sources of power may be more cost effective (see the fact sheet titled *Potentially Inappropriate Uses of Compressed Air* in Section 2). Compressed air also plays a vital role in many non-manufacturing sectors, including the transportation, construction, mining, agriculture, recreation, and service industries. Examples of some of these applications are shown in Table 1.2.

Table 1.1 Industrial Sector Uses of Compressed Air

Industry	Example Compressed Air Uses
Apparel	Conveying, clamping, tool powering, controls and actuators, automated equipment
Automotive	Tool powering, stamping, control and actuators, forming, conveying
Chemicals	Conveying, controls and actuators
Food	Dehydration, bottling, controls and actuators, conveying, spraying coatings, cleaning, vacuum packing
Furniture	Air piston powering, tool powering, clamping, spraying, controls and actuators
General Manufacturing	Clamping, stamping, tool powering and cleaning, control and actuators
Lumber and Wood	Sawing, hoisting, clamping, pressure treatment, controls and actuators
Metals Fabrication	Assembly station powering, tool powering, controls and actuators, injection molding, spraying
Petroleum	Process gas compressing, controls and actuators
Primary Metals	Vacuum melting, controls and actuators, hoisting
Pulp and Paper	Conveying, controls and actuators
Rubber and Plastics	Tool powering, clamping, controls and actuators, forming, mold press powering, injection molding
Stone, Clay, and Glass	Conveying, blending, mixing, controls and actuators, glass blowing and molding, cooling
Textiles	Agitating liquids, clamping, conveying, automated equipment, controls and actuators, loom jet weaving, spinning, texturizing

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Table 1.2 Non-Manufacturing Sector Uses of Compressed Air

Sector	Example Compressed Air Uses
Agriculture	Farm equipment, materials handling, spraying of crops, dairy machines
Mining	Pneumatic tools, hoists, pumps, controls and actuators
Power Generation	Starting gas turbines, automatic control, emissions controls
Recreation	Amusement parks - air brakes
	Golf courses - seeding, fertilizing, sprinkler systems
	Hotels - elevators, sewage disposal
	Ski resorts - snow making
	Theaters - projector cleaning
	Underwater exploration - air tanks
Service Industries	Pneumatic tools, hoists, air brake systems, garment pressing machines, hospital respiration systems, climate control
Transportation	Pneumatic tools, hoists, air brake systems
Wastewater Treatment	Vacuum filters, conveying