COMPRESSED AIR CHALLENGE

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CAC-Fact Sheets

(Documents are in PDF format.)

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For more information on the Compressed Air Challenge, call **1-800-862-2086**.

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Assessing Compressed Air Needs

Office of Industrial Technologies

Compressed Air Systems Fact Sheet #1

air needs are defined by the air quality, quantity, and level of pressure required by the end uses in your plant. Assessing needs carefully will ensure that a compressed air system is configured properly.

Air Quality

As illustrated in the following table, compressed air quality ranges from plant air to breathing air.

Quality	Applications
Plant Air	Air tools, general plant air
Instrument Air	Laboratories, paint spraying, powder coating, climate control
Process Air	Food and pharmaceutical process air, electronics
Breathing Air	Hospital air systems, diving tank refill stations, respirators for cleaning and/or grit blasting

Industrial applications typically use one of the first three air quality levels. Quality is determined by the dryness and contaminant level required by the end-uses, and is accomplished with filtering and drying equipment. The higher the quality, the more the air costs to produce. Higher quality air usually requires additional equipment, which not only increases initial capital investment, but also makes the overall system more expensive to operate in terms of energy consumption and maintenance costs.

One of the main factors in determining air quality is whether or not lubricant-free air is required. Lubricant-free air can be produced with either lubricant-free compressors, or with lubricant-injected compressors that have additional separation and filtration equipment. Lubricant-free rotary screw and reciprocating compressors usually have higher first costs, lower efficiency, and higher maintenance costs than lubricant-injected compressors. However, the additional separation and filtration equipment required by lubricant-injected compressors will cause some reduction in efficiency, especially if systems are not properly maintained. Careful consideration should be given to the specific end-use for the lubricant-free air, including the risk and cost associated with product contamination, before selecting a lubricant-free or lubricant-injected compressor.

Air Quantity - Capacity

Required compressed air system capacity can be determined by summing the requirements of the tools and process operations (taking into account load factors) at the site. The total air requirement is not the sum of the maximum requirements for each tool and process, but the sum of the average air consumption of each. High short-term demands should be met by air stored in an air receiver. Systems may have more than one air receiver. Strategically locating air receivers near sources of high demand can also be effective. In most cases, a thorough evaluation of system demand may result in a control strategy that will meet system demand with reduced overall compressor capacity.

Oversized air compressors are extremely inefficient because most systems use more energy per unit volume of air produced when operating at part-load. In many cases it makes sense to use multiple, smaller compressors with sequencing controls to allow for efficient operation at times when demand is less than peak.

If a system is properly designed and maintained but is still experiencing capacity problems, an alternative to adding another compressor is to re-examine the use of compressed air for certain applications. For some tasks, blowers or electric tools may be more effective or appropriate. See the Fact Sheet titled *Inappropriate Uses of Compressed Air* for more information on this system improvement opportunity.

Load Profile

Another key to properly designing and operating a compressed air system is assessing a plant's compressed air requirements over time, or load profile. The variation of demand for air over time is a major consideration in system design. Plants with wide variations in air demand need a system that operates efficiently under part-load. Multiple compressors with sequencing controls may provide more economical operation in such a case. Plants with a flatter load profile can use simpler control strategies.

Artificial Demand

Artificial demand is defined as the excess volume of air that is required by unregulated end uses as a result of supplying higher pressure than necessary for applications. Flow controllers (see the Fact Sheet titled *Compressed Air System Controls*) can help to minimize artificial demand.

Pressure

Different tools and process operations require different pressures. Pneumatic tool manufacturers rate tools for specific pressures, and process operation pressure requirements should be specified by the process engineers. Required pressure levels must take into account system losses from dryers, separators, filters, and piping. A rule of thumb is that every 2 psi increase in operating pressure requires an additional 1% in operating energy costs.

See the Fact Sheet titled *Pressure Drop and Controlling System Pressure* for information on ways to reduce system pressure and save energy while maintaining high performance.

Inappropriate Uses of Compressed Air

Office of Industrial Technologies

Compressed Air Systems Fact Sheet #2

Compressed air is probably the most expensive form of energy available in a plant. Compressed air is also clean, readily-available, and simple-to-use. As a result, compressed air is often chosen for applications in which other energy sources are more economical. Users should always consider more cost-effective forms of power before considering compressed air.

Many operations can be accomplished more economically using alternative energy sources. For example, plants should:

- Use air conditioning or fans to cool electrical cabinets instead of compressed air vortex tubes;
- Apply a vacuum system instead of creating a vacuum using compressed air venturi methods that flow high pressure air past an orifice;
- Use blowers instead of compressed air to provide cooling, aspirating, agitating, mixing, or to inflate packaging;
- Use brushes, blowers, or vacuum systems instead of compressed air to clean parts or remove debris;
- Use blowers, electric actuators, or hydraulics instead of compressed air blasts to move parts;
- Use low pressure air instead of compressed air for blow guns, air lances, and agitation; and
- Use efficient electric motors for tools or actuators (although electric tools can have less precise torque control, shorter lives, and lack the safety of compressed air powered tools).

Other improper uses of compressed air are unregulated end-uses and supply air to abandoned equipment, both of which are described below.

Unregulated End-Uses

A pressure regulator is used to limit maximum end-of-use pressure and is placed in the distribution system just prior to the tool. If a tool operates without a regulator, it uses full system pressure. This results in increased system air demand and energy use, since the tool is using air at this higher pressure. High pressure levels can also increase equipment wear, resulting in higher maintenance costs and shorter tool life.

Abandoned Equipment

Many plants undergo numerous equipment configuration changes over time. In some cases, plant equipment is no longer used. Air flow to this unused equipment should be stopped, preferably as far back in the distribution system as possible without affecting operating equipment.

Using Compressed Air

As a general rule, compressed air should only be used if safety enhancements, significant productivity gains, or labor reductions will result. Typical overall efficiency is around 10%.

If compressed air is used for an application, the amount of air used should be of minimum quantity and pressure and used for the shortest possible duration of time. Compressed air use should also be constantly monitored and re-evaluated.

Compressed Air System Audits

Office of Industrial Technologies

Compressed Air Systems Fact Sheet #3

A compressed air system audit can highlight the true costs of compressed air and identify simple opportunities to improve efficiency and productivity. In some cases, the local electric utility will help finance such an audit.

Compressed air system users should consider using an independent auditor to examine their compressed air system. Several firms exist that specialize in compressed air system audits. Audits are also performed by electric utilities, equipment distributors and manufacturers, energy service companies, and engineering firms. An informed consumer should be aware that the quality and comprehensiveness of audits can vary. Independent auditors should provide recommendations which are systems-neutral and commercially impartial. Independent auditors should neither specify nor recommend any particular manufacturer's products.

A comprehensive compressed air system audit should include an examination of both air supply and usage and the interaction between the supply and demand. Auditors typically measure the output of a compressed air system, calculate energy consumption in kilowatt-hours, and determine the annual cost of operating the system. The auditor may also measure total air losses due to leaks and locate those that are significant. All components of the compressed air system are inspected individually and problem areas are identified. Losses and poor performance due to system leaks, inappropriate uses, demand events, poor system design, system misuse, and total system dynamics are calculated, and a written report with a recommended course of action is provided. Important aspects of a basic compressed air system audit are discussed below.

System Issues

System issues go beyond examining the performance of an individual compressed air system component and, instead, examine how components on both the supply and demand side of the system interact. Auditors typically address a number of systems issues. These are discussed below, and many are addressed in more detail in other Compressed Air Systems Fact Sheets.

Level of Air Treatment. The auditor typically examines the compressed air applications and determines the appropriate level of air treatment required for proper operation of the equipment. Actual air quality levels are then measured. If the air is not being treated enough, alternative treatment strategies are recommended. If the air is being over-treated (an indication of energy being wasted), recommendations are made to modify the system. In some cases, only certain end-use equipment requires highly treated air, and the auditor may recommend a system that allows for different treatment levels at different points in the system.

Leaks. The auditor should identify and quantify leaks in the system and recommend a leak management program.

Pressure Levels. An auditor also typically determines the lowest possible pressure level required to operate production equipment effectively. In many cases, system pressure can be lowered, thereby saving energy. Most systems have one or more critical applications that determine the minimum acceptable pressure in the system. In some cases, the application of dedicated storage or differential reduction on the critical applications will allow a reduction in overall system pressure.

Controls. The existing control system is evaluated to determine if it is appropriate for the system demand profile. Performance gains available from operating the system in a different mode or using an alternative control strategy should be estimated.

Heat Recovery. Auditors will identify potential applications for the use of heat recovery, if it is not already being used.

Demand Side Issues

The demand side of the system refers to how compressed air is actually used in the plant.

Distribution System. The overall layout of the distribution system (piping) is examined. Pressure drop and efficiency are measured or estimated, and the effectiveness of the condensate removal system is evaluated. Simple changes that can enhance system performance are suggested if appropriate.

Load Profile. Auditors typically estimate the compressed air load profile in terms of how the demand in cubic feet per minute (cfm) changes over time. A facility with a varying load profile will likely benefit from advanced control strategies. A facility with short periods of heavy demand may benefit from implementing storage options.

To establish the load profile, an auditor will measure system flow and pressure across the system under different demand conditions, while observing the loading effect on the existing compressors. This may require a number of measurements over a 24-hour period (or even several days) if demand varies significantly over time. Some auditors may use data logging equipment to obtain both demand and power consumption profiles.

End-Use Equipment. The equipment and processes that use compressed air will also be examined. In some cases, recommendations such as specifying equipment that operates at a lower pressure will be made. An auditor may also recommend replacing existing compressed air-powered equipment with equipment that uses a source of energy other than compressed air (see the Fact Sheet titled *Inappropriate Uses of Compressed Air).* Critical pressure applications are examined in detail. Local storage and other modifications may be recommended.

Supply Side Issues

The supply side refers to how the compressed air is generated and treated.

Compressor Package. The compressors are evaluated in terms of appropriateness for the application and general appearance and condition. Compressor efficiency is usually estimated based on manufacturer-supplied data, corrected to site conditions. The installation is also evaluated in terms of its location, connection to cooling water, and ventilation. A general appraisal and any recommendations for alternative systems are also made.

Filters. Filters are examined for cleanliness and suitability for the application. Pressure drop across the filters is measured to estimate energy losses from the filter. A maintenance schedule for changing the filters, and possibly higher performance filters, may be recommended.

Aftercooler. Aftercooler and separator efficiency, cooling effectiveness, and condensate separation effectiveness are all measured and evaluated, and feasible modifications or alternative systems are recommended.

Dryer. Dryer appropriateness is assessed based on the facility's end-use applications. Dryer size, pressure drop, and efficiency are measured and evaluated. Modifications and replacements are recommended if needed.

Automatic Drains. Location, application, and effectiveness of both supply-side and demand-side drains are evaluated and alternatives recommended if necessary.

Air Receiver/Storage. The effectiveness of the receiver tank is evaluated in terms of location and size, and the receiver drain trap is examined to see if it is operating properly. Storage solutions to control demand events should also be investigated.

More Comprehensive Evaluations

System audits are designed to identify system inefficiencies. If a system is found to be poorly designed, in unsatisfactory operating condition, or in need of substantial retrofit, a more detailed analysis of the system may be recommended.

A comprehensive evaluation may also include extensive measurements and analysis of supply and demand interactions. Some auditors will also prepare a detailed systems flow diagram. A financial evaluation may also be performed, including current and proposed costs after retrofits are taken.

COMPRESSED AIR CHALLENGE

Pressure Drop and Controlling System Pressure

Office of Industrial Technologies

Compressed Air Systems Fact Sheet #4

Pressure drop is a term used to characterize the reduction in air pressure from the compressor discharge to the actual point of use. Pressure drop occurs as the compressed air travels through the treatment and distribution system. A properly designed system should have a pressure loss of much less than 10% of the compressor's discharge pressure, measured from the receiver tank output to the point of use.

Excessive pressure drop will result in poor system performance and excessive energy consumption. Flow restrictions of any type in a system require higher operating pressures than are needed, resulting in higher energy consumption. Minimizing differentials in all parts of the system is an important part of efficient operation. Pressure drop upstream of the compressor signal requires higher compression pressures to achieve the control settings on the compressor. The most typical problem areas include the aftercooler, lubricant separators, and check valves. This particular pressure rise resulting from resistance to flow can involve increasing the drive energy on the compressor by 1% of the connected power for each 2 psi of differential.

An air compressor capacity control pressure signal normally is located at the discharge of the compressor package. When the signal location is moved downstream of the compressed air dryers and filters, to achieve a common signal for all compressors, some dangers must be recognized and precautionary measures taken. The control range pressure setting must be reduced to allow for actual and potentially increasing pressure drop across the dryers and filters. Provision also must be made to prevent exceeding the maximum allowable discharge pressure and drive motor amps of each compressor in the system.

Pressure drop in the distribution system and in hoses and flexible connections at points of use results in lower operating pressure at the points of use. If the point of use operating pressure has to be increased, try reducing the pressure drops in the system before adding capacity or increasing the system pressure. Increasing the compressor discharge pressure or adding compressor capacity results in significant increases in energy consumption.

Elevating system pressure increases unregulated uses such as leaks, open blowing and production applications without regulators or with wide open regulators. The added demand at elevated pressure is termed "artificial demand", and substantially increases energy consumption. Instead of increasing the compressor discharge pressure or adding additional compressor capacity, alternative solutions should be sought, such as reduced pressure drop, strategic compressed air storage, and demand/intermediate controls. Equipment should be specified and operated at the lowest efficient operating pressure.

What Causes Pressure Drop?

Any type of obstruction, restriction or roughness in the system will cause resistance to air flow and cause pressure drop. In the distribution system, the highest pressure drops usually are found at the points of use, including in undersized or leaking hoses, tubes, disconnects, filters, regulators and lubricators (FRLs). On the supply side of the system, air/lubricant separators, aftercoolers, moisture separators, dryers and filters are the main items causing significant pressure drops.

The maximum pressure drop from the supply side to the points of use will occur when the compressed air flow rate and temperature are highest. System components should be selected based upon these conditions and the manufacturer of each component should be requested to supply pressure drop information under these conditions. When selecting filters, remember that they will get dirty. Dirt loading characteristics are also an important selection criteria. Large end-users that purchase substantial quantities of components should work with their suppliers to ensure that products meet the desired specifications for differential pressure and other characteristics.

The distribution piping system often is diagnosed as having a high pressure drop because a point of use pressure regulator cannot sustain the required downstream pressure. If such a regulator is set at 85 psig and the regulator and/or the upstream filter has a pressure drop of 20 psi, the system upstream of the filter and regulator would have to maintain at least 105 psig. The 20 psi pressure drop may be blamed on the system piping rather than on the components at fault. The correct diagnosis requires pressure measurements at different points in the system to identify the component(s) causing the high pressure drop. In this case, the filter/regulator size needs to be increased, not the piping.

Minimizing Pressure Drop

Minimizing pressure drop requires a systems approach in design and maintenance of the system. Air treatment components, such as aftercoolers, moisture separators, dryers, and filters, should be selected with the lowest possible pressure drop at specified maximum operating conditions. When installed, the recommended maintenance procedures should be followed and documented. Additional ways to minimize pressure drop are as follows:

- Properly design the distribution system.
- Operate and maintain air filtering and drying equipment to reduce the effects of moisture, such as pipe corrosion.
- Select aftercoolers, separators, dryers and filters having the least possible pressure drop for the rated conditions.
- Reduce the distance the air travels through the distribution system.
- Specify pressure regulators, lubricators, hoses, and connections having the best performance characteristics at the lowest pressure differential.

Controlling System Pressure

Many plant air compressors operate with a full load discharge pressure of 100 psig and an unload discharge pressure of 110 psig or higher. Many types of machinery and tools can operate efficiently with an air supply at the point of use of 80 psig or lower. If the air compressor discharge pressure can be reduced, significant savings can be achieved. Check with the compressor manufacturer for performance specifications at different discharge pressures.

Demand controls require sufficient pressure drop from the primary air receiver into which the compressor discharges, but the plant header pressure can be controlled to a much narrower pressure range, shielding the compressor from severe load swings. Reducing and controlling the system pressure downstream of the primary receiver can result in a reduction in energy consumption of up to 10% or more, even though the compressors discharge pressure has not been changed.

Reducing system pressure also can have a cascading effect in improving overall system performance, reducing leakage rates, and helping with capacity and other problems. Reduced pressure also reduces stress on components and operating equipment. However, a reduced system operating pressure may require modifications to other components, including pressure regulators, filters, and the size and location of compressed air storage.

Lowering average system pressure requires caution since large changes in demand can cause the pressure at points of use to fall below minimum requirements, which can cause equipment to function improperly. These problems can be avoided with careful matching of system components, controls, and compressed air storage capacity and location (see the Fact Sheet titled *Compressed Air System Controls*).

For applications using significant amounts of compressed air, it is recommended that equipment be specified to operate at lower pressure levels. The added cost of components, such as larger air cylinders, usually will be recouped quickly from resulting energy savings. Production engineers often specify end-use equipment to operate at an average system pressure. This results in higher system operating costs. Firstly, the point of use installation components such as hoses, pressure regulators, and filters will be installed between the system pressure and the end-use equipment pressure. Secondly, filters will get dirty and leaks will occur. Both result in lower end-use pressure. This should be anticipated in specifying the available end-use pressure.

If an individual application requires a higher pressure, instead of raising the operating pressure of the whole system it may be best to replace or modify this application. It may be possible to have a cylinder bore increased, gear ratios may be changed, mechanical advantage improved, or a larger air motor may be used. The cost of the improvements probably will be insignificant compared with the energy reduction achieved from operating the system at the lower pressure.

It is also important to check if manufacturers are including pressure drops in filters, pressure regulators, and hoses in their pressure requirements for end-use equipment, or if the pressure requirements as stated are for after those components. A typical pressure differential for a filter, pressure regulator, and hose is 7 psid, but it could be much higher in poorly designed and maintained systems.

When demand pressure has been successfully reduced and controlled, attention then should be turned to the compressor control set points to obtain more efficient operation, and also to possible unloading or shutting off of a compressor to further reduce energy consumption.

Maintenance of Compressed Air Systems for Peak Performance

Office of Industrial Technologies

Compressed Air Systems Fact Sheet #5

Like all electro-mechanical equipment, industrial compressed air systems require periodic maintenance to operate at peak efficiency and minimize unscheduled downtime. Inadequate maintenance can have a significant impact on energy consumption via lower compression efficiency, air leakage, or pressure variability. It can also lead to high operating temperatures, poor moisture control, and excessive contamination. Most problems are minor and can be corrected by simple adjustments, cleaning, part replacement, or the elimination of adverse conditions. Compressed air system maintenance is similar to that performed on cars; filters and fluids are replaced, cooling water is inspected, belts are adjusted, and leaks are identified and repaired.

All equipment in the compressed air system should be maintained in accordance with manufacturers' specifications. Manufacturers provide inspection, maintenance, and service schedules that should be followed strictly. In many cases, it makes sense from efficiency and economic standpoints to maintain equipment more frequently than the intervals recommended by manufacturers, which are primarily designed to protect equipment.

Basic Maintenance Checklist

- 9 **Inlet Filter Cartridges.** Inspect and clean or replace per manufacturer specifications. Required frequency is often related to operating conditions. Dirty filters increase energy consumption.
- 9 **Drain Traps.** Clean out debris and check operation periodically.
- 9 **Compressor Lubricant Level.** Inspect daily and top-off or replace per manufacturer specifications. Change lubricant filter per manufacturer specifications.
- 9 **Air Lubricant Separator (Lubricant-injected Rotary Screw Compressors).** Change per manufacturer specifications, or when pressure drop exceeds 10 psid, whichever is less.
- 9 **Lubricant Selection.** Select compressor and electric motor lubricant per manufacturer specifications.
- 9 **Belt Condition.** Check belts for wear and check/adjust tension per manufacturer specifications.
- 9 **Operating Temperature.** Verify that operating temperature is per manufacturer specification.
- 9 **Air Line Filters.** Replace particulate and lubricant removal elements when pressure drop exceeds 2 to 3 psid. Inspect all elements at least annually regardless of pressure drop indication.
- 9 **Water Cooling System.** For water-cooled systems, check water quality (especially pH and total dissolved solids), flow, and temperature, and clean/replace filters and heat exchangers per manufacturer specifications.
- 9 **System Leaks.** Check lines (especially joints), fittings, clamps, valves, hoses, disconnects, regulators, filters, lubricators, gauge connections, and end-use equipment for leaks.
- 9 **System Cleanliness.** Check system for compressor and motor lubricant leaks and cleanliness.

One way to tell if a system is being maintained well and is operating properly is to periodically benchmark the system by tracking power, pressure, and flow. If power use at a given pressure and flow rate goes up, the system's efficiency is degrading. This bench marking will also let you know if the compressor is operating a full capacity, and if the capacity is decreasing over time. On new systems, specifications should be recorded when the system is first set-up and operating properly.

Maintenance issues for specific system components are discussed below.

Compressor Package

The main areas of the compressor package in need of maintenance are the compressor, heat exchanger surfaces, air lubricant separator, lubricant, lubricant filter, and air inlet filter.

The compressor and intercooling surfaces need to be kept clean and foul-free. If they are dirty, compressor efficiency will be adversely affected. Fans and water pumps should also be inspected to ensure that they are operating at peak performance.

The air lubricant separator in a lubricant-cooled rotary screw compressor generally starts with a 2-3 psid pressure drop at full-load when new. Maintenance manuals usually suggest changing them when there is about a 10 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.

The compressor lubricant and lubricant filter need to be changed per manufacturer's specification. Lubricant can become corrosive and degrade both the equipment and system efficiency.

For lubricant-injected rotary compressors, the lubricant serves to lubricate bearings, gears, and intermeshing rotor surfaces. The lubricant also acts as a seal and removes most of the heat of compression. Only a lubricant meeting the manufacturer=s specifications should be used.

Inlet filters and inlet piping also need to be kept clean. A dirty filter can reduce compressor capacity and efficiency. Filters should be maintained at least per manufacturer's specifications, taking into account the level of contaminants in the facility's air.

Compressor Drives

If the electric motor driving a compressor is not properly maintained, it will not only consume more energy, but be apt to fail before its expected lifetime. The two most important aspects of motor maintenance are lubrication and cleaning.

Lubrication. Too much lubrication can be just as harmful as too little and is a major cause of premature motor failure. Motors should be lubricated per the manufacturer's specification, which can be anywhere from every 2 months to every 18 months, depending on annual hours of operation and motor speed. On motors with bearing grease fittings, the first step in lubrication is to clean the grease fitting and remove the drain plug. High quality new grease should be added, and the motor should be run for about an hour before the drain plug is replaced. This allows excess grease to be purged from the motor without dripping on the windings and damaging them.

Cleaning. Since motors need to dissipate heat, it is important to keep all of the air passages clean and free of obstruction. For enclosed motors, it is vital that cooling fins are kept free of debris. Poor motor cooling can increase motor temperature and winding resistance, which shortens motor life and increases energy consumption.

Belts. Motor v-belt drives also require periodic maintenance. Tight belts can lead to excessive bearing wear, and loose belts can slip and waste energy. Under normal operation, belts stretch and wear and, therefore, require adjustment. A good rule-of-thumb is to examine and adjust belts after every 400 hours of operation.

Air Treatment Equipment

Fouled compressed air treatment equipment can result in excessive energy consumption as well as poor-quality air that can damage other equipment. All filters should be kept clean. Dryers, aftercoolers, and separators should all be cleaned and maintained per manufacturer's specifications.

Automatic Drain Traps

Most compressed air systems have numerous moisture traps located throughout the system. Traps need to be inspected periodically to ensure that they are not stuck in either the open or closed position. An automatic drain trap stuck in the open position will leak compressed air; a drain trap stuck in the closed position will cause condensate to backup and be carried downstream where it can damage other system components. Traps stuck in the open position can be a major source of wasted energy in some plants.

End-Use Filters, Regulators, and Lubricators

Point-of-use filters, regulators, and lubricators are needed to ensure that a tool is receiving a clean, lubricated supply of air at the proper pressure. Filters should be inspected periodically because a clogged filter will increase pressure drop, which can either reduce pressure at the point of use or increase the pressure required from the compressor, thereby consuming excessive energy. A filter that is not operating properly will also allow contaminants into a tool, causing it to wear out prematurely. The lubricant level should also be checked often enough to ensure that it does not run dry. Tools that are not properly lubricated will wear prematurely and use excess energy.

Leaks

Leak detection and repair is an important part of any maintenance program. For more information on finding and fixing leaks, see the Fact Sheet titled *Compressed Air System Leaks*.

Establishing a regular, well-organized maintenance program and strictly following it is critical to maintaining the performance of a compressed air system. One person should be given the responsibility of ensuring that all maintenance is performed properly, on schedule, and adequately documented.

Compressed Air System Controls

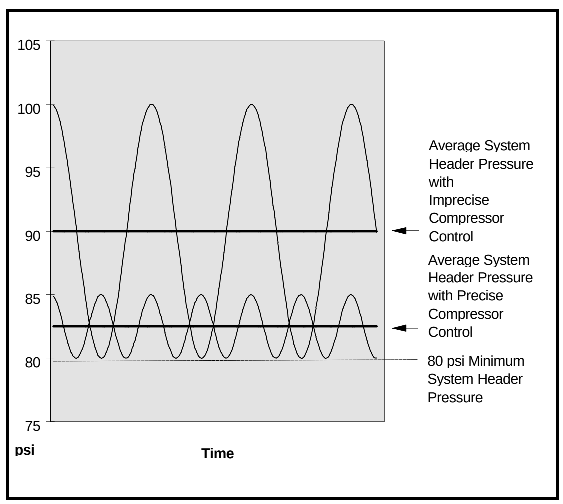
Office of Industrial Technologies

Compressed Air Systems Fact Sheet #6

Compressed air system controls match the compressed air supply with system demand (although not always in real-time) and are one of the most important determinants of overall system energy efficiency. This Fact Sheet discusses both individual compressor control and overall system control of plants with multiple compressors. Proper control is essential to efficient system operation and high performance. The objective of any control strategy is also to shut off unneeded compressors or delay bringing on additional compressors until needed. All units which are on should be run at full-load, except for one unit for trimming.

Compressor systems are typically comprised of multiple compressors delivering air to a common plant air header. The combined capacity of these machines is sized, at a minimum, to meet the maximum plant air demand. System controls are almost always needed to orchestrate a reduction in the output of the individual compressor(s) during times of lower demand. Compressed air systems are usually designed to operate within a fixed pressure range and to deliver a volume of air which varies with system demand. System pressure is monitored and the control system decreases compressor output when the pressure reaches a predetermined level. Compressor output is then increased again when the pressure drops to a lower predetermined level.

The difference between these two pressure levels is called the control range. Depending on air system demand, the control range can be anywhere from 2-20 psi. In the past, individual compressor controls and non-supervised multiple machine systems were slow and imprecise. This resulted in wide control ranges and large pressure swings. As a result of these large swings, individual compressor pressure control set points were established to maintain pressures higher than needed. This ensured that swings would not go below the minimum requirements for the system. Today, faster and more accurate microprocessor-based system controls with tighter control ranges allow for a drop in the system pressure set points. This advantage is depicted in the figure below, where the precise control system is able to maintain a much lower average pressure without going below the minimum system requirements. Every 2 psi of pressure difference is equal to about a 1%



Impacts of Controls on System Pressure

change in energy consumption. Narrower variations in pressure not only use less energy, but avoid negative effects on production quality control.

Caution needs to be taken when lowering average system header pressure because large, sudden changes in demand can cause the pressure to drop below minimum requirements, leading to improper functioning of equipment. With careful matching of system controls and storage capacity, these problems can be avoided.

Few air systems operate at full-load all of the time. Part-load performance is therefore critical, and is primarily influenced by compressor type and control strategy.

Controls and System Performance

The type of control specified for a given system is largely determined by the type of compressor being used and the facility's demand profile. If a system has a 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 strategy. In any case, careful consideration should be given to both compressor and system control selection because they can be the most important factors affecting system performance and efficiency.

Individual Compressor Control Strategies

Over the years, compressor manufacturers have developed a number of different types of control strategies. Controls such as start/stop and load/unload respond to reductions in air demand, increasing compressor discharge pressure by turning the compressor off or unloading it so that it does not deliver air for periods of time. Modulating inlet and multi-step controls allow the compressor to operate at part-load and deliver a reduced amount of air during periods of reduced demand.

Start/Stop. Start/stop is the simplest control available and can be applied to either reciprocating or rotary screw compressors. The motor driving the compressor is turned on or off in response to the discharge pressure of the machine. Typically, a simple pressure switch provides the motor start/stop signal. This type of control should not be used in an application that has frequent cycling because repeated starts will cause the motor to overheat and other compressor components to require more frequent maintenance. This control scheme is typically only used for applications with very low duty cycles.

Load/Unload. Load/unload control, also known as constant speed control, allows the motor to run continuously, but unloads the compressor when the discharge pressure is adequate. Compressor manufacturers use different strategies for unloading a compressor, but in most cases, an unloaded rotary screw compressor will consume 15-35% of full-load horsepower while delivering no useful work. As a result, some load/unload control schemes can be inefficient.

Modulating Controls. Modulating (throttling) inlet control allows the output of a compressor to be varied to meet flow requirements. Throttling is usually accomplished by closing down the inlet valve, thereby restricting inlet air to the compressor. This control scheme is applied to centrifugal and rotary screw compressors. This control method, when applied to displacement compressors, is an inefficient means of varying compressor output. When used on centrifugal compressors, more efficient results are obtained, particularly with the use of inlet guide vanes which direct the air in the same direction as the impeller inlet. The amount of capacity reduction is limited by the potential for surge and minimum throttling capacity.

Multi-step (Part-load) Controls. Some compressors are designed to operate in two or more partially-loaded conditions. With such a control scheme, output pressure can be closely controlled without requiring the compressor to start/stop or load/unload.

Reciprocating compressors are designed as two-step (start/stop or load/unload), three- step (0%, 50%, 100%) or five-step (0%, 25%, 50%, 75%, 100%) control. These control schemes generally exhibit an almost direct relationship between motor power consumption and loaded capacity.

Some rotary screw compressors can vary their compression volumes (ratio) using sliding or turn valves. These are generally applied in conjunction with modulating inlet valves to provide more accurate pressure control with improved part-load efficiency.

Variable Frequency Drives. Historically, the use of variable frequency drives (VFDs) for industrial air compressors has been rare, because the high initial cost of a VFD could not justify the efficiency gain over other control schemes. Cost is no longer a major issue. VFDs may gain acceptance in compressor applications as they become more reliable and efficient at full-load.

System Controls

By definition, system controls orchestrate the actions of the multiple individual compressors that supply air to the system. Prior to the introduction of automatic system controls, compressor systems were set by a method known as cascading set points. Individual compressor operating pressure set points were established to either add or subtract compressor capacity to meet system demand. The additive nature of this strategy results in large control ranges as depicted in the figure on the first page of this Fact Sheet.

The objective of an effective automatic system control strategy is to match system demand with compressors operated at or near their maximum efficiency levels. This can be accomplished in a number of ways, depending on fluctuations in demand, available storage, and the characteristics of the equipment supplying and treating the compressed air.

Single Master (Sequencing) Controls. Sequencers are, as the name implies, devices used to regulate systems by sequencing or staging individual compressor capacity to meet system demand. Sequencers are referred to as single master control units because all compressor operating decisions are made and directed from the master unit. Sequencers control compressor systems by taking individual compressor capacity on- and off-line in response to monitored system pressure (demand). The control system typically offers a higher efficiency because the control range around the system target pressure is tighter. This tighter range allows for a reduction in average system pressure. Again, caution needs to be taken when lowering average system header pressure because large, sudden changes in demand can cause the pressure to drop below minimum requirements, leading to improper functioning of equipment. With careful matching of system controls and storage capacity, these problems can be avoided (see also flow controller).

Multi-Master (Network) Controls. Network controls offer the latest in system control. It is important that these controllers be used to shut down any compressors running unnecessarily. They also allow the operating compressors to function in a more efficient mode. Controllers used in networks are combination controllers. They provide individual compressor control as well as system control functions. The term multi-master refers to the system control capability within each individual compressor controller. These individual controllers are linked or networked together, thereby sharing all operating information and status. One of the networked controllers is designated as the leader. Because these controllers share information, compressor operating decisions with respect to changing air demand can be made more quickly and accurately. The effect is a tight pressure control range which allows a further reduction in the air system target pressure. Although initial costs for system controls are often high, these controls are becoming more common because of the resulting reductions in operating costs.

Flow Controllers

Flow controllers are system pressure or density controls used in conjunction with the individual compressor or system controls described previously. A flow controller does not directly control a compressor and is generally not included as part of a compressor package. A flow controller is a device that serves to separate the supply side of a compressor system from the demand side. This allows compressors to be operated at or near their optimum pressures for maximum efficiency while the pressure on the demand side can be reduced to minimize actual usage requirements. Storage, sized to meet anticipated fluctuations in demand, is an essential part of this control strategy. Higher pressure supply air enters a storage tank at a predetermined rate and is available to reliably meet fluctuations in demand at a constant, lower pressure level. A well designed and managed system integrates control strategy, demand control, signal locations, differentials, compressor controls, and storage. The goal is to operate demand at the lowest possible pressure, support transient events as much as possible with stored air, and take as long as possible to replenish storage. This should result in the lowest possible energy consumption.

Air Storage and Controls

Storage can be used to control demand events (peak demand periods) in the system by reducing both the amount of pressure drop and the rate of decay. Storage can be used to protect critical pressure applications from other events in the system. Storage can also be used to control the rate of pressure drop in demand while supporting the speed of transmission response from supply. For some systems, it is important to provide a form of refill control such as a flow control valve.

Many systems have a compressor operating in modulation to support demand events, and sometimes strategic storage solutions can allow for this compressor to be turned off.

Compressed Air System Leaks

Office of Industrial Technologies

Compressed Air Systems Fact Sheet #7

Leaks can be a significant source of wasted energy in an industrial compressed air system, sometimes wasting 20-30% of a compressor's output. A typical plant that has not been well maintained will likely have a leak rate equal to 20% of total compressed air production capacity. On the other hand, proactive leak detection and repair can reduce leaks to less than 10% of compressor output.

In addition to being a source of wasted energy, leaks can also contribute to other operating losses. Leaks cause a drop in system pressure, which can make air tools function less efficiently, adversely affecting production. In addition, by forcing the equipment to cycle more frequently, leaks shorten the life of almost all system equipment (including the compressor package itself). Increased running time can also lead to additional maintenance requirements and increased unscheduled downtime. Finally, leaks can lead to adding unnecessary compressor capacity.

While leakage can come from any part of the system, the most common problem areas are:

C Couplings, hoses, tubes, and fittings,
C Pressure regulators,
C Open condensate traps and shut-off valves, and
C Pipe joints, disconnects, and thread sealants.

Size	Cost per Year
1/16"	$523
1/8"	$2,095
1/4"	$8,382

Costs calculated using electricity rate of $0.05 per kWh, assuming constant operation and an efficient compressor.

The Cost of Leaks

Estimating Amount of Leakage

For compressors that use start/stop controls, there is an easy way to estimate the amount of leakage in the system. This method involves starting the compressor when there are no demands on the system (when all the air-operated end-use equipment is turned off). A number of measurements are taken to determine the average time it takes to load and unload the compressor. The compressor will load and unload because the air leaks will cause the compressor to cycle on and off as the pressure drops from air escaping through the leaks. Total leakage (percentage) can be calculated as follows:

Leakage (%) = [(T x 100)/(T+t)]

where: T=on-load time (minutes)
t=off-load time (minutes)

Leakage will be expressed in terms of the percentage of compressor capacity lost. The percentage lost to leakage should be less than 10% in a well-maintained system. Poorly maintained systems can have losses as high as 20-30% of air capacity and power. Leakage can be estimated in systems with other control strategies if there is a pressure gauge downstream of the receiver. This method requires an estimate of total system volume, including any downstream secondary air receivers, air mains, and piping (V, in cubic feet). The system is then started and brought to the normal operating pressure (P1). Measurements should then be taken of the time (T) it takes for the system to drop to a lower pressure (P2), which should be a point equal to about one-half the operating pressure.

Leakage can be calculated as follows:

$$\text{Leakage (cfm free air)} = (V \times (P1-P2)/T \times 14.7) \times 1.25$$

where: V is in cubic feet
P1 and P2 are in psig
T is in minutes

The 1.25 multiplier corrects leakage to normal system pressure, allowing for reduced leakage with falling system pressure. Again, leakage of greater than 10% indicates that the system can likely be improved. These tests should be carried out quarterly as part of a regular leak detection and repair program.

Leak Detection

Since air leaks are almost impossible to see, other methods must be used to locate them. The best way to detect leaks is to use an ultrasonic acoustic detector, which can recognize the high frequency hissing sounds associated with air leaks. These portable units consist of directional microphones, amplifiers, and audio filters, and usually have either visual indicators or earphones to detect leaks. A simpler method is to apply soapy water with a paint brush to suspect areas. Although reliable, this method can be time consuming.

How to Fix Leaks

Leaks occur most often at joints and connections. Stopping leaks can be as simple as tightening a connection or as complex as replacing faulty equipment such as couplings, fittings, pipe sections, hoses, joints, drains, and traps. In many cases leaks are caused by bad or improperly applied thread sealant. Select high quality fittings, disconnects, hose, tubing, and install them properly with appropriate thread sealant.

Non-operating equipment can be an additional source of leaks. Equipment no longer in use should be isolated with a valve in the distribution system.

Another way to reduce leaks is to lower the demand air pressure of the system. The lower the pressure differential across an orifice or leak, the lower the rate of flow, so reduced system pressure will result in reduced leakage rates. Stabilizing the system header pressure at its lowest practical range will minimize the leakage rate for the system. For more information on lowering system pressure, see the Fact Sheet titled *Pressure Drop and Controlling System Pressure*.

Once leaks have been repaired, the compressor control system should be re-evaluated to realize the total savings potential.

A Leak Prevention Program

A good leak prevention program will include the following components: identification (including tagging), tracking, repair, verification, and employee involvement. All facilities with compressed air systems should establish an aggressive leak program. A cross-cutting team involving decision-making representatives from production should be formed.

A leak prevention program should be part of an overall program aimed at improving the performance of compressed air systems. Once the leaks are found and repaired, the system should be re-evaluated.

Packaged Compressor Efficiency Ratings

Office of Industrial Technologies

Compressed Air Systems Fact Sheet #8

Evaluating and comparing industrial air compressor capacities and efficiencies can be a daunting task. Standards exist for testing the performance of a compressor, but they have not always been applied in a consistent manner, and performance test results and efficiency ratings are not always published in consistent, standard formats. The result is that purchasers of air compressors can find it difficult to compare the equipment performance.

The Compressed Air and Gas Institute (CAGI), the primary compressed air industry trade association, has developed performance testing standards. CAGI, in conjunction with its European counterpart PNEUROP, has developed simplified performance testing standards which have been incorporated as addenda in International Standards Organization (ISO) Standard ISO 1217, Displacement Compressors Acceptance Tests. These Simplified Test Codes were adopted by the membership of CAGI and will be reflected in performance data published in manufacturers' literature. Some CAGI members also have ISO 9001 Certification which requires documentation of compliance with published performance and procedures.

Compressed air system users should be aware that not all manufacturers marketing compressors in the United States are members of CAGI, and some may test their compressors using different standards.

The following standards have been developed for measuring air compressor performance:

- CAGI/PNEUROP – Acceptance Test Code for Bare Displacement Air Compressors (PN2CPTC1)
- CAGI/PNEUROP – Acceptance Test Code for Electrically-Driven Packaged Displacement Air Compressors (PN2CPTC2)
- CAGI/PNEUROP – Acceptance Test Code for I.C. Engine-Driven Packaged Displacement Air Compressors (PN2CPTC3)
- American Society of Mechanical Engineers (ASME) – Power Test Code 9, Displacement Compressors, Vacuum Pumps, and Blowers
- International Standards Organization (ISO) – ISO 1217, Displacement Compressors Acceptance Tests [distributed in the United States by the American National Standards Institute (ANSI)]

The revised ISO 1217 with Simplified Test Codes will likely be the most commonly used standard in the future. CAGI is also currently developing Data Sheets outlining a common format and style for reporting compressor performance, including efficiency. For more information on CAGI Data Sheets, see Appendix B of this Sourcebook.

The industry norm for comparison of compressor efficiency is given in terms of bhp/100 acfm (brake horse power per actual cubic feet per minute) at a compressor discharge pressure of 100 psig. A typical single-stage lubricant-injected rotary screw compressor will have a rating of approximately 22 bhp/100 acfm (referenced to standard inlet conditions). Users need to remember that performance at site conditions will be different from test data because of differences in factors such as ambient temperature, pressure, and humidity.

Even when accurate, consistent efficiency information is available, it may only be specified for full-load operation (i.e., full capacity and specified full-load discharge pressure). Since most systems operate at part-load much of the time, it is also important to compare part-load efficiencies when evaluating the performance of different compressors. The variety of control methods can, however, make this difficult.

When gathering information on compressor performance and comparing different models, users should make sure the compressors have been tested using the same standard, at the same conditions, and that the data is being reported in a consistent manner. Some situations can lead to "apples and oranges" comparisons. For example:

C Manufacturers may test their compressors under different "standard" conditions. Standard conditions should be at 14.5 psia (1 bar); 68EF (20EC) and dry (0% relative humidity).

C The actual full-load power required by a typical air compressor package will exceed the nominal nameplate rating of the main drive electric motor. Such motors have a continuous service factor, usually 15%, which allows continuous operation at 15% above the nominal rating. Most manufacturers use up to two thirds of the available service factor, so that full-load power will be 10% above the nominal motor rating. It is therefore important to use the bhp rating, not the motor nameplate hp rating, when comparing efficiency ratings in hp/acfm. To include the motor efficiency and all package accessories and losses, use a rating in total kW input per acfm to provide more precise data.

C Manufacturers may use a flange-to-flange rating that does not include inlet, discharge, and other package losses. This can affect overall efficiency by 5% or more.

C Energy consumption for accessory components, such as cooling fan motors, may not be treated consistently.

C Manufacturers may apply ranges or tolerances to performance data.

- Performance is usually based on perfect intercooling, which may not be realized under actual operating conditions. Perfect intercooling requires the air inlet temperature at each stage to be the same, requiring a cooling water temperature approximately 15°F below the ambient air temperature. Poor intercooling will adversely affect compressor performance.

As the revised ISO standard and CAGI Compressor Data Sheets become more commonly used, these equipment comparison problems should become less significant.

Compressed Air System Economics

Office of Industrial Technologies

Compressed Air Systems Fact Sheet #9

Delivering compressed air to a manufacturing facility is an expensive operation. Delivery requires costly equipment that consumes significant amounts of electricity and needs frequent maintenance. In spite of this, many facilities have no idea how much their compressed air systems cost on an annual basis, or how much money they could save by improving the performance of these systems.

Electricity costs are by far the largest expense of owning and operating a compressed air system. The initial cost for a 100-hp compressor is $30,000-$50,000, depending on the type of compressor and manufacturer, while annual electricity charges for the same system can reach $50,000. Added to this are annual maintenance costs, which can be 10% or more of the initial cost of the system.

This Fact Sheet presents a simple calculation to estimate annual electricity costs, and a more accurate calculation requiring electrical measurements.

Calculating Electricity Costs

Full-load Operation. Even if an air compressor is not separately metered, estimating annual electricity cost is simple. For more analysis techniques, see the AIRMaster software referenced in the *Resource and Tools* section, and/or call the Compressed Air Challenge™ number listed in the *Directory* section.

A Simple Calculation. The following data is needed for a quick calculation of electricity costs for a compressor operating at full-load:

- Compressor motor nameplate rating (bhp),
- Motor nameplate efficiency (or an estimate of efficiency),
- Annual hours of operation (hrs/year), and
- Cost of electricity ($/kWh).

Annual electricity costs can be calculated by inserting this information into the equation in the following text box:

Simple Calculation
(100 hp Compressor)

Annual Electricity Costs =
(Motor full-load brake horsepower) x (0.746 kW/hp) x (1/0.9) x (Annual Hours of Operation) x (Electricity Cost in $/kWh)

For example:

- Motor full-load bhp = 100 hp
- Annual hours of operation = 8,760 hours (3-shift, continuous operation)
- Full Cost of electricity = $0.05/kWh

Annual electricity costs =
(100 hp) x (0.746 kW/hp) x (8,760 hours) x ($0.05/kWh)/0.9
= $36,305

This equation assumes the electric motor driving the compressor is 90% efficient (the 90 in the 1/0.9 factor) -- a reasonable estimate for a modern system larger than 50 hp. Newer energy-efficient motors may have even higher efficiencies, especially since the Energy Policy Act minimum motor efficiency levels went into effect in late 1997. If the system uses an older motor that has been rewound several times, or has a smaller motor, 80% efficiency (or the motor nameplate efficiency rating) should be used. For a more accurate assessment, add the horsepower ratings for the parasitic loads from any auxiliary motors to the compressor motor rating.

It should be noted that the common practice in the industry is to apply motors having a 15% continuous service factor and to use about two-thirds of this service factor. This means that a motor having a nominal nameplate rating of 100 hp may, in fact, be loaded to 110 bhp at compressor full capacity and pressure. This may not be expressed in the manufacturer=s sales literature, however, so engineering data sheets for the specific air compressor should be consulted. If the motor is running into the service factor, the higher horsepower estimate should be used instead of the nameplate horsepower rating.

A Calculation with Measurements. A more accurate way to determine electricity consumption and costs involves taking electrical measurements of both full-load amps and volts. Motor full-load bhp and efficiency are not required for this calculation, although full-load power factor, which can be obtained from motor manufacturers, is. The calculation takes full-load amps, converts to full-load kW, and then multiplies by hours of operation and electricity costs. A calculation is shown in the next text box.

More Detailed Calculation (100-hp Compressor with 30 Power)

Annual Electricity Costs =
[(Full-load amps)x(volts)x(1.732)x(power factor)]/1000
(Annual Hours of Operation) x (Electricity Cost in $/kWh)

For example:

C Full-load amps = 115 amps
C Voltage=460 volts
C Full-load power factor = 0.85
C Annual hours of operation = 8,760 hours (3-shift, continuous operation)
C Cost of electricity = $0.05/kWh
• Correction factor for 30 power= 1.732

Annual electricity costs =
((115 amps) x (460 volts) x (1.732) x (0.85) / 1000) x
(8,760 hours) x ($0.05/kWh)
= $34,111

Part-load Operation. If the compressed air system operates below full-load at times, and has a good control system, electricity costs will be less than if the compressor ran at full-load during all hours of operation. Estimate the percentage of time the compressor is running at full-load, and add the percentage as another multiplier in the equation shown previously. Repeat the calculation for the percentage of time the compressor is running unloaded (or at part-load) and include a factor to compensate for the reduced load on the motor (0.20 to 0.30 is a good estimate for unloaded operation for rotary screw compressors and 0.10 to 0.15 for reciprocating compressors -- 0.30 is used in the equation in the next text box). Add the two results for total energy costs.

For a more accurate calculation of energy costs for compressors running at part-load, create a number of "tiers" with the percentage of time running at different percentages of load. Manufacturers' data on energy consumption for the different percentages of load will be needed.

The following text box shows an example calculation taking into account unloaded operation.

Calculation with Part-Load Operation (100-hp Compressor)

Annual Electricity Costs =
[(Motor full-load brake horsepower) x (0.746 kW/hp) x (Annual Hours of Operation) x (Electricity Cost in $/kWh)] x [(Percent of time running fully loaded) + (0.30) x (Percent of time running unloaded)]

For example:

- Full load motor efficiency = 90%
- Motor full-load bhp = 100 hp
- Annual hours of operation = 8,760 hours (3-shift, continuous operation)
- Runs 65% of the time fully loaded, 35% of the time unloaded
- Unloaded operation consumes 30 percent of the electricity of fully loaded operation
- Cost of electricity = $0.05/kWh

Annual electricity costs =
[(100 hp) x (0.746 hp/kW) x (8,760 hours) x ($0.05/kWh) /0.9] x [0.65 + (0.30) x (0.35)]
= $27,410

Remember, the calculations shown will only provide a good estimate of energy consumption, not an exact number.

Energy and Demand Charges -- Understanding Your Electricity Bill

The calculations shown previously use electricity rates stated in terms of dollars per kilowatt-hour ($/kWh). Electric utilities bill industrial customers using more complicated rate structures that typically include both energy ($/kWh) and demand charges ($/kW), and have different rates depending on the level of consumption or seasons. Demand charges are based on the peak demand for a given month or season and can have significant impacts on electricity costs for some customers. When the economic impacts of efficiency measures are calculated, the actual marginal cost of the electricity needs to be considered, taking into account energy and demand charges, seasonal rates, and different rates for different levels of consumption.

Pressure and Electricity Cost

High pressure air is more expensive to produce and deliver than low pressure air. For a system operating at around 100 psig, a rule of thumb is that every 2 psi in operating pressure requires an additional 1% in operating energy costs. In the system described in the first example shown, running the system at 110 psig instead of 100 psig would increase the energy costs by 5%, or $1,800 per year. See the Fact Sheet titled *Pressure Drop and Controlling System Pressure* for more information.

Savings From Performance Improvements

Due to the relatively low initial cost of the compressor when compared to lifetime electricity expenses, users should utilize life-cycle cost analysis when making decisions about compressed air systems. In addition, a highly efficient compressed air system is not merely a system with an energy-efficient motor or efficient compressor design. Overall system efficiency is the key to maximum cost savings. Too often users are only concerned with initial cost and accept the lowest bid on a compressed air system, ignoring system efficiency.

Thorough analysis and design will be required to obtain an efficient system. Many compressed air system users neglect these areas, thinking they are saving money, but end up spending much more in energy and maintenance costs.

Following the steps outlined in the Sourcebook can lead to substantial energy savings for most compressed air systems. A system that has undergone numerous modifications and has only been maintained enough to keep it running can frequently achieve energy savings of 20-50% or more. For the 100-hp system described previously, this represents annual savings of $7,000-$18,000. Larger systems will have correspondingly greater energy savings.

Too many decisions regarding compressed air systems are made on a first-cost basis, or with an "if it ain't broke, don't fix it" attitude. To achieve optimum compressed air system economics, compressed air system users should select equipment based on life-cycle economics, properly size components, turn off unneeded compressors, use appropriate control and storage strategies, and operate and maintain the equipment for peak performance.

Heat Recovery with Compressed Air Systems

Office of Industrial Technologies

Compressed Air Systems Fact Sheet #10

As much as 80-93% of the electrical energy used by an industrial air compressor is converted into heat. In many cases, a properly designed heat recovery unit can recover anywhere from 50-90% of this available thermal energy and put it to useful work heating air or water.

Typical uses for recovered heat include supplemental space heating, industrial process heating, water heating, makeup air heating, and boiler makeup water preheating. Recoverable heat from a compressed air system is not, however, normally hot enough to be used to produce steam directly.

Heat recovery systems are available for both air- and water-cooled compressors.

Heat Recovery with Air-Cooled Rotary Screw Compressors

Heating Air. Air-cooled packaged rotary screw compressors are very amenable to heat recovery for space heating or other hot air uses. Ambient atmospheric air is heated by passing it across the system's aftercooler and lubricant cooler, where it extracts heat from both the compressed air and the lubricant that is used to lubricate and cool the compressor.

Since packaged compressors are typically enclosed in cabinets and already include heat exchangers and fans, the only system modifications needed are the addition of ducting and another fan to handle the duct loading and to eliminate any back pressure on the compressor cooling fan. These heat recovery systems can be modulated with a simple thermostatically-controlled hinged vent. When heating is not required -- such as in the summer months -- the hot air can be ducted outside the building. The vent can also be thermostatically regulated to provide a constant temperature for a heated area.

Hot air can be used for space heating, industrial drying, preheating aspirated air for oil burners, or any other application requiring warm air. As a rule of thumb, approximately 50,000 Btu/hour of energy is available for each 100 cfm of capacity (at full-load). Air temperatures of 30 to 40°F above the cooling air inlet temperature can be obtained. Recovery efficiencies of 80-90% are common.

Caution should be applied because if the supply air for the compressor is not from outside, and the recovered heat is used in another space, you can decrease the static pressure in the cabinet and reduce the efficiency of the compressor. If outside air is used, some return air may be required to avoid damaging the compressor with below freezing air.

Heating Water. Using a heat exchanger, it is also possible to extract waste heat from the lubricant coolers found in packaged water-cooled reciprocating or rotary screw compressors and produce hot water. Depending on design, heat exchangers can produce non-potable (gray) or potable water. When hot water is not required, the lubricant is routed to the standard lubricant cooler.

Hot water can be used in central heating or boiler systems, industrial cleaning processes, plating operations, heat pumps, laundries, or any other application where hot water is required. Heat exchangers also offer an opportunity to produce hot air and hot water, and allow the operator some ability to vary the hot air/hot water ratio.

Heat Recovery with Water-Cooled Compressors

Heat recovery for space heating is not as common with water-cooled compressors because an extra stage of heat exchange is required and the temperature of the available heat is lower. Since many water-cooled compressors are quite large, however, heat recovery for space heating can be an attractive opportunity. Recovery efficiencies of 50-60% are typical.

Calculating Energy Savings

When calculating energy savings and payback periods for heat recovery units, it is important to compare heat recovery with the current source of energy for generating thermal energy, which may be a low-price fossil fuel such as natural gas. The equations in the text box below illustrate the annual energy and costs savings available by recovering heat for space heating from an air-cooled rotary screw compressor.

Energy Savings Calculations

Energy Savings (Btu/yr) = 0.80 x Compressor bhp x 2,545 Btu/bhp-hour x hours of operation

Example: A 100 hp compressor running two shifts, 5 days per week
(0.80) x (100 bhp) x (2,545 Btu/bhp-hour) x (4,160 hours per year) =
846,976,000 Btu per year

where: 0.80 is the recoverable heat as a percentage of the unit's output
2,545 is a conversion factor

Cost Savings ($/yr) = ((Energy Savings in Btu/yr)/(Btu/unit of fuel) x ($/unit fuel))/ Primary Heater Efficiency

Example: Waste heat will be displacing heat produced by a natural gas forced-air system with an efficiency of 85%
((846,976,000 Btu per year)/(100,000 Btu/therm)x($0.40/therm))/0.85 =
$3,986 per year

* Cost of operating an additional fan for duct loading has not been included

Proven Opportunities at the Component Level

Compressed Air Systems Fact Sheet #11

In some cases, taking a systems approach to analyzing compressed air systems can facilitate the analysis of an individual component as well as performance issues relating to individual system components. In general, compressed air systems contain five major subsystems: (1) compressors; (2) prime mover; (3) controls; (4) air treatment equipment and other accessories; and (5) the air distribution subsystem. Performance aspects of each of these subsystems are discussed in detail below.

Compressors

While there are many different types of compressors, all compressor types theoretically operate more efficiently if they are designed to include multiple stages. With multiple stages, the final discharge pressure is generated over several steps, thereby saving energy. Many multi-stage compressors save energy by cooling the air between stages, reducing the volume and work required to compress the air. In spite of this, many industrial compressors only have a single stage because equipment manufacturing costs are lower. Performance and efficiency issues of the three most common types of compressors -- single- and double-acting reciprocating compressors, rotary positive-displacement compressors, and centrifugal compressors -- are discussed below.

Single- and Double-Acting Reciprocating Compressors. In the past, reciprocating air compressors were the most widely used compressors in industrial plant air systems. Single-acting reciprocating compressors are generally air-cooled, in the smaller hp sizes, and do not require substantial foundations. However, these compressors are less efficient than other types. Double-acting reciprocating air compressors are generally water-cooled and require substantial foundations. Multi-stage versions are usually considered to be the most efficient air compressors but have high initial and installation costs and higher maintenance requirements.

Rotary Positive-Displacement Compressors. Today, lubricant-injected rotary screw compressors are used in most industrial plant air applications and for large applications in the service industries. They have some advantages over reciprocating compressors, including lower initial installation and maintenance costs; smaller size; reduced vibration and noise; reduced floor space requirements; and the ability to be installed on a level industrial plant floor. Rotary screw compressors provide continuous flow and do not have the type of pressure pulsations typically associated with reciprocating compressors. Two-stage rotary-screw compressors are more efficient than single-stage units. Lubricant-injected rotary screw compressors are typically less efficient than two-stage double-acting reciprocating compressors or three-stage centrifugal compressors. In general, rotary screw compressors are also less efficient at part-load than reciprocating compressors.

A wide range of models is usually available from different manufacturers for any given application. Users should try to select the most efficient model available (see the Fact Sheet titled *Packaged Compressor Efficiency Ratings).*

Centrifugal Compressors. The use of centrifugal compressors is usually limited to high-volume industrial plant applications, such as chemical manufacturing, textile plants, petroleum refining, or general plant air systems in large manufacturing facilities. The compressors operate at high speeds and therefore use smaller, more compact equipment. Three-stage centrifugal compressors are generally more efficient than rotary screw compressors and can approach the efficiency levels of double-acting reciprocating compressors. Centrifugal air compressors are available for 100 psig discharge pressure from 100-hp, but most are 300-hp or larger, with an increasing number of stages and improving efficiency as size increases. Centrifugal compressors are best suited to applications where demand is relatively constant or in industrial plants where they can be used primarily for base-load operation, allowing other compressor types to be as used as trim machines to meet peak demands.

Lubricant-Free Compressors. Lubricant-free versions of reciprocating and rotary air compressors are available. Centrifugal air compressors are inherently lubricant-free. Lubricant-free compressors may be appropriate for specific applications or to meet specific environmental regulations. Lubricant-free rotary screw and reciprocating compressors are generally less efficient than lubricant-injected machines.

Prime Movers

The majority of industrial compressed air systems use electric motors as the prime mover. Standard, three-phase squirrel-cage induction motors are used in 90% of all industrial compressor applications due to their reliability, level of efficiency (85-95%, depending on size), and excellent starting torque, and despite their high inrush current requirements. Inrush current is the amount of current that is required to start the motor and motor-driven equipment. Most major manufacturers of industrial packaged compressed air systems now offer both standard and energy-efficient motors. As of October 24, 1997, standard three-phase induction motors between 1 and 200 hp are required to meet minimum federal efficiency levels. This means that all general-purpose motors are at the efficiency levels of those formerly labeled "high efficiency" or "energy-efficient." Even with these new minimum efficiency levels, there is a range of efficiencies available for any given application, and manufacturers will likely offer lines of premium-efficiency motors that have higher efficiencies than standard-efficiency motors.

Motors can be flange mounted, connected with a v-belt, or direct coupled. Proper alignment is critical for all applications. Direct coupling results in the least loss of efficiency, while v-belt applications may allow for more compact packaging. V-belts should always be inspected and tensioned per manufacturer's specification to avoid increased power transmission losses.

Due to the heavy duty and load cycles on most compressors, it almost always makes sense to buy the most efficient motor available. The incremental cost for a more efficient motor is typically paid back in less than one year from the resulting energy savings. Users should be aware that new energy-efficient motors sometimes have lower available starting torque than standard motors and often have slightly higher operating speeds because of reduced slip. Match operating speeds as closely as possible when replacing a motor.

Controls

Compressor control mechanisms are used to match the compressed air volume and pressure delivered by the compressor with facility demand. Compressor controls are often the most important factor determining a compressor's ability to perform at part-load efficiently. Controls are frequently configured poorly, and proper control strategies can lead to substantial reductions in energy consumption.

For more information on controls and compressed air system performance, see the Fact Sheet titled *Compressed Air System Controls*.

Air Treatment Equipment and Other Accessories

Air treatment equipment must provide for both contaminant removal and preparation of the air for equipment use. The level of air conditioning and accessories needed is often dependent on air quality requirements. For optimum performance, air treatment equipment should be operated as close to manufacturers' design conditions as possible. A discussion of important compressor system accessory equipment and performance follows.

Dryers. Compressed air system performance is typically enhanced by the use of dryers, but since they require added capital and operating costs (including energy), drying should only be performed to the degree that it is needed for the proper functioning of the equipment and the end-use.

Single tower chemical deliquescent dryers use little energy, but provide pressure dewpoint suppression of 15 to 50EF below the dryer inlet temperature, depending on the desiccant selected. They are not suitable for some systems that have high drying needs.

Refrigerant-type dryers are the most common and provide a pressure dewpoint of 35 to 39EF, which is acceptable for many applications. In addition to the pressure drop across the dryer (usually 3-5 psid), the energy to run the refrigerant compressor must be considered. Some refrigerant-type dryers have the ability to cycle on and off based on air flow, which may save energy.

Twin tower desiccant-type dryers are the most effective in the removal of moisture from the air and typically are rated at a pressure dewpoint of -40EF. The purge air requirement can range from 10 to 18% of the total air flow, depending on the type of dryer. This energy loss, in addition to the pressure drop across the dryer, must be considered. The heated-type requires less purge air for regeneration, as heaters are used to heat the desiccant bed or the purge air. The heater energy must also be considered against the reduction in the amount of purge air, in addition to the pressure drop. Heat-of-compression dryers may be used where the lubricant-free compressor discharge temperature is sufficiently high to achieve regeneration of the desiccant. There is no reduction of air capacity with this type of dryer since hot, unsaturated air from the compressor discharge is used for regeneration, then cooled and some of the moisture is removed as condensate before passing through the drying section. Vacuum-assisted regeneration is typically the most efficient, with unheated purge air flow the least efficient.

Compressed Air Filters. These include particulate filters to remove solid particles, coalescing filters to remove lubricant and moisture, and adsorbent filters for very fine contaminants. 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, and at least annually, to minimize pressure drop and energy consumption.

Air Receiver. Air receivers are designed to provide a supply buffer to meet short-term demand spikes which can exceed the compressor capacity. They also serve to dampen compressor pulsations, separate out particles and liquids, and make the compressed air system easier to control. Installing a larger receiver tank to meet occasional peak demands can even allow for the use of a smaller compressor.

In most systems, the receiver will be located just after the dryer. In some cases, it makes sense to use multiple receivers, one prior to the dryer and one closer to points of intermittent use.

Storage can be used to control demand events (peak demand periods) in the system by controlling both the amount of pressure drop and the rate of decay. Storage can be used to protect critical pressure applications from other events in the system. Storage can also be used to control the rate of pressure drop in demand while supporting the speed of transmission response from supply. Many systems have a compressor operating in modulation to support demand events, and sometimes, strategic storage solutions can allow for this compressor to be turned off. Storage can also help systems ride through a compressor failure or short energy outages.

Condensate/Lubricant Separators. It is no longer acceptable to discharge condensate from a compressed air system to sewer lines without treatment to remove contaminants such as entrained lubricants (except for condensate from some lubricant-free compressor systems). Condensate/lubricant separators are available in the marketplace to achieve separation by means of settling tanks and/or permeable membranes. This equipment helps to avoid the potentially high costs of contaminated waste disposal, although some lubricants are water soluble and biodegradable and can be disposed of in the sewer system (check local regulations).

Air/Lubricant Separators. The air/lubricant separator in a lubricant-cooled rotary screw compressor generally starts with a 2-3 psid pressure drop at full-load when new. Maintenance manuals usually suggest changing them when there is a 10-12 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.

Heat Recovery Systems. Most systems do not employ heat recovery, even though economics can be good, with typical paybacks of less than one year. Heat recovery systems require electricity for fans or pumps, but can decrease the need for fossil fuels usually used for heating. See the Fact Sheet titled *Heat Recovery with Compressed Air Systems* for more information on this energy saving opportunity.

The Air Distribution Subsystem.

The air distribution subsystem, which connects the major components, is one of the most important parts of the compressed air system. It is made up of main trunk lines, hoses and valves, drops to specific usage points, pressure regulators and lubricators, additional filters and traps, and supplementary air treatment equipment. It is throughout this subsystem that most leaks occur, energy is lost, and maintenance required. Equipment should be chosen to avoid excessive pressure drops and leakage. In addition, consideration of appropriate sizing of equipment and layout will provide for proper air supply, good tool performance, and optimal production. The complete drying, filtration, and distribution system should be sized and arranged so that the total pressure drop from the air compressor to the points of use is much less than 10% of the compressor discharge pressure.

Some users leave automatic condensate traps partially open at all times to allow for constant draining. This practice wastes substantial energy and should never be undertaken. If a float-operated automatic condensate drain is not functioning properly, clean and repair it instead of leaving it open. If maintenance of float-operated drain traps is a burden, consider replacing them with more reliable demand-type drain traps.

The efficiency of the entire system can be enhanced by the proper selection, application, installation, and maintenance of each component.