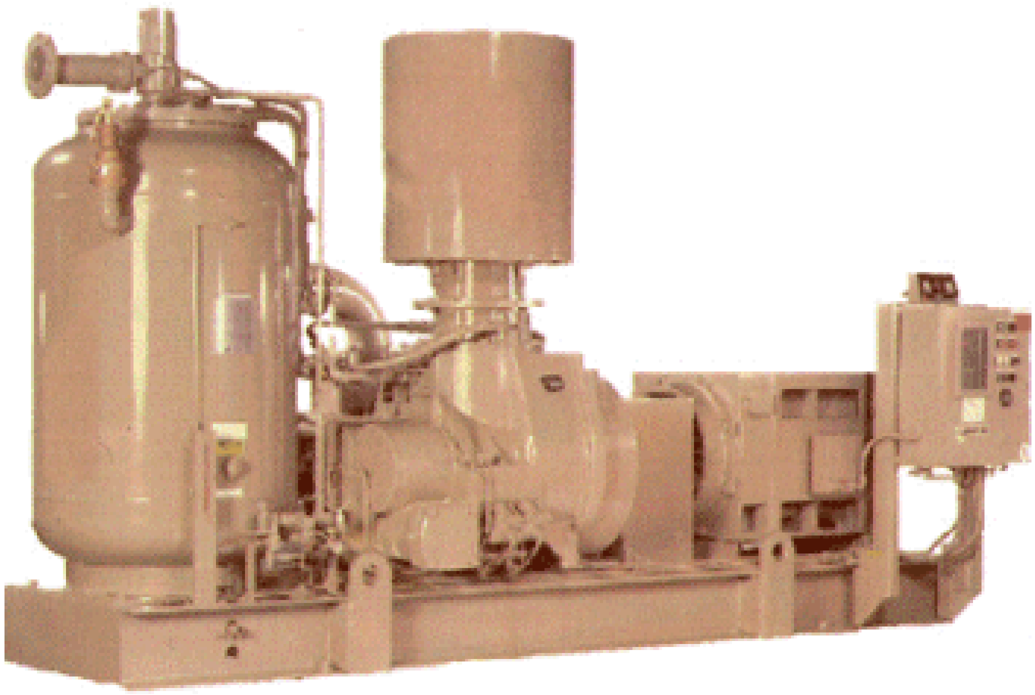
# Assessing Industrial Air Compressors



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## Preface

Compressing air is quite inefficient, losing as much as 90% of compressor work to heat during the process. However, most industries require compressed air. The aim of this guide is to provide an introduction to air compressor technology, as well as offer some guidelines for improving system efficiencies.

This guide focuses mainly on screw and reciprocating compressors. These are the most common types of compressors used in the northwest. Other types of compressors such as rotary vane, centrifugal, lobe and radial compressors are much less common and are only introduced in this guide.

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ASSESSING INDUSTRIAL COMPRESSED AIR SYSTEMS

This guide is broken into the following seven sub-sections:

## 1. TECHNOLOGY PRIMER

A concise overview of compressed air equipment, systems and performance. Review this section before going to the plant as a reminder of what to look for and why.

## 2. WALKTHROUGH CHECKLIST

A checklist to use during the initial plant visit to identify potential compressed air system efficiency improvements. Only the most common of these are developed in the recommendations section; (Section 5).

## 3. COLLECTING DATA

Assessment Data and Tools: Specific data needed to analyze system improvements are described in this section along with how it is gathered. Included in this section are sample data sheets to use in collecting the needed information.

## 4. DATA SHEETS

Assessment Data collection sheets.

## 5. ANALYSIS TOOLS & METHODS

Common equations and relationships used to analyze the performance of compressed air systems are presented in this section.

## 6. RECOMMENDATIONS

This section includes five common compressor related energy-savings recommendations. Each recommendation identifies data to collect, and presents a methodology for estimating savings.

## 7. TECHNOLOGY APPENDIX

Additional information on compressors, savings opportunities and analysis tools are presented in the appendix.

## 1. Technology Primer

The goal of this section is to familiarize you with the equipment and terms you will usually encounter in compressed air systems. The section is divided into three sub-sections:

### Definitions

### Compressed Air Equipment

How to identify key components of industrial compressed air systems and associated equipment.

### Compressor Performance Relationships

This section provides performance relationships for the different types of system controls. Performance profiles are included which graphically show the relationship between airflow and power.

## Definitions

| Term | Meaning |
|---|---|
| ACFM | Actual airflow delivered after compressor losses |
| ACFM-FAD | Airflow before filter (Free Air Delivery) |
| CFM | Cubic Feet per Minute of airflow |
| ICFM | Airflow at inlet flange |
| Modulation Control | Method of reducing airflow to match part load requirements, includes throttle, turn, spiral, or poppet valve. |
| Psi | Pressure in pounds per square inch |
| Psig | Psi gauge, referenced to atmospheric pressure |
| Psia | Psi absolute, which is 14.7 psi at sea level |
| SCFM | Equivalent airflow at Standard Conditions (2 different standards, CAGI and ASME, use this same term ) |
| Standard Conditions | |
| CAGI (Compressed Air & Gas Institute): | 14.7 psia, 60°F, 0% rh (relative humidity) |
| ASME: | 14.7 psia, 68°F, 36% rh |
| Unloading and Unload Point | Pressure at which compressor unloads |

## Compressed Air Equipment

To evaluate compressed air systems it is important to be able to identify the type of equipment in use, and understand generally how that equipment works. The following section presents common equipment you are likely to encounter in a compressed air system along with important details.

### Compressors

Reciprocating and Screw compressors are the most common types of air compressors. Other types of compressors are described in the appendix. Air compressors usually require ancillary equipment to dry the air, remove oil and to buffer pressure fluctuations.

### Reciprocating compressors

Reciprocating compressors, use pistons to compress air in cylinders. Their operation is similar to automotive engines. Small reciprocating compressors use a single action compression stroke, while larger ones use double acting pistons. Double acting pistons compress air on both the up and the down stroke. Reciprocating compressors offer good efficiencies over a wide range of operating conditions and are quite efficient for low-pressure applications. However, reciprocating compressors require more maintenance than screw compressors. In the northwest reciprocating compressors are less common than screw compressors. A more complete description and illustration of a reciprocating compressor is given in the appendix.

### Screw compressors

Screw compressors are the most prevalent types of compressor in the northwest. Screw compressors use two mated screws. These turn, forcing air between them. As air progresses through the screws the volume of the gap between the screws decreases, thereby compressing the air. A diagram of a screw compressor is shown in the appendix.

### Air Dryer

Air dryers are included in most compressed air systems. Many industrial applications require air with low moisture content. For example, pneumatic controls typically require dry air. In colder climates moisture-laden air can lead to ice which blocks or breaks the lines. High moisture content can also lead to corrosion in any compressed air system. Drying requirements and the volume of the air required dictate the type and size of air dryer required. Typical air dryers either use refrigeration or desiccant to remove moisture from the air.

- **Aftercoolers** provide initial cooling of hot compressed air from over 150 F. Water cooling can be more effective by using cooling tower water near the wet bulb temperature. Air from the compressor room is often warmer than outside air. Aftercoolers condense some water vapor in the compressed air, but usually not adequately for air tools or pneumatic controls. Consider uses for the waste heat. Avoid city water cooling flowing down the drain.

- **Refrigerated Air Dryers** are able to drop the dew point (the temperature at which the air becomes completely saturated and moisture in the air begins to liquefy) of compressed air to 35-50 $^{o}$F. Often these are all that is required and are typically the most economical means of drying air. Refrigerated air dryers work by cooling the compressed air with a refrigeration system. Moisture condenses out of the cooled air and is captured at the dryer. Operating costs are roughly $5.00 to $8.00 per million cubic feet of air. This is associated with 130 kWh per million cubic feet of air.

- **Desiccant Air Dryers** can reach a lower dew point than refrigerated dryers; down to –150$^{o}$ F. Desiccant air dryers consist of two desiccant beds through which the compressed air flows. A control system channels all of the air through one bed while the other is regenerated. The regeneration process varies among desiccant dryers and has a large impact on operating costs. All systems blow dry compressed air across the desiccant bed to regenerate it and then purge the air and moisture to the atmosphere. Some models heat the dried air first to increase its capacity to absorb moisture. Heated types have better efficiencies because the energy required to heat the air to 300$^{o}$ F is less than the energy required to compress and dry the additional air that would otherwise be necessary to dry the bed. Heated air dryers require only about 1-7% of the total compressed air to purge the desiccant bed, while non-heated dryers require 15% or more. Desiccant dryers are more expensive to purchase, maintain and operate than refrigerated air dryers, but to achieve low dew points these are often the only option. Operating costs range from $15 to $30 per million cubic feet of compressed air. This is associated with 300 to 500 kWh per million cubic feet of air. This cost includes the energy used by the dryer, but it does not include the cost of the compressed air used to regenerate the dryer. The extra compressed air required can be a huge cost.

- **Membrane Dryers** are relatively new to the market place. They use a semi-permeable membrane that allows dry air to pass through while holding back the water vapor. These dryers are easy to maintain and achieve dew points as low as 35$^{o}$ F, however, they cause a 9-10% drop in system capacity as much compressed air is lost along with the water vapor in the membrane system. The operating costs for this type of air-drying are minimal, as the membranes need to be replaced infrequently.

## Receiver Tank

Compressors with unloading or on-off controls require a receiver tank to store a volume of compressed air for later use. Receiver tanks should be large enough to limit the amount of compressor cycling to a minimum. A common rule-of-thumb is a gallon of receiver space per SCFM of output, however, like in Texas, bigger is better since it lengthens the compressor on-off cycles.

## Oil Separator

In screw compressors the two screws that mesh to compress air would wear quickly without oil. The oiling procedure employed by many screw compressors introduces oil into the compressed air. Oil separators remove this oil after the compression process. An oil separator is essentially a coalescing filter mated with a metal baffle. A coalescing filter traps microscopic oil particles in its consumable elements. As air moves through the filter the entrained oil coalesces and drops out. Any oil remaining in the air would shorten tool life so it pays to keep the separator working. A poorly maintained oil separator often introduces an excessive pressure drop into the compressed air system. The pressure drop should not be more than 5 psi across the separator. When the pressure drop is greater than 5 psi maintenance is required.

## Air Reheater

Some air compressors are equipped with an air reheater to heat the air after it is dried. The heated air expands, increasing the pressure and reducing the work the compressor has to do to achieve a given pressure. The degree of the heating and the effectiveness of this system varies from one situation to another. A reheater does not help if heat is lost in the distribution system, which is why the strategy is not used or recommended often.

## Compressor Performance Relationships

Following is an introduction to the relationships between *power* and *airflow*. This relationship is central to all the calculations used in analyzing potential savings.

- **Power (%P)** refers to compressor power expressed as a percentage of full load power (FLP). For example, if a compressor's full load power is 100 kW and at a particular load the compressor uses 74 kW then its percent power for that load is 74% (74/100).

- **Airflow (%C)** refers to air delivered by the compressor expressed as a percent of capacity. For example if a compressor's capacity is 200 acfm and at a particular load it delivers 120 acfm its percent capacity is 60% (120/200).

Power and airflow can be compared to create a compressor performance curve. The relationship between power and airflow depends on the strategy used for matching compressor output with the load. The following section presents power and airflow relationships for different control strategies.

**Information on each type of control includes:**

- A brief explanation of the control strategy.
- Equations relating power (%P) and airflow (%C).
- Advantages and disadvantages.
- Compressor performance charts showing the relationship between power and airflow.

## 1. Throttle Control

Compressor Type: Screw

### Operation:

Throttle control works by using a slide or butterfly valve to create a partial vacuum at the compressor inlet. The partial vacuum limits the air mass that enters the compression chamber, lowering the amount of air that is compressed.

### Power and airflow relationships:

Power: %P = (Full Load %P – No Load %P) x Load %C + No Load %P

= $(100\% - \%P_{nl}) \times \%C + \%P_{nl}$

Airflow: %C = (Load %P – No Load %P)/(Full Load %P - No Load %P)

= $((\%P - \%P_{nl})/(\%P_{fl} - \%P_{nl})) \times 100\%$

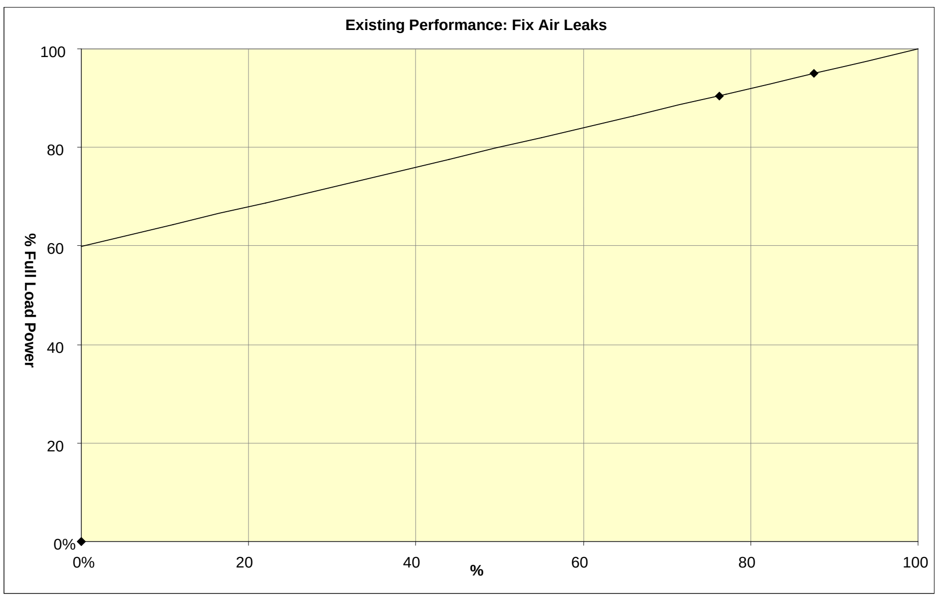
### Advantages:

- Constant Discharge Pressure
- Good high load efficiency

### Disadvantages:

- Poor Low Load Efficiency

**Operating Profile**




**Typical No Load Power Consumption:** 60-72% of Full Load Power

## 2. Turn Valve or Poppet Valve Control

**Compressor Type:** Screw

**Operation:**

Turn Valve controls vary the amount of air that is compressed by varying the effective length of the compression chamber. A threaded shaft rotates to open ports in the compressor housing. Air compression cannot begin in rotor sectors with open ports. This changes the chamber length experienced by the air and changes the volumetric compression ratio.

Poppet valves work similarly to turn valves. Instead of a rotating valve, a series of valves, similar to automotive engine valves, at discrete positions along the length of the screws allows the air to exit without further compression.

In both cases, the valves are operated to match compressor output with plant air demand.

**Power and airflow relationships:**

Power: %P = (Full Load %P – No Load %P) x Load $\%C^2$ + No Load %P

= $(100\% - \%P_{nl}) \times \%C^2 + \%P_{nl}$

Airflow: %C = ((Load %P - No Load %P)/( Full Load %P – No Load %P))½

$$= \left(\sqrt{\frac{\%P - \%P_{nl}}{100\% - \%P_{nl}}}\right) x 100\%$$

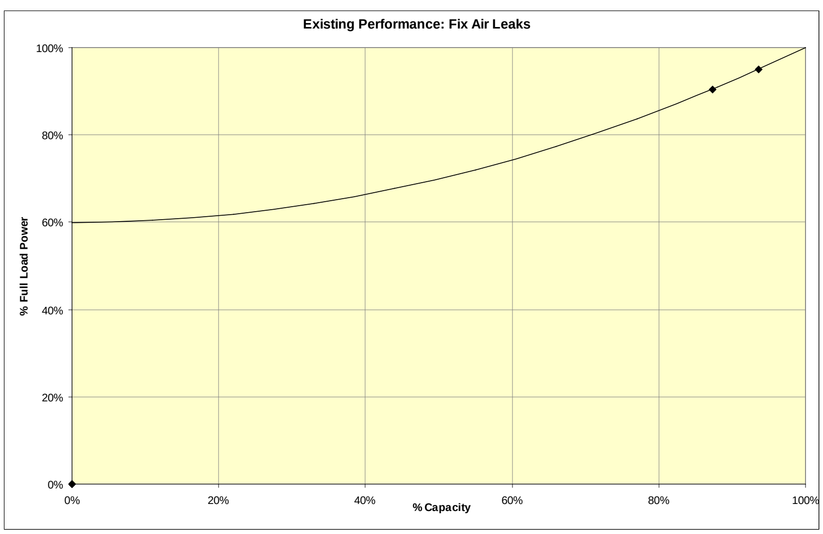
**Advantages:**

- Good High Load Efficiency
- Low receiver capacity requirement
- Constant Discharge Pressure

**Disadvantages:**

- Poor Low Load Efficiency

**Operating Profile**




**Power Consumption:** 55-60% of Full Load Power

## 3. On-Off Control

**Compressor Type:** Screw, Reciprocating

**Operation:**
On-Off controls turn the compressor on and off as needed. The compressor works at full load until it reaches maximum pressure, then turns off. Starting and stopping larger compressors can be hard on both the compressor and the motor, and therefore is more common on smaller compressors. On-Off controls can also be coupled with other modulation strategies to reduce or eliminate energy use at low or no air demand.

**Power and Airflow relationships:**

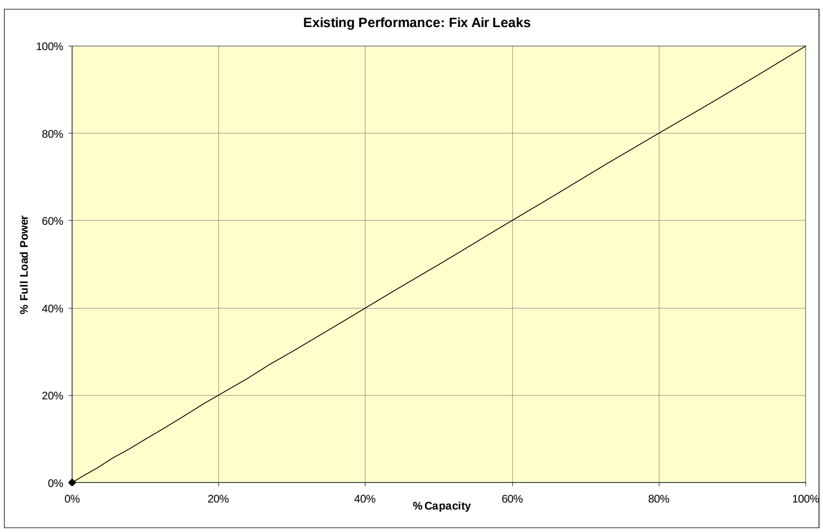
Power = Airflow

%P = %C

**Advantages:**
- Maximum efficiency at all loads

**Disadvantages:**
- High receiver capacity requirement

**Mechanical Wear on Start up**




Usually on small (<20 hp) compressors

**Typical No Load Power Consumption:** 0% of Full Load Power

## 4. Unloading Controls

A compressor will typically be modulated by one of the above controls, however, unloading controls may be added to a compressor to increase part load efficiencies. Unloading controls allow the compressor to spend unloaded time at reduced power. There are two types of unloading strategies, Load-Unload and Low-Unload.

### A. Load-Unload Control

**Compressor Type:** Screw, Reciprocating

**Operation:**

Load-Unload controls operate in a manner similar to On-Off controls. Instead of turning off, the compressor unloads. When the compressor reaches maximum pressure a solenoid valve opens, reducing the discharge to atmospheric or at least lower pressure. The compressor then with lower pressure difference from the intake to the discharge side. A check valve prevents backflow of air at system pressure. The compressor uses less energy while unloaded.

**Power and airflow relationships:**

Power:%P = (Full Load %P – No Load %P) x Load %C + No Load %P

= (100% - $\%P_{nl}$) x %C + $\%P_{nl}$

Airflow: %C = ((Load %P - No Load %P)/( Full Load %P – No Load %P))

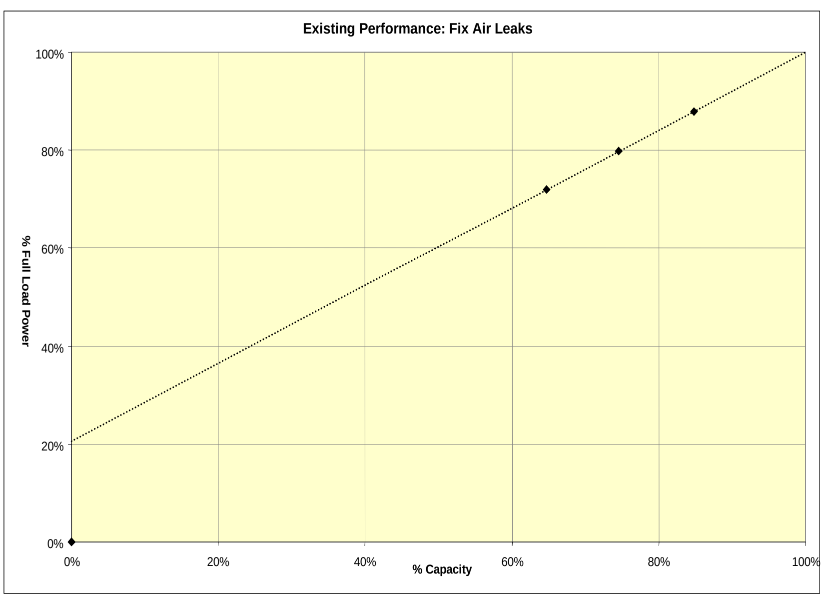
= (( %P - $\%P_{nl}$/)(100% - $\%P_{nl}$)) x 100%

**Advantages:**

- Good Efficiency at all Loads

**Disadvantages:**

- High receiver capacity requirement
- Small air loss during unloading




**Typical No Load Power Consumption:** 20% of Full Load Power

## B. Low – Unload Control

**Compressor Type:** Screw

### Operation:

Low-Unload controls are a combination of load-unload and modulation controls. They modulate the compressor at higher loads and unload the compressor at lower loads. Low-Unload controls have a set unload point above which the compressor modulates and below which the compressor unloads.

### Power and capacity relationships:

Above the Unload Point

The modulating power and airflow formulas depend on the type of control the compressor employs. (See earlier descriptions.)

Below the Unload Point

Power: %P = (Unloading %P – No Load %P) x Load %C + No Load %P

= $(\%P_{ul} - \%P_{nl}) \times \%C + \%P_{nl}$

Airflow: %C = ((Load %P - No Load %P)/(Full Load %P – No Load %P))

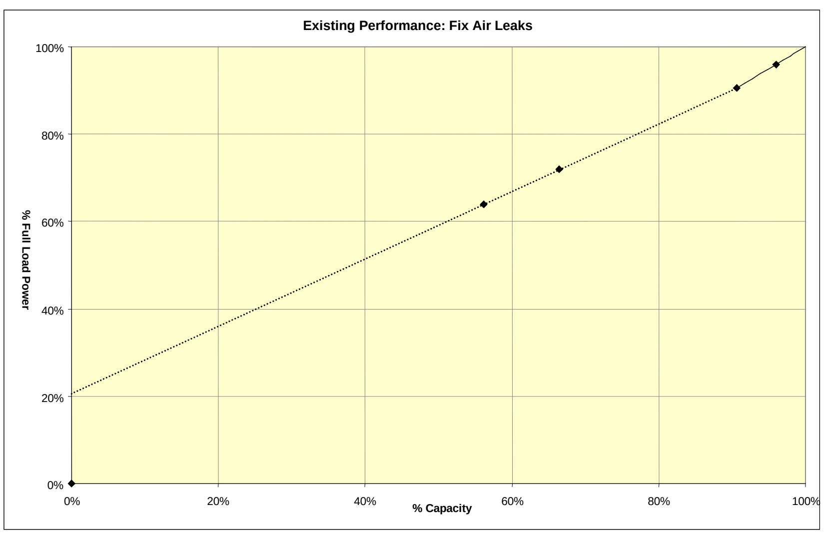
= $(\%P - \%P_{nl})/(\%P_{ul} - \%P_{nl}) \times 100\%$

### Advantages:

- Good High Load Efficiency
- Efficient for a variety of operating loads
- Requires less receiver capacity & pressure range for reasonable operation

### Disadvantages:

- Not as efficient as load unload
- Small air loss during unloading




**Typical No Load Power Consumption:** 20% of Full Load Power

## 2. Walkthrough Checklist

This section provides a checklist of things to look for while at the plant. It provides an overview of the major compressor savings opportunities. It is designed to help assure that major savings opportunities are addressed, and to help identify areas on which to focus a more detailed analysis.

During a site evaluation, it is important to record gauge readings on air compressors, other equipment, and at other locations where it can be obtained throughout the plant. Many air compressors include airflow and pressure gauges, while other equipment often includes pressure gauges, making it possible to measure pressure drop across the oil separator and dryer. Look for high pressure drops through equipment and lines. Look for intentional pressure reductions, such as with valves and pressure regulators. More detailed aids for recording and analyzing compressor data are provided in later chapters.

See Reference & Data Collection sections for more detail on opportunities identified.

### Major Savings Opportunities

ρ **Large compressor serving minimal system needs in off hours (e.g. fire suppression system).**

- Install small dedicated air compressor to serve minimal after hour needs such as a fire suppression system and isolate from main plant air system.

  *It is common to leave a large compressor on continuously – 7 days a week – to serve a small use such as a dry fire suppression system. The compressor may operate for long periods at an extremely inefficient part load condition. System leaks also consume air and energy continually. It is generally cost effective to install a separate dedicated compressor for such a need and separate it from the main compressed air system to avoid losing air and energy to system leaks during nonproduction times.*

ρ **Multiple compressors operating at part load.**

When more than one compressor is operating, all but one should operate at full capacity and maximum efficiency. A final trim compressor can match output to system requirements. In the best case, the “trim” compressor can have more sophisticated controls for greater efficiency at part load operation.

- Manually sequence multiple compressors

  *Set existing controls to load compressors sequentially so that unneeded compressors can be turned off manually or automatically. The downside of this option is the increase in pressure variations unless electronic controls are installed.*

- Install automatic compressor sequencing controls

  *Sequence compressors to avoid operating several compressors at part load. Fewer compressors will operate more efficiently at higher loads. The largest savings come from the sequencer turning unneeded compressors off.*

- **Throttle controlled screw compressor operating at partial capacity for large part of time.**

Generally: A throttle-controlled compressor should not operate below 70-80% capacity for much of the time. A throttle-controlled compressor consumes approximately 70% of its full load power when delivering no air and 85% power at half capacity.

- Install load-unload controls for more efficient air compressor operation.

  *Load unload control allows a compressor to operate either at full output and maximum efficiency or unloaded. Because the compressor does not turn off, the motor is not damaged. However, load-unload control requires larger receiver capacity and a significant variation in system pressure to create an acceptable cycle time.. An unloaded screw compressor with the discharge pressure reduced to near atmosphere consumes approximately 17% to 26% of the energy required for the compressor to operate at full capacity. When the compressor discharge pressure drops to an intermediate pressures, such as 40-50 psig, there are fewer savings.*

  *This recommendation does not work everywhere because;*

  - Some processes are too sensitive to allow the variation in pressure required.
  - The load/unload cycle can make maintenance personnel uncomfortable. It is often set to unload at low load causing the compressor to operate at inefficient part loads. Potential savings are lost.
  - A small amount of compressed air is released to atmosphere when the compressor unloads. If the compressor cycles too often this air loss can be significant.

- Install low-unload controls for more efficient air compressor operation.

  *Low-unload control is a variation on load-unload. Throttle control is used to vary compressor airflow down to a set level. Below this point the compressor unloads. The air compressor can operate efficiently with throttle control during peak production with higher airflows and lower pressure variation. Then the control system can save energy by unloading during periods of lower air use. When discharging at atmospheric pressure, the unloaded compressor will consume approximately 17% to 26% of full power. If the unload point is set low; the compressor may be no more efficient than a standard throttle controlled compressor.*

- Install ASD and controls for efficient part load air compressor operation

  *ASDs control airflow with little pressure variation. ASDs are expensive. This is also a rather new and less accepted application of ASDs. Electronic or low/unload controls are nearly as efficient and more reliable than ASDs for air compressors.*

- Install On-off control on air compressor for operation on demand

  *On-off control allows a compressor to operate only full output and maximum efficiency and then turn off. However, on-off control requires larger receiver capacity and a significant variation in system pressure. Because the constant on-off cycle can damage larger motors, on-off control is not usually used in an industrial setting except as a secondary control on a compressor that may operate at low to zero capacity for an extended period of time.*

*Warning:  In an industrial setting, this is often not a viable option because:*

- Some processes are too sensitive to allow the variation in pressure required for on-off control.
- Frequent on-off cycle can damage large motors.
- Short cycling will reduce the life of the air compressor.
- On-off control may not be an option with many compressors

ρ **Compressor operating at no load for extended time.**

- Manually shut off air compressor

  *If an air compressor is left on over the weekend or through the night, it can be turned off manually.  This measure is only as reliable as the operator(s).*

- Install automatic shut-off timers on air compressor

  *Shut-off timers can be set to de-energize a compressor if it operates unloaded for a set period of time greater than 15 minutes. This works well if air is needed for short periods such as during night clean-up. The compressor will shut off at the end of the production shift and only start again when needed.*

ρ **System running at a higher pressure than required.**

If compressors are operating in a range higher than 90 psi, ask why. Common end uses frequently require no more than 80 psi. It is also common to operate from 100 to 110 psi to overcome line losses. It is possible to have greater end use requirements but verify them. Even 90 to 110 psi can be higher than required to ensure adequate air delivery to the end use.

It takes more power to compress air to a higher pressure.  Higher system pressures also cause unregulated air uses to use more air. (Any end use that does not include a regulator to keep air pressure from exceeding that required is an unregulated air use.

System air leaks are an unregulated use common to all compressed air systems).  The power required to compress air increases by about 0.5% for each PSI increase in system pressure.

- Reduce pressure delivered by air compressor to the minimum required by the system

  *Determine required end use pressures on equipment, group by requirements. This will help establish the actual pressure required.*

- Install closed looped piping system

  *A looped piping system balances pressure throughout the plant. End uses are served from both directions, with line losses at different points balancing out in the two paths. With a balanced system compressor discharge pressures can often be reduced.*

- Install larger pipes

  *Larger pipes reduce pressure losses by reducing air velocity, and provide additional surge capacity to reduce pressure fluctuations. Both effects help improve air delivery and system efficiency.*

- Install receivers

  *System pressure may be higher than necessary to ensure that pressure doesn't fall below a minimum acceptable level during short periods of high air use, such as a sand blaster starting. A surge may be met by air stored in a receiver, allowing system pressure to be reduced.*

ρ **Is system pressure held high when the required pressure is reduced?**

- Reductions are often possible during slow shifts and or evenings.

  *Reduce pressure at night or during slow shifts with less air use either manually or automatically. Beyond the issues relating to airflow, this also must address equipment requirements.*

ρ **Can any compressed air end uses be served otherwise?**

Compressed air is often chosen for its convenience; safety in explosive situations; and comparative high energy density for hand held tools, robotics, or other equipment. Unfortunately it also is a much less efficient method to get work done. Verify that compressed air is actually the best method to accomplish a given end use.

- Switch end use device to another energy source. For example, replace an air motor with an electric or hydraulic motor, or replace a venturi-type vacuum generator with a vacuum pump.

ρ **Low-Unload controls unload only at low airflow.**

A low-unload controlled screw compressor is no more efficient than a standard throttle controlled compressor until it unloads. Unfortunately they are often set to unload at low flows, sometimes as low as 40% of capacity. They only unload during breaks or off hours. During production potential savings are lost.

- Adjust/repair air compressor controls to allow unloading earlier in the cycle.

ρ **Pressure reducer in compressed air line.**

Sometimes when an end use needs a significantly lower air pressure than delivered by the air system, a pressure reducer will be installed. Power required to compress to higher pressure is wasted. Look for pressure regulators on the entire system and major uses. While it is undesirable to reduce air pressure significantly (20 psi or more) it is often good practice to include a pressure regulator before end uses to keep airflow from fluctuating with pressure variations and exceeding that required.

ρ **Low pressure air use served with compressed air.**

Compressed air may be used for inappropriate applications such as part drying or aeration when a low pressure blower or fan would serve as well. Power is wasted to compress air to higher pressures than needed. These end uses should be met with lower pressure air source (blower, fan, lower pressure air system).

ρ **Air leaks.**
Some leaks are easy to find because of their location, sound, and air volume. Some "leaks" are intentional; such as an open compressed air line directed at a hot bearing.

- Leaks are indicated when a compressor is delivering air when no use is active

*Most specific leaks are difficult to pinpoint and quantify. Leaks are easiest to find when the plant is quiet, not in operation. Common leak locations include: valve packing, pneumatic cylinders, hoses, quick release hose fittings for hand equipment, hand equipment itself).*

- To quantify total air leaks in a plant record compressor power and/or airflow during breaks or other times when there is no air use. Air leaks exceeding 35% of the air used are excessive in any plant (plant load can be determined by subtracting leak load found during the break from the compressor load during plant operation.)

Estimating cost of air leaks @ 100 psig (assumes 5 cfm per kW, $0.05 per kWh, and 8,760 annual hrs).

| OPENING DIA. | 1/64" | 1/32" | 1/16" | 1/8" | 1/4" | 1/2" |
|---|---|---|---|---|---|---|
| Air Loss | 1/2 cfm | 1-1/2 cfm | 6-1/2 cfm | 26 cfm | 104 cfm | 415 cfm |
| Annual kWh | 876 kWh | 2,630 kWh | 11,390 kWh | 45,550 kWh | 182,210 kWh | 727,080 kWh |
| Annual cost | $45 | $130 | $570 | $2,280 | $9,110 | $36,350 |

Air loss calculated from

$$\text{Cfm} = \sqrt{k \cdot R \cdot T} \cdot A \cdot \frac{\rho_{atm.}}{\rho_{compressed}} \cdot C$$

Where

R = Gas constant for air

T = Temperature of air

K = Compressibility of air

A = Hole area

ρ = Density of air at given conditions

C = Orifice Coefficient

- Repair air leaks

  *In the best cases, reducing air leaks can allow compressors to be shut off. If the leak reduction does not allow one compressor to be shut off, consider a control strategy for efficient part load operation to realize significant savings.*

ρ **Desiccant air dryer.**

Desiccant air dryers can produce very dry air, however they use more energy than refrigerated dryers. Evaluate whether the increased drying capacity is necessary. Desiccant air dryers without heaters purge the most air and waste the most energy. From 10% to 15% of total air produced by the air compressor can be purged in regenerating a desiccant dryer that does not have a heater. Dryer dewpoints: refrigerated - +35°F to +38°F, desiccant - 40°F.

- Replace desiccant air dryer with refrigerated air dryer
- Install capacity controlled regenerative dryer

  *If drier air is required, control the desiccant recharge cycle to stop when the humidity drops to a set level. Savings will depend on air use.*

- Install internally heated desiccant air dryer

  *If drier air is required, internally heated desiccant dryers only require 3-5% of the total airflow for purging moisture.*

- Isolate moisture sensitive equipment (such as pneumatic controls).

  *Some equipment, including pneumatic controls, can be particularly sensitive to moisture. However it is unnecessary to dry all plant air to the level required by a minority of the equipment. If the sensitive equipment is grouped on one branch of the compressed air circuit, a desiccant dryer can serve that line only and drying costs can be greatly reduced.*

ρ **Compressor cooling water flowing down drain.**

- Use compressor cooling water to replace warm water for other uses, such as cleaning or boiler makeup water. This strategy can save on both energy and water costs. Oil contamination of the cooling water can be a problem. Although more costly, a preferred option may be to install a heat exchanger to transfer heat from the cooling water to the boiler make up water.

ρ **High pressure drop across equipment such as dryers, oil separators, or filters.**

Some compressors or equipment display pressure drop across these devices. Pressure drop should not exceed 5 psig for oil separator and dryer, and 0.5 -1 for the filter.

- Replace filters, overhaul equipment to reduce pressure drop

  *Clogged filters and fouled lines increase air velocity and pressure drop.*

- Size equipment to accommodate airflow with acceptable pressure drop.

  *Equipment such as a refrigerated dryer causes excessive pressure drop when airflow exceeds design.*

ρ **Are compressed air end uses designed for maximum efficiency?**

- Install engineered nozzles

  *Nozzles used for blowing off parts or equipment and other uses are frequently site built. Commercially available engineered nozzles can offer better efficiency and performance.*

ρ **Is the air compressor maintained on a regular schedule?**

- Maintain modulating controls
- Modulating controls on screw compressors can fail over time. The result is a compressor that never operates at full load or unloads properly, reducing both efficiency and airflow.
- Lubricate compressor

  *Proper lubrication and oil changes extend compressor life and improve efficiency.*

- Clean or replace intake filter

  *A clogged intake filter reduces compressor performance and efficiency.*

ρ **Rotary Vane Compressors.**

These types of compressors are rare. When they are present however, venting excess air to atmosphere commonly controls airflow on rotary vane compressors. In such cases there is no reduction in power with reduced airflow.

- Replace rotary vane compressors with more efficient compressors.

ρ **General Design Opportunities.**

- Reduce piping and distribution system losses

  *When system pressure losses are reduced, compressor discharge pressures can be set lower while still delivering minimum required pressure to end uses. See recommendations under high system pressures.*

- Install pressure reducing valves before air consuming equipment and reduce to lowest pressure required

  *It would be best to meet lower pressure end uses requirements with equipment delivering air at lower pressure. However if system pressure is to be maintained above an end use's maximum required pressure, pressure reducers will keep fixed orifice uses from consuming more air than required.*

- Install air leak test device

  *One reason air leaks are so prevalent in industrial facilities is that maintenance personnel do not realize their cost. An air leak test device coupled with a regular testing procedure allows personnel to confirm the size and cost of leaks and the return on efforts to correct them.*

## 3. Collecting Data

This step of an assessment is performed at the plant. After familiarizing yourself with the equipment and terms involved with compressed air systems, examine plant equipment and identify the type of compressed air system. Data can then be collected for each specific piece of equipment.

This section includes data collection tools and methods for gathering standard system data.

### Data Collection Tools

- **Digital Multimeter (DMM):** Power used by an electric motor can be directly measured or calculated from voltage and amperage. Use a DMM to measure the voltage at the motor starter or control panel. Measure line-to-line or line-to-ground voltages depending on probe placement. Use caution and understand important safety precautions when measuring high voltage.
- **Clamp-on Ammeter:** Amperage is needed to calculate power. A clamp-on ammeter senses line current by measuring the current induced in the ammeter by the magnetic field produced by the current. Use the clamp-on ammeter to measure the current in all three phases for power calculations. It is important to measure amperage at as many operating conditions as possible to allow accurate modeling of equipment operation.
- **Power Analyzer:** A power analyzer measures and stores power use over time. A 3 phase-power analyzer, for example, has three clamp-on ammeters, three voltage probes, a neutral probe, and a ground probe. Connecting these to the motor leads allows the power analyzer to measure all line-to-line voltages, line-to-ground voltages, all line currents, phase shifts, and to calculate power. Read the instructions carefully to connect leads correctly for the type of power system (delta (Δ) or wye (Y))
- **Pressure Gauge:** Many air compressors include a pressure gauge on the control panel. For compressors that do not have a gauge use a pressure gauge that fits in to quick disconnect fittings to measure system pressure at several places.
- **Capacity Gauge:** Many compressors include a capacity gauge that displays the airflow, usually in acfm, that is being delivered. Record the acfm at as many operating loads as possible to accurately model the operation of the compressor. The gauge may be a vacuum gauge that measures air density at a throttled inlet, or be connected to an airflow meter.
- **Stopwatch:** Useful to measure on/off & load-unload cycles for use factor calculation.
- **Rag:** Useful to wipe off dirty nameplates.
- **Flashlight:** Compressors are often located in dark catacombs of the plants. Their location makes reading gauges and nameplates difficult.
- **Tape Measure:** For pipe, receiver, or duct dimensions.

## Standard Air Compressor Data

The data sheets found in this section include spaces for all data to be collected during a compressed air assessment. This section is a guide for completing these sheets, including nameplate data and key operating conditions.

**Nameplate Information:**

Nameplate data is important when contacting manufacturers to obtain specifications and operating characteristics of specific equipment.

### Compressor Nameplate Data

- Manufacturer
- Model
- Type (Screw or Reciprocating)
- Serial Number
- Rated Pressure

### Motor Nameplate Data

- Manufacturer
- Model Number
- Horse Power
- Full Load Amps
- Volts
- RPM
- Type (Standard, Efficient, Variable Speed, etc.)
- Is a capacitor dedicated to the motor
- Efficiency
- pf

**Operating Data:**

### Compressor Operating Data

To effectively model compressed air system operation, you must collect data for each operating condition. You will need to develop an operating profile for each compressor that includes the number of hours the compressor operates at each load. To calculate energy use at each distinct load you must record either airflow for each load or power in kilowatts.

**Performance Points**

Performance points are specific operating conditions that are important for modeling compressor performance. They include:

- No Load Power: The compressor is valved off from the plant, working at 0% capacity
- Full Load Power: The compressor working at full load (100% capacity). Frequently this is observed as the compressor works to restore the system when it is reconnected to the plant after being valved off to observe no load power.
- Unloading Point: (Only for low-unloading compressors) When the compressor unloads. Note: If it is not possible to valve off the plant you must estimate the no load. This estimate will depend on the type of compressor controls (Throttle, Turn or Poppet Valves).

## Operating Points

Operating points are loads on a compressor that depend on plant air requirements. Identical data is required for operating points as for performance points. (This is power which if not measured directly, can be calculated from voltage and current.) An operating point is a load associated with a unique plant operation. Examples are production shift, swing shift, or plant clean up. Use simple descriptions to relate operating points to plant loads. Note the annual plant operating hours and description for each compressor load. You will model the compressors annual energy from the duration and power used at each point you identify. It may be necessary to select average conditions to represent each operating condition.

### Data required at each Performance and Operating Point

- **Power:** Use either a power analyzer or calculate power from clamp-on ammeter and voltmeter measurements*.*

- **Pressure:** Read pressure gauge on the compressor, receiver, dryer, or attached to a quick release fitting.

- **Airflow (%C):** Many compressors have a capacity gauge that displays airflow as a percentage of power. This can also be calculated from airflow measurements.

- **Operating Hours:** Obtain from plant personnel an operating schedule or get their help in estimating operating hours. These should represent the amount of time the compressor spends at each operating point.

- **Line Plumbing :** Air lines will either be plumbed in a loop or linearly. It is important to be able to calculate the volume in the piping from measurements of length and diameter. It is preferable to have airlines looped, as line pressure drop is equalized around the plant.

- **Receiver Capacity:** Receiver capacity must be sufficiently large for unloading compressors to avoid cycling on and off too often.

- **Line Diameter*:*** Line diameter should be as large as economically feasible to minimize pressure drop from frictional losses in the line. Larger lines also create additional “receiver” capacity.

- **End Use Pressure/ Intentional Pressure Reductions:** Devices or designs implemented to intentionally reduce pressure should be kept to an absolute minimum. The greatest efficiency is obtained when the system pressure does not exceed the minimum required.

## **4. Data Sheets**

Three data sheets are included to be used in collecting compressor information. Each data sheet provides a form on which to record nameplate information and data that is observed or measured under various operating conditions such as dayshift, maintenance, and summer operation.   If all the data is not available, make reasonable approximations.

# AIR COMPRESSOR DATA

Audit #: ____________ Date: ____________ Name: ____________

## NAMEPLATE INFORMATION

| COMPRESSOR | | MOTOR | | | |
|---|---|---|---|---|---|
| Manufacturer: | ____________ | Manufacturer: | ____________ | Volts: | ____________ |
| Model: | ____________ | Model: | ____________ | FL Amps | ____________ |
| Type: | ____________ | Horsepower: | ____________ | RPM: | ____________ |
| Serial Number: | ____________ | Type: | ____________ | Effeciency: | ____________ |
| Rated Pressure: | | | | | |

## CONTROLS

| | | |
|---|---|---|
| Circle One → | Modulating | Unloading Controls |
| Circle All That Apply | Throttle | Load-Unload |
| | Turn Valve | Low-Unload |
| | Poppet Valve | On-Off |

## PERFORMANCE POINTS

| | Measured Volts | Measured Amps | Pressure psi | % Capacity | Power kW |
|---|---|---|---|---|---|
| Unloaded | | | | 0% | |
| Fully Modulated | | | | 0% | |
| Unloading Point | | | | | |
| Full Load | | | | 100% | |

## DISCHARGE PRESSURE (psig)

Full Load Pressure ($P_{min}$) ____________ Pressure Range ($P_{min}$ to $P_{max}$) ____________

Notes:

# MEASURED LOAD DATA

Audit #: ____________ Date: ____________ Name: ____________

**Single Modulating Compressor**

| Operating Loads | Measured (Volts) | Measured (Amps) | Pressure (psi) | % Capacity | Power (kW) | Use Factor (UF%) |
|---|---|---|---|---|---|---|
| | | | | | | |
| | | | | | | |
| | | | | | | |
| Leak Load | | | | | | |

**Single Unloading Compressor**

| | Measured (Volts) | Measured (Amps) | Pressure (psi) | % Capacity | Power (kW) | Operating Hours |
|---|---|---|---|---|---|---|
| Loaded | | | | | | |
| Unloaded | | | | | | |

| Operating Loads | Load Clock Time | Unload Clock Time | Loaded Time | Unloaded Time | Duty Cycle | Operating Hours |
|---|---|---|---|---|---|---|
| | | | | | | |
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Notes:

AIR COMPRESSOR SAVINGS WORKSHEET

| Existing Operating Conditions | | | | | |
|---|---|---|---|---|---|
| **Load Points** | Power (% FL) | Demand (kW) | Annual Hours | Energy (kWh) | Airflow (%Capacity) |
| Unloaded | | | | | |
| Fully Modulated | | | | | |
| Unloading | | | | | |
| Full Load | | | | | |
| **Operating Points** | Power (% FL) | Demand (kW) | Annual Hours | Energy (kWh) | Airflow (%Capacity) |
| Leak Load | | | | | |
| Plant Load | | | | | |
| | | | | | |
| | | | | | |

| Proposed Operating Conditions | | | | | |
|---|---|---|---|---|---|
| **Load Points** | Power (% FL) | Demand (kW) | Annual Hours | Energy (kWh) | Airflow (%Capacity) |
| Unloaded | | | | | |
| Fully Modulated | | | | | |
| Unloading | | | | | |
| Full Load | | | | | |
| **Operating Points** | Power (% FL) | Demand (kW) | **Annual Hours** | **Energy (kWh)** | Airflow (%Capacity) |
| Leak Load | | | | | |
| Plant Load | | | | | |
| | | | | | |
| | | | | | |

## 5. Analysis Tools & Methods

This section of the assessment guide presents analysis tools and methods that will be used later in the recommendation section. The recommendation section outlines data required, procedures, and ideas needed to analyze energy use in compressed air systems. Refer to equations in this chapter when directed by the recommendation section.

## Standard Analysis Methods

### Calculate Existing ENERGY USE PROFILE

Before analyzing potential recommendations you must be able to calculate compressor energy use under different operating conditions and control strategies.

**Data Required**

- All Standard Air Compressor Data

**Tools Required**

- Air Compressor Data worksheets
- Measured Operating Conditions worksheets
- Air Compressor Savings Worksheets

The Measured Operating Conditions and the Air Compressor Savings Worksheets, found in the Data Collection Tools section, provide a convenient way to record data required to calculate energy use. Calculating energy use requires an understanding of the relationship between power and airflow for different control strategies. These relationships are outlined in the Technology Primer section as well as in the Appendix.

Use this section as a guide to using these relationships to calculate air compressor energy use.

Enter measured data into the Measured Operating Conditions Worksheet. The subsequent energy calculation procedure depends on whether you entered airflow (%C) or power (kw). Examples of how to calculate energy use are provided for each case. Apply this method to each operating condition you have identified.

### Calculating Existing Energy Use (using measured power (kw)):

Data Entry. Enter annual hours and power into the Existing Conditions table of the Air Compressor Savings Worksheet. Divide the compressor power of the selected operating condition by the power at full load. Calculate energy use by multiplying power by annual hours of operation for each operating condition.

Calculate Percent Power from Power:

1. Percent Power = Operating Point Power / Full Load Power

$$\%P = P_{OL} / P_{FL}$$

2. Calculate Energy from Operating Point Power

Energy = Power x Annual Operating Hours

$$E = P_{OL} \times OH$$

**Energy Calculations (using measured power (kw)):**

3. Calculate Airflow

The relationship between airflow and power depends on control strategy. Conversion formulas for typical controls follow (More information can be found in the **Error! Not a valid link.** section.):

Throttle:

$$\%C = (\text{Load }\%P - \text{No Load }\%P)/(\text{Full Load }\%P - \text{No Load }\%P)$$

$$= \frac{(\%P - \%P_{nl})}{100\% - \%P_{nl}} \times 100$$

---

Turn /Poppet Valve:

$$\%C = ((\text{Load }\%P - \text{No Load }\%P)/(\text{Full Load }\%P - \text{No Load }\%P))^{1/2}$$

$$\%C = \left(\sqrt{\frac{\%P - \%P_{nl}}{100\% - \%P_{nl}}}\right) x100\%$$

---

On-Off:

$$\%C = \%P$$

---

Load-Unload:

$$\%C = (\text{Load }\%P - \text{No Load }\%P)/(\text{Full Load }\%P - \text{No Load }\%P)$$

$$= ((\%P - \%P_{nl})/(100\% - \%P_{nl})) \times 100\%$$

---

Low-Unload:

*Below the Unload Point:*

$$\%C = ((\text{Load }\%P - \text{No Load }\%P)/(\text{Full Load }\%P - \text{No Load }\%P))$$

$$= (\%P - \%P_{nl})/(\%P_{ul} - \%P_{nl}) \times 100\%$$

*Above the Unload Point:*

Airflow depends on the type of compressor control. (See *Section* **Error! Not a valid link.**.*)*

**<u>Calculating Energy Use (using recorded or estimated Airflow (%C)):</u>**

*Enter Measured Data. Enter annual hours and airflow (%C) into the Existing Conditions table of the Air Compressor Savings Worksheet.*

1. Calculate Power from Airflow:

This calculation depends on the control strategy of the compressor. Conversion formulas for typical controls follow.

---

Throttle:

$$\%P = (100\% - \%P_{nl}) \times \%C + \%P_{nl}$$

---

Turn/Poppet Valve:

$$\%P = (100\% - \%P_{nl}) \times (\%C/100)^2 + \%P_{nl}$$

---

On-Off:

$$\%P = \%C$$

---

Load Unload:

$$\%P = (100\% - \%P_{nl}) \times \%C + \%P_{nl}$$

---

Low Unload:

*Below the Unload point:*

$$\%P = (\%P_{ul} - \%P_{nl}) \times \%C + \%P_{nl}$$

*Above the Unload Point:*

Power formulas depend on the type of control. (See *Section* **Error! Not a valid link.**.)

2. Calculate Power

Power = Percent Power x Full Load Power

$$P = \%P \times P_{FL}$$

3. Calculate Energy from Power

Energy = Power x Annual Operating Hours

$$E = P \times OH$$

Repeat these calculations for all operating conditions of plant

**Calculate Savings:**

Estimate savings by calculating the difference between existing and proposed conditions for power and energy. Demand savings are the difference between existing and proposed power for the largest power use period, which usually will occur during peak production; usually during a weekday day shift.

## 6. Recommendations

This section contains methods for estimating savings from efficiency improvements. Overview this section at the plant to determine which recommendation are feasible and what data is required to accurately calculate savings.

## RECOMMENDATION No. 1 - Reduce Air Leaks

**Summary:** Reduce the amount of compressed air lost to leaks.

**When to Apply:** Generally, reducing leaks to the following percentages of plant load is possible:

- 30% high power, dirty environments, ex. Sawmills
- 20% medium power environments, ex. Plastic manufacturing
- 10% light power, clean environments, ex. Electronics

If leak load is smaller than this the action will be more difficult to justify economically. On air compressors that only operate part time, the payback periods are longer.

**Key Engineering Concepts:**

- Reducing airflow saves some energy.
- Turning off a compressor provides more significant savings.
- Avoiding the purchase of a new compressor saves both capital and energy expenses.
- Although it is not direct, compressor energy use is related to the amount of air compressed.

**Preparation:**

- Data Required
  - All Standard Air Compressor Data, including leak load. (See Section 3. **Error! Not a valid link.**.)
- Tools Required
  - DMM or Ammeter or Power Analyzer
  - Air Compressor Data worksheets
  - Measured Operating Conditions worksheets
  - Air Compressor Savings Worksheets
  -

**Analysis Process:**

1. **Enter Existing Operating Conditions on Worksheets.**

   See Section 5. Analysis Tools & Methods.

2. **Calculate Peak Plant Load.**

   The Peak Plant Load is the peak production airflow minus air leaks.

- Plant Load = Peak Production Load - Leak Load
- $\%C_P = \%C_{OL} - \%C_L$

3. **Calculate Existing Leak Load as a percentage of the Peak Plant Load.**

   The Leak Load Percentage relates the air lost to leaks to air used by the plant.

- Leak Load % = Leak Load / Plant Load
- $LL_E\% = (\%C_L / \%C_P) \times 100\%$

## 4. Enter Proposed Leak Percentage ($LL_p$%).

A typical proposed leak load is 30% of plant load for a relatively leaky system, 20% is fairly average, and 10% is a tight, clean system. If the current leak load is at or below 30% of plant load, this recommendation is not likely to offer significant savings.

Calculating Proposed Leak Load:

- Proposed Leak Load = Plant Load x Proposed Leak Load Percentage
- $\%C_{LP} = \%C_P \times LL_P\%$

## 5. Calculate Proposed Airflows for each operating load.

- Proposed Airflow = Existing Airflow – Existing Leak Load %C + Proposed Leak Load %C
- $\%C_{POL} = \%C_{OL} - \%C_L + \%C_{LP}$

## 6. Calculate proposed energy use for each operating condition

Calculate proposed energy use using proposed airflows. Also, see *Section 5. Analysis Tools & Methods.*

## 7. Complete the Air Compressor Savings Worksheets for reduced air leaks.

## 8. Estimate implementation cost and determine payback

Leaks typically arise from faulty fittings, lines, valves, and hoses. These leaks are generally easy to repair, with little or no material cost. If pneumatic rams or cylinders are leaking, they will have to be rebuilt or replaced. Rebuild kits and labor may cost several hundred dollars, depending on the size and location of the leak. Typically repairing leaks has payback less than one year.

# RECOMMENDATION No. 2 - Use Unload Controls

**Summary:** Use low-unload or load-unload controls with a modulating compressor to increase the part load efficiency.

**When to Apply:** Modulating compressors have poor part load efficiencies. Any time a modulating compressor operates at a part load there may be an opportunity for savings with unloading controls. This recommendation applies best to modulating compressors operating at part load for a significant percentage of time. Sometimes the unloading controls are already present, but are not being used.

### Key Engineering Concepts:

- Inlet and discharge pressures are reduced when a compressor unloads. Lower pressures result in lower power requirements, generally in the range of 20% of full load power when discharge pressure is reduced to atmospheric pressure.
- Unload controls allow an air compressor to unload when airflow drops or system pressure increases to a predetermined set point.
- Successful implementation may require adding receiver capacity. The air system must also allow pressure variations up to 10 psi typically.

### Preparation:

- Data Required
  - All Standard Air Compressor Data. (See Section 3. **Error! Not a valid link.**.)
  - Proposed Unload Point and existing Unloaded Operating Conditions.

### Analysis process:

#### 1. Calculate Air Compressor Energy Use for Existing Operating Conditions.

See *Section 5. Analysis Tools & Methods*.

#### 2. Determine a Proposed Unload Point.

Choosing an unload control strategy will determine the unloading point. Load-unload controls dictate a 100% Capacity Unload Point, while Low-Unload controls will have an unload point that is adjustable or set by the compressor manufacturer. The compressor manufacturer will quote both an Unloaded Power and a range for the Unload point. Use this information from the manufacturer or dealer to choose a proposed unload point and calculate proposed power for all operating conditions of interest.

#### 3. Calculate Proposed Power.

Airflow will not change for any loads when adding unload controls. Calculate power for typical plant operating points using the appropriate formula.

- If airflow < Unload Point (%C <%CUL):
- Power = (Unload Point %P – Unloaded %P) x Load %C + No Load %P
- %P = (%Pul - %Pnl) x %C +%Pnl

If airflow is above the Unload Point, calculate power with the appropriate formula for the appropriate type of modulating controls. Refer to *Section 5. Analysis Tools & Methods*.

## 4. Calculate Energy Use for Proposed Operating Conditions.

See *Section 5. Analysis Tools & Methods*.

## 5. Determine energy savings.

Use differences in proposed and existing Operating Conditions to calculate energy and dollar savings.

## 6. Estimate implementation cost and determine payback.

Costs for implementing this recommendation can include unloading controls, additional receiver capacity, and labor.

Prices for unloading controls vary from compressor to compressor. Contact the manufacturer for their prices. Estimate $1,500 for retrofit, $700 option for a new compressor.

Unload controls perform better if the system has adequate receiver capacity. The receiver must be large enough to allow the air compressor to stay unloaded for at least 2 minutes per cycle. To size system storage, a rule of thumb estimate is one gallon of storage for each CFM of peak airflow. Estimate $4/gallon of received capacity installed.

Alternately, you can get vendor quotes for receivers and estimate labor time and cost to install receivers. Many plants have maintenance crews that could install additional receivers. Generally, labor costs for outside contractors run $50 to $60 an hour with the installation requiring from 5 to 10 hours.

## RECOMMENDATION No. 3 - Reduce System Pressure

**Summary:** Power is required to compress air from atmospheric pressure to system pressure. A lower system pressure will require less power per cfm. Set compressors to the lowest possible pressure required by plant equipment, plus line losses between the air compressors and equipment.

**When to Apply:** This recommendation applies when system pressure is significantly greater than required by end-uses. There may be pressure-regulators on some equipment to limit pressure. If the pressure drop across regulators is significant, reduce system pressure. This may require segregating end uses by pressure requirements.

**Key Engineering Concepts:**

- Compressor power decreases approximately 1/2% for each psi reduction in discharge pressure.
- With reduced system pressure, air lost to regulated air uses is reduced by approximately ¾% per psi.
- The minimum pressure for oil separators is typically 80 psi but it varies from compressor to compressor.

**Preparation:**

- Data Required
  - All Standard Air Compressor Data. (See Section 3. **Error! Not a valid link.**.)
  - System Operating Pressure
  - Minimum required pressure
- Tools Required
  - DMM
  - Air Compressor data sheets

**Analysis process:**

**1. Calculate Air Compressor Power for Existing Operating Conditions**

See *Section 5. Analysis Tools & Methods.*

**2. Determine Proposed Full Load Power with reduced pressure.**

Full load motor power decreases by reducing pressure differential across the compressor.

Calculate proposed Full Load Power:

$$\text{Full Load Power} = \text{Existing Full Load Power} \times \left(\left(\frac{\ln\left(\frac{\text{Proposed Pressure}}{\text{Atmospheric Pressure}}\right)}{\ln\left(\frac{\text{Existing Pressure}}{\text{Atmospheric Pressure}}\right)}\right)\right)$$

$$FL_P = FL_E \times \left(\left(\frac{\ln\left(\frac{P_p}{P_{atm}}\right)}{\ln\left(\frac{P_E}{P_{atm}}\right)}\right)\right)$$

## 3. Calculate Reduction in Airflow

By reducing system there will be less airflow to most loads, including leaks.

Calculate Proposed Airflows:

Proposed Airflow = Existing Airflow x (Proposed Pressure + Atm. Pressure) / (Existing Pressure + Atm. Pressure)

$$\%C_p = \%C_E \times \left( \frac{P_P + P_{atm}}{P_E + P_{atm}} \right)$$

* This estimate will not be accurate if there are many regulated air uses.

## 4. Calculate Air Compressor Energy Use for Proposed Operating Conditions

See *Section 5. Analysis Tools & Methods*.

## 5. Determine energy savings

Use differences in proposed and existing Operating Conditions to calculate energy and dollar savings.

## 6. Estimate implementation cost and determine payback

Implementation for this recommendation is often negligible, as the only requirement is to adjust the pressure of the compressor. However, if excessive system losses require high pressure then the implementation cost will include correcting this situation.

## RECOMMENDATION No. 4 - Replace Air Dryer

**Summary:** Industrial processes require varying amounts and dryness of dried air. Several types of air dryers exist that dry air to varying dew points using different methods.

**When to Apply:** Dry air only to a minimum dew point required for plant operations. When the volume of air being dried or dryness is beyond what is required, there is an opportunity for savings.

**Key Engineering Concepts:**

Atmospheric air contains water vapor. When compressed air cools, this vapor condenses and causes problems with corrosion and air uses that are sensitive to water.

Drying air is an energy intensive process.

| Type | Dew Point Capability | Direct Energy Consumption | Bypass Air Required | Pressure Drop | Cost/$10^6$CFM |
|---|---|---|---|---|---|
| Refrigerated | 35-50°F | Refrigeration Compressor | None | ≈5 psi | ≈$5.00-8.00 |
| Capacity Controlled Unheated Desiccant | -150°F | None | 15% of Capacity | Negligible | ≈$30.00 |
| Moisture Controlled Unheated Desiccant | -150°F | None | <15% of Capacity | Negligible | ≈$30.00 |
| Capacity Controlled Heated Desiccant | -150°F | Heating Elements | 3-5% of Capacity | Negligible | ≈$15.00-25.00 |
| Moisture Controlled Heated Desiccant | -150°F | Heating Elements | <3-5% of Capacity | Negligible | ≈$15.00-25.00 |
| Membrane | 35°F | None | 9-10% of Capacity | 5-10 psi | ≈$30.00 |

- Data Required
  - All Standard Air Compressor Data. (See **Error! Not a valid link.**.)
  - Type of air dryer
  - Air Dryer Energy Use
  - The Required dew point for plant air
- Tools Required
  - DMM
  - Air Compressor data sheets

## Analysis process:

### 1. Estimate existing air dryer operating costs.

Air dryers are expensive to operate and maintain. Costs arise from a number of sources. Calculate the cost of each of the following:

**Direct Energy Requirements (DER)**

Refrigerated dryers use energy to cool the compressed air. Heated desiccant dryers use energy to heat the compressed air used to purge the desiccant beds. Calculate refrigeration and heating energy by measuring and recording volts and amps or power being used by the dryer.

**Pressure Drop (PD)**

Air Dryers introduce a pressure drop to the air system that costs an extra 1/2% power from the compressor for each psi of pressure drop. Refrigerated air dryers will induce a pressure drop of about 5 psi. Desiccant air dryers cause a negligible pressure drop. Membrane air dryers will have a pressure drop of about (I am still looking for this). If gauges are available, compare pressures before and after the air dryer to determine pressure drop.

**Air to Regenerate Desiccant Tanks (PA)**

Desiccant air dryers use dry air to regenerate the desiccant beds. Heated dryers heat the compressed air before passing it through the beds, while others pass unheated dry air through the beds. The added energy required to heat the air is more than offset by the amount of compressed air saved. The cost of compressed air used to regenerate desiccant beds can be calculated by estimating the airflow (acfm) required to regenerate, and referring to *Section 5. Analysis Tools & Methods*.

Purge frequency can be controlled by two means: capacity control (constant time interval); or moisture control.

Capacity control diverts a portion of the dried compressed airflow through the desiccant beds, usually for a fixed time interval. Then, the regenerated desiccant bed is switched on line while the other bed is regenerated.

The moisture (humidity) sensor initiates regeneration when a set level of moisture is reached in the desiccant bed, and can also terminate regeneration when the bed is dry. This type is generally more efficient as only the amount of dry air required is used. Estimate the regeneration airflow by observing the time that the desiccant beds are being regenerated and from manufacturer's specifications.

**Replacing Desiccants and Filters (CP)**

Desiccant dryers require periodic replacement of desiccant material. Depending on the quantity and frequency of replacement this cost can be substantial. Plant personnel might have records of how often the desiccant is replaced

**Maintenance Requirements (MR)**

Membrane type dryers claim to be virtually maintenance free. Refrigerated and desiccant dryers all have parts that can wear and will need maintenance. The plant personnel should be able to estimate maintenance requirements.

The total cost of drying air is the sum of the following costs:

- Direct Energy
- Pressure Drop
- Regeneration Air
- Consumable Parts
- Maintenance

## 2. Determine appropriate Dew Point.

In mild climates it is not often cold enough where airlines are exposed to outdoor temperatures to require dew points below about $35^{o}$-$50^{o}$ F. However, some locations and applications do require dryer air. Ask plant personnel about how dry the air needs to be. If they are drying the air much below $35^{o}$ F confirm that they really require air that dry. If there are only one or two pieces of equipment that require extremely dry air consider isolating those air uses (refer to **Error! Not a valid link.**).

## 3. Choose appropriate air dryer.

Use catalogs and distributors to select an appropriate air dryer. Estimate the operating costs for that dryer. Estimate the energy required by a new dryer from manufacturer's specifications. Available types of air dryers vary in cost and ability to dry air. Following is a brief guide to the operating costs and capabilities of various air drying methods.

Refrigerated Air Dryers are usually the best option for plants without extreme drying requirements. Refrigerated dryers are effective for drying air down to 35-$50^{o}$F.

Desiccant Air Dryers are required for dew points below $35^{o}$F. The most efficient desiccant air dryers include capacity controlled regeneration and a system to heat the dry air before regeneration.

Membrane Air Dryers are capable of reaching similar dewpoints to refrigerated dryers, however they cause a larger pressure drop through the membrane.

## 4. Determine energy savings.

Calculate differences in proposed and existing Operating Conditions to determine energy and dollar savings.

## 5. Estimate implementation cost and determine payback.

Implementation cost includes the air dryer and installation. Rough installed costs / 1000 SCFM are:

- Refrigerated air dryer - $10,000
- Heated Regenerative air dryer - $25,000
- Heater-less Regenerative air dryer - $12,500

## RECOMMENDATION No. 5 - Isolate Air Uses

**Summary:** Often plants have one large air compressor providing air to all applications. Isolating high pressure, high hour or particularly low moisture requirements from the main air system can save energy.

**When to Apply:** When one application dictates the pressure, drying requirement, and/or the operating hours for the compressed air system while all of the other uses could be met with lower pressure air, fewer operating hours, or less energy intensive air drying processing.

### Key Engineering Concepts:

Power and energy are proportional to the pressure difference. Stringent drying requirements are expensive to maintain.

### Preparation:

- Data Required
  - All Standard Air Compressor Data. (See Section 3. **Error! Not a valid link.**.)
  - Required Airflow, Pressure and Operating Hours of processes that can be isolated.
- Tools Required
  - DMM
  - Air Compressor data sheets

### Analysis process:

1. **Identify Processes that may be isolated from the main plant air system**

Any time there is a plant process that requires higher pressure air, dryer air, or more operating hours than the rest of the plant there is an opportunity to isolate that process. Examples are:

- Fire Suppression Systems

In dry fire suppression systems large plant air compressors are often employed to keep the pipes charged with compressed air. This requires that the compressors be left on all the time although fire systems generally require no airflow. During non-production periods the air compressors may only be supplying leaks. By isolating fire systems the large plant air compressor can be turned off during down time, while a small air compressor can maintain fire system pressure.

- Paint Booths

Painting applications generally require low pressures. If this pressure is significantly lower than that required for the rest of the plant, consider isolating the paint booth. Use one air compressor to fulfill the low-pressure requirements of the paint booth and another to fulfill the higher pressure demands of the rest of the plant is often a good idea.

- Dry air

Some material handling systems or painting applications require dryer air than the rest of the plant. Isolating these uses and only stringently dry the air that requires it.

Calculate the energy savings for the air system.

Savings result from reducing pressure, switching to less expensive air-drying, and reducing run time. If reducing pressures, refer to the Reduce Pressure recommendation guide. If changing air-drying requirements, refer to Replace air dryer recommendation guide. If reducing run time, use the calculations below.

Calculate Energy Savings from Reducing Run Time

- Energy Savings = Operating Power x Saved Hours
- ES = D x SH

### 3. Estimate the required airflow, pressure and operating hours of the isolated process.

### 4. Size an appropriate new compressor to meet the isolated loads.

Air compressor manufacturers publish specifications in both ACFM and pressure. To size a compressor, select one that meets the isolated load pressure and airflow requirements, or refer the requirements to a manufacturer or vendor. To be conservative in your savings estimates assume the compressor will operate at rated power, even though this will not always be the case. If the compressor is to be used to pressurize a dry fire suppression system, the compressor will only need to maintain minimum pressure in a fixed volume of pipes. With small or no leaks in the pipes, the compressor will use little or no energy. If the compressor is to be used to run a paint booth you will need to find out pressure and airflow requirements. Use this information to estimate compressor energy use.

Calculate Energy Use for a new compressor

- Energy Usage = Rated Power x Operating Hours x Use Factor x Load Factor
- E = P x OH x UF x LF

### 5. Determine energy savings

Calculate differences in proposed and existing Operating Conditions to determine energy and dollar savings.

### 6. Estimate implementation cost and determine payback.

The implementation cost includes purchase and installation of a new air compressor. Obtain these costs from a compressor manufacturer or dealer.

## 7. Technology Appendix

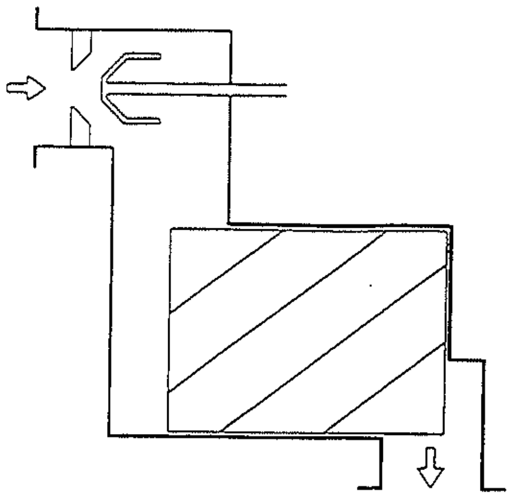
This section of the air compressor assessment guide will answer common questions that may have risen during previous reading. Many of the following topics are simply expansions of previous subject matter, but there are a few new topics introduced. The expanded subject matter was collected here to make the guide read more efficiently.

This appendix has been adapted from SCREW COMPRESSOR CONTROLS GUIDEBOOK written by John Maxwell, 1992.

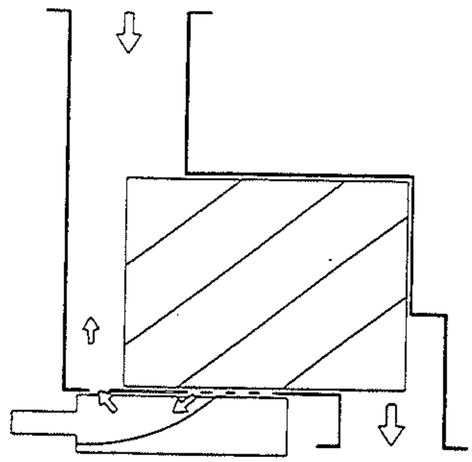
# APPENDIX A:   SCREW COMPRESSOR CONTROLS GUIDEBOOK

# Screw Air Compressor Controls:

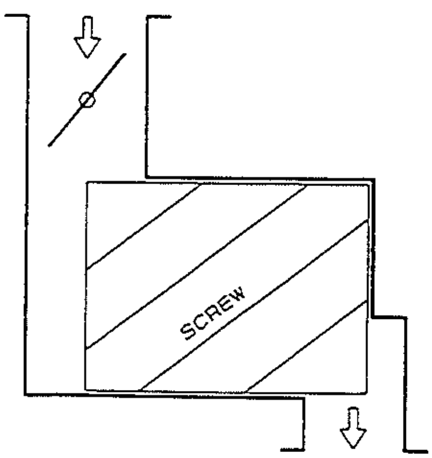
## Selection and Operation for Energy Efficiency



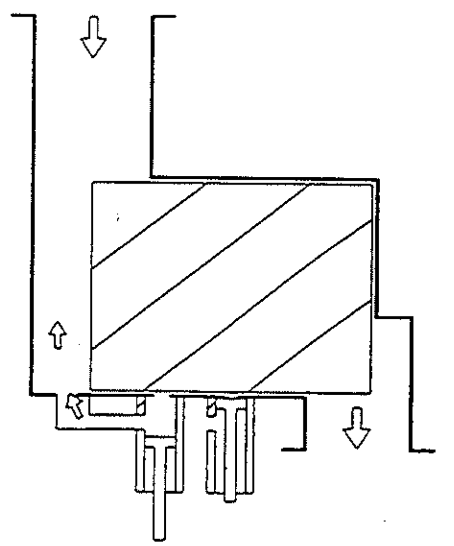
SLIDE



TURN-VALVE




BUTTERFLY



POPPET VALVES

Bonneville Power Administration

February 1994

# Screw Air Compressor Controls:

## Selection and Operation for Energy Efficiency

February 1994

Prepared for:

Bonneville Power Administration

Prepared by:

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Oregon State University
Corvallis, Oregon

## WHO SHOULD USE THIS GUIDEBOOK

This guidebook was written primarily for two audiences. The first intended group is composed of people who want to learn about the various types of control strategies produced in industry today for part load control of rotary screw air compressors. The second group includes maintenance personnel, facilities engineers, and other purchasers who are actively shopping for a compressor system and would like an objective presentation of the different approaches to improved energy efficiency at part load.

## DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

## ACKNOWLEDGEMENTS

I would like to thank Greg Wheeler for the opportunity to gain enough experience to pen this guide and for sharing his knowledge with me. The employees at the Energy Analysis and Diagnostic Center have taught me a great deal through both their questions and answers. I would also like to extend my appreciation to representatives of Quincy, Sullair, Gardner-Denver, LeRoi, and Atlas-Copco, who collectively have shared a considerable amount of time with me. Lyle Wells of Rogers Machinery deserves special recognition for dropping his pearls of wisdom my way.

TABLE OF CONTENTS

# INTRODUCTION

> "It is stated that the entire power cost for running the air compressors to supply the whole shop is not more than ten cents per day... However the air may be used, and however profitable it may be to use it, it will always be in order to get it as cheaply as possible, and economy in air-compression must always be a clear gain." (from Practical Information Upon Air Compression and the Transmission and Application of Compressed Air, 1895)[1]

In 1895, energy efficiency in air compression was a significant issue, because electricity was gradually winning the battle between the two methods as the better large scale energy transfer mechanism. In modern times, we are motivated to be thrifty instead by rising energy rates induced by environmental concerns and shrinking natural resources. However, the goal of economy in air-compression still rings true 97 years later.

Compressed air remains a wonderfully convenient form of energy for the end user. Pneumatic tools are fast. Pneumatic cylinders are cleaner than hydraulic ones, especially if leaks occur. Compressed air is great for cleaning off equipment. Compressed air is safer to use than an electric motor in an explosive environment. And to the user, compressed air is as easy to use as electricity. Unfortunately, the energy provided by compressed air is not cheap. The amount of electric energy purchased to drill a hole in a piece of wood may be 20 times higher for an air-powered drill compared to an electric one. Nonetheless, the unique qualities of compressed air make it an indispensable resource in the industrial processing environment, and will continue to provide a convenient form of energy in the foreseeable future.

Over the last thirty years, rotary-screw air compressors have gradually permeated the plant air systems (90-140 psig) market. Screw compressors now share the market about equally with reciprocating compressors and are still growing in popularity. They are beginning to dominate sales of large compressors. The success of screw compressors can be attributed to lower first costs compared to double-acting reciprocating compressors, more dependability than single-acting compressors, low maintenance requirements, ease of installation, and in the case of very sensitive equipment, less pulsation than reciprocating compressors.

In general, the full load efficiency of screw compressors is similar to that of reciprocating compressors. Full load efficiency is only part of the story, however. In practice, very few compressors operate at full load all of the time. One manufacturer estimates the average load to be 60-70% of full capacity.[2] Traditionally, part load efficiency has been the Achilles heel of screw air compressors. This is where controls become important.

There are many different methods to match the amount of air provided by a compressor with plant air requirements. Each approach has strengths and weaknesses. This guidebook first presents the different types of air compressors, and then introduces a basic screw compressor-based system. The report next explains existing approaches to part load control, and evaluates them for meeting different types of demand and for energy efficiency.

## AIR COMPRESSOR TYPES

There are many ways to compress air. The chart below shows a typical method of grouping mechanical air compressors. The most fundamental division between compressor types is that between positive-displacement compressors and dynamic compressors. Positive-displacement compressors draw in a fixed volume of air, reduce the volume occupied by air, and then eject it (see Figure 1). In contrast, dynamic compressors introduce energy to the air through transfer of momentum. Dynamic compressors do not compress discrete volumes of air. As the chart indicates, screw, reciprocating and rotary vane compressors are all positive-displacement compressors. These are by far the most common type of compressors used to supply plant air. Different types of air compressors are shown in Figure 2, below. Before exploring the details of compressed air systems, each general type of compressor will be introduced.

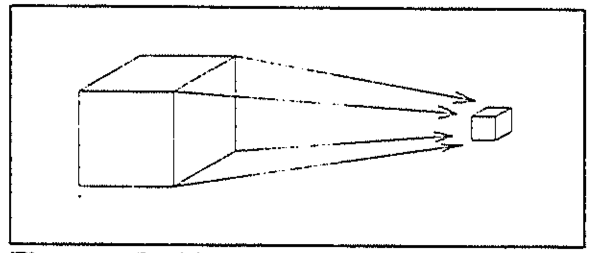

**Figure 1**: Positive Displacement Compression

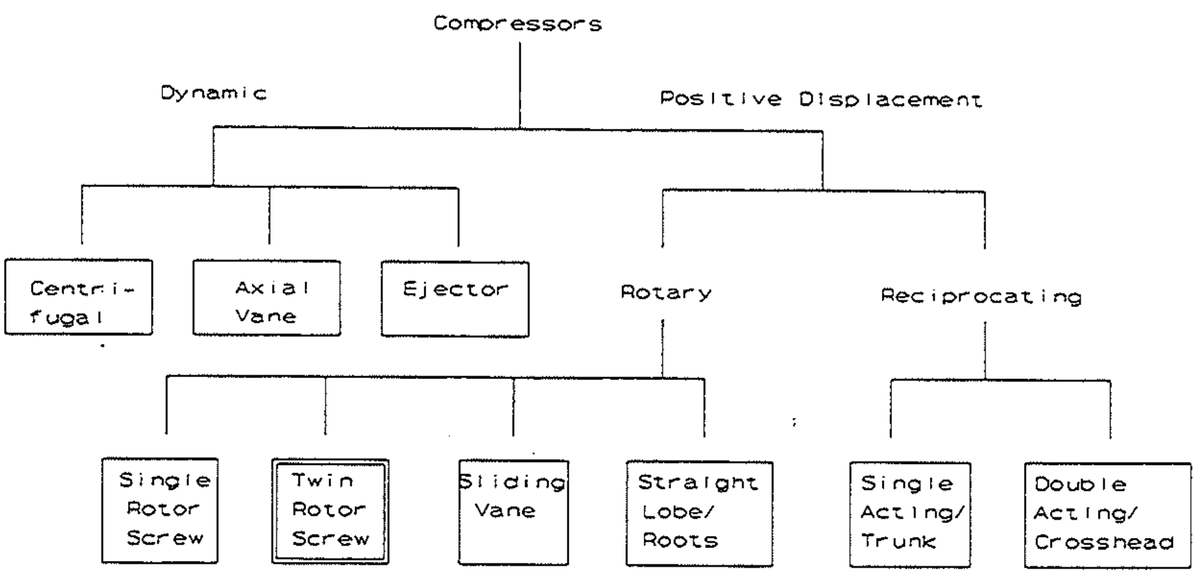


**Figure 2**: Basic Compressor Types

**Screw compressors:** There are both single screw and twin screw compressors, as well as multistage screw compressors. This guidebook focuses on the most common version, single stage twin screw compressors.

A screw compressor is shown in Figure 3. In operation, filtered air is drawn in at the "front" of the compressor through the inlet port as shown in the top diagram. As the screws rotate, the male and female lobes intermesh. A portion of air is drawn into the compressor, and is trapped between the two lobes and the casing. The trapped air is shown as the shaded region in the middle diagram. Since the rotors are spiraled, the air gradually moves "backward" as the rotors spin. The air is compressed because the space between the lobes gets smaller as the air approaches the discharge port of the compressor. After compression is complete, typically about 3/4 of a rotation of the male rotor, the portion of air is released to the system through the discharge port. This compression process repeats as often as 25,000 times/minute.

The male rotor commonly will have between three and five lobes and is driven by the motor. The female rotor is most often driven by the male rotor and typically will have one or two more lobes than the male rotor.

Oil normally provides the seal necessary to prevent air leakage, but water and other oil-free lubricants also can be used. Dry compressors are also marketed. They require external cooling and usually will compress the air in two lower ratio stages in order to reach plant air pressure levels without leakage.

Two stage units use two pairs of screws and are more expensive than single stage compressors. Since the overall compression ratio is the same as for single stage units but the number of stages is doubled, each stage performs less compression. The reduced compression ratio for each stage reduces the pressure difference across the screw threads during compression. This in turn reduces internal leakage, called slip. Efficiency at full load for two stage units is likely to be about 10-13% higher than single stage unit efficiency.[3] Two stage compressors usually have the same controls and part load performance characteristics as single stage units.

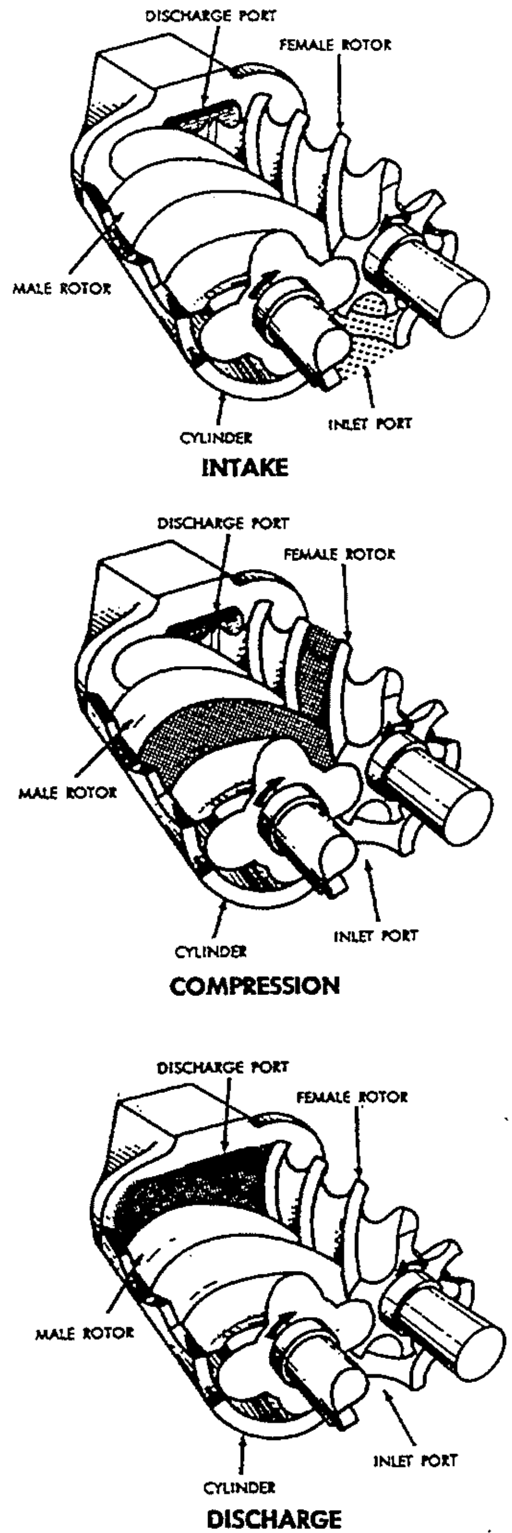


**Figure 3:** Screw Compressor

**Reciprocating Compressors:** In the past, reciprocating compressors were the workhorses of the plant air market, and some partisans would argue that they still are preferable to screw compressors. Single acting, or trunk, compressors operate like an automotive piston. Air is compressed in a chamber on one side of the piston head (see Figure 4). Most small reciprocating compressors are single acting models. Double acting, or crosshead, compressors compress air on both sides of the piston head. They are more expensive, more efficient, and have a longer average life than single acting units. Most new large reciprocating compressors are double acting.

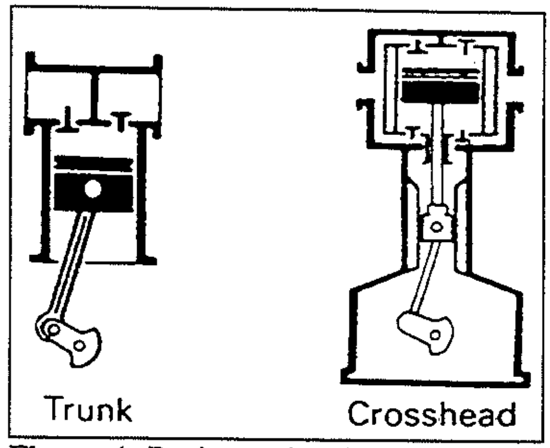

**Figure 4:** Reciprocating Compressors

Reciprocating compressors are made as both single stage and multiple stage machines. Multi-stage machines compress the air in two or more stages and are required for high pressure applications. They are also often used in lower pressure applications because they are more efficient than single stage units. The additional machinery does make multi-stage compressors more expensive than single stage compressors. The part load efficiency of reciprocating compressors is very good. Compared to screw compressors, they offer similar full load efficiency (water cooled crossheads may be up to 15% higher) and as good or better part load efficiency. However, capital and installation costs are likely to be higher. Depending on whom you ask, operating & maintenance costs may also be higher.

**Rotary vane compressors:** Vane compressors appear to be vanishing breed in this country's plant air market. A cylinder with free sliding radial vanes rotates off-center in a larger cylinder (see Figure 5). The vanes slide in and out to follow the inner surface of the outer cylinder. Air is drawn in at the point where the pocket between the two vanes is largest. The air is trapped between the vanes and the cylinder walls, compressed, and then discharged as the rotor turns. Vane compressors are often less expensive and only require moderate maintenance, but they are generally less efficient than rotary screw compressors.

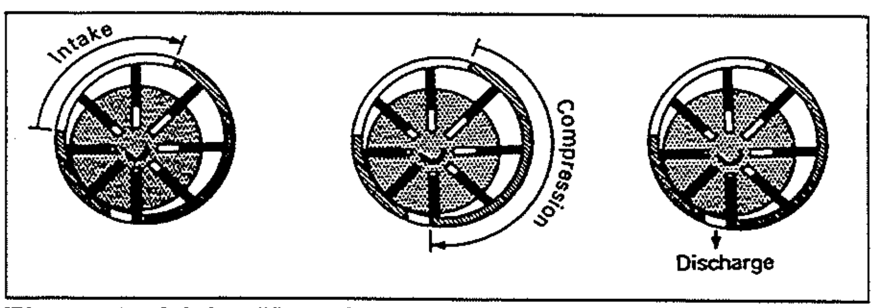

**Figure 5:** Sliding Vane Compressor

**Straight Lobe Blower:** As indicated by the term 'blower,' this type of machine only supplies compressed air up to about 15 psig. An argument could be made that lobe blowers should not be classified as true compressors. Two intermeshing rotating lobes trap segments of air one at a time, and force the air through the discharge (see 'Roots' in Figure 6). They don't actually compress air, but force air from the inlet to the discharge without allowing reverse flow. Lobe blowers are more efficient at providing low pressure air than reducing 100 psig plant air to low pressure (see The Compressed Air Energy Conservation Opportunities section for more details).

**Liquid Ring compressors:** Liquid ring or liquid piston compressors look like rotary vane models but use a compressant liquid that moves in and out like a radial piston. Liquid ring compressors are less efficient than rotary vane compressors, but are extremely reliable. They are also used in vacuum service.

**Centrifugal compressors:** Centrifugal, or radial, compressors work by slinging air radially out through an impeller and increasing its momentum. The energy added by momentum transfer is converted to pressurized air partly by the end of the impeller, and by using a diffuser. Single stage centrifugal compressors usually have a pressure ratio of less than three, and normally several stages are used together. Centrifugal compressors are quite dependable, but inefficient at the lower flow rates normally required for plant air. They are likely to be used when large flow rates (up to 150,000 cfm) are required.

**Axial vane compressors:** Turbines are the most glorified type of axial vane compressors. Like centrifugal compressors, axial compressors add energy by momentum transfer, but air flows parallel to the rotor shaft instead of perpendicular to it. Axial compressors are basically multistage fans. Almost always multi-staged, the vast majority of vane compressors are found in aircraft applications and as gas turbine compressors.

**Ejector compressors:** For the sake of completeness, ejector compressors deserve mention. In operation, a jet of steam or other vapor is ejected from a nozzle into an air stream. The gas is entrained in the steam jet and is compressed as the mixture passes through another nozzle, where energy changes state, from velocity to pressure. Ejector compressors are most often used to compress gases from a partial vacuum up to atmospheric pressure.

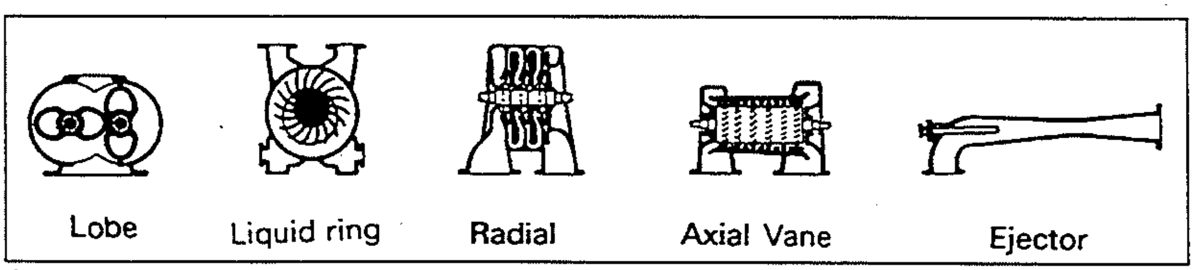


**Figure 6:** Other Compressor Types

## COMPRESSED AIR EQUIPMENT

This section introduces the basic components of a compressed air system.

**COMPRESSOR** - The heart of the system is the compressor itself. From this point on, the guidebook focuses on rotary screw compressors.

**AIR FILTER** - Just like automotive engines, all compressors will have an air filter preceding the intake. A simple schematic below, Figure 7, introduces the motor, screw compressor, and air filter. Other components will be added to the diagram as they are described.

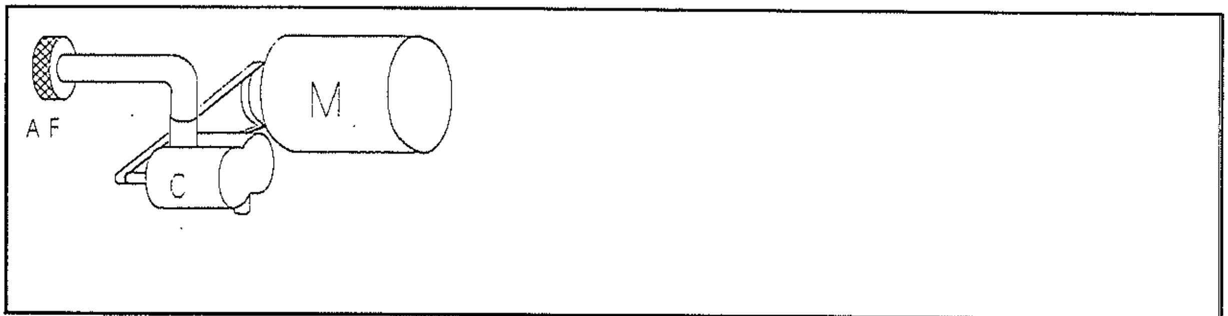


**Figure 7:** Air Filter (AF), Compressor (C), and Motor (M)

**OIL SEPARATOR** - The majority of screw compressors use oil, transmission fluid, or other lubricant for cooling, lubrication, and as a seal between moving parts. Recently, synthetic lubricants have been promoted as a route to increased efficiency for air compressors as well as automobiles. Most of the oil is injected into the compressor at the beginning of the compression zone, see Figure 8. A small amount of oil may be introduced into the air to be compressed prior to the intake. The air leaving through the compressor discharge port is therefore a mixture of air and oil. A properly working oil separator will remove virtually all of the oil in the air. One test found that the air leaving the oil separator actually had less suspended oil in it than the ambient air drawn into the compressor intake port![4] Most separators do not work quite this well. The element itself is normally composed of a coalescing filter supported by a perforated metal baffle. As the mixture rushes up through the separator, gravity causes the larger oil droplets to fall into a sump at the bottom of the separator. The filter causes the smaller droplets to collide and collect into larger into larger droplets (coalesce) that then fall into the sump.

**OIL COOLING** - The compression process generates considerable heat energy. Some of the generated heat is due to friction, but the majority of the heat is due to the fact the air gets hot as it is compressed. A lot of this energy is absorbed by the oil. Consequently the oil needs to be cooled before it is injected back into the compressor. This can be done with either an oil-air heat exchanger (radiator, OC) as shown in the diagram, or with a oil-water heat exchanger. The diagram also includes an oil filter (OF).

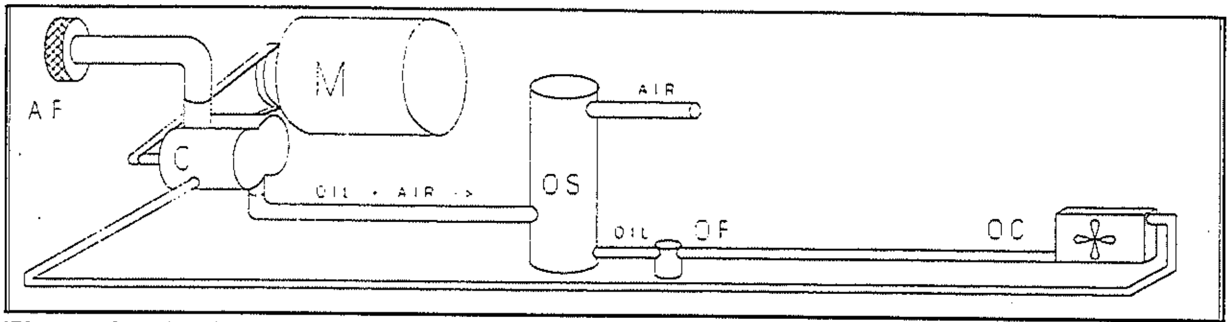

**Figure 8:** Oil Separator (OS), Oil Filter (OF), and Oil Cooling (OC)

**AIR DRYING** - Unless your compressor operates in a desert, moisture will need to be removed from the hot compressed air before it can be delivered to equipment for use. The most common method is to cool the air, like the oil, with either an air or a water heat exchanger, see Figure 9. This causes the water vapor in the compressed air to condense and fall out of the air. A moisture trap collects the water until it is drained from the system. Refrigerated, heated, and desiccant dryers can be used to supplement the air/water heat exchanger.

**REHEAT (optional)** - Since the delivery of compressed air is fundamentally an energy transfer process, it is normally economical to reheat the cooled air with either the hot oil or the hot pre-dried air. The oil-air heat exchanger shown below adds energy back to the compressed air.

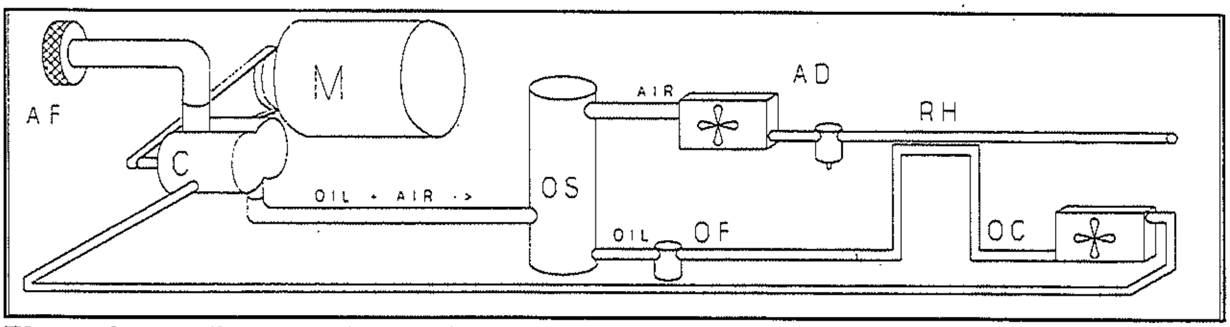

**Figure 9:** Air Drying (AD) and Reheat Option (RH)

**RECEIVER** - Finally, the compressed air arrives at the receiver. From the point of view of the air, the volume of space available for storage includes not only the receiver, but the miles of air lines that may be scattered throughout the plant. The main job of the receiver is to smooth out the erratic starts and stops of equipment into a manageable amount of pressure fluctuation. For a compressor with only modulating controls, a huge receiver may not be necessary. However, any compressor that unloads will benefit from a large receiver. With regards to cycling, bigger is unconditionally better. In fact, any application that can tolerate a 10 psi range for system pressure can use the efficient load-unload or even on-off control strategies if enough storage capacity is available. This is a low-tech. solution for major energy savings and will be re-emphasized as the guidebook continues. One manufacturer recommends a minimum of 1 gallon capacity per scfm output. If air use is intermittent, a larger receiver should be considered.

## AIR COMPRESSOR CONTROLS

For some types of machinery, people can treat controls conveniently as magic black boxes with little penalty. Unfortunately, air compressor controls play a major role in the performance of the compressor. A bad choice may silently absorb thousands of dollars in unnecessary energy costs, or even render the equipment incapable of meeting plant air requirements. The good news is that compressor controls are understandable if not altogether simple, and selecting the proper control strategy can be a rational and financially rewarding process.

Full load conditions do not require intricate and confusing control strategies. All control systems leave the compressor running the same way - flat out. But few compressors operate at full capacity at all times. New compressors are bought oversized in anticipation of future growth; cutbacks in production reduce air demand, a compressor sized for peak air demand is twice as large as necessary for normal demand. In practical terms, a compressor is not usually going to be fully loaded unless perhaps it is one in a series of sequenced compressors. The objective of a good control strategy is to balance less-than-ideal part load efficiency with adequate capacity to reliably provide compressed air to users.

**Performance Table:** For each control strategy that is presented, a summary of part load performance characteristics is included in the header. They are:

<u>Minimum Storage Capacity.</u> This indicates the minimum receiver size required for proper operation. Control strategies employ cycling require more storage capacity than those that modulate, particularly if demand is high.
<u>Low Demand Efficiency.</u> This rating represents the relative efficiency of the control strategy based on average power required for a compressor operating uniformly between 0% and 50% capacity.
<u>High Demand Efficiency.</u> This indicates relative efficiency between 50% and 100% capacity.
<u>Controlled Variable(s).</u> Controlled variables are those conditions that are directly manipulated by the controller.

Efficiency ratings are based on the following table:

| Rating | Part Load Efficiency (Percent Full Load cfm/hp) |
|---|---|
| Excellent | 85-100% |
| Good | 70-85% |
| Average | 55-70% |
| Fair | 40-55% |
| Poor | 25-40% |

**Thermodynamics.** This section describe the effect of changes made in the controlled variable(s) cited in the table. Ignoring mechanical inefficiencies, the following equation applies to air compression up to a few hundred pounds.[5]

$$p_i V_i^n = p_o V_o^n$$

where,

$p_i$ = Inlet pressure
$p_o$ = Outlet pressure
$V_i$ = Inlet volume
$V_o$ = Outlet volume
$n$ = Polytropic constant

The polytropic constant is fixed for a given gas (such as air) and compression process. For any screw compressor control strategy, the other four parameters can be physically adjusted to reduce compressor capacity. The discharge pressure ($p_d$) may also be manipulated. The discharge pressure is the pressure of the air at the discharge port and in the oil separator, while the outlet pressure represents the pressure of the small compressed volume of air immediately **before** it is released to the discharge port. Therefore, the outlet pressure may be affected by changes in inlet conditions even when the discharge pressure is not affected.

Finally, the duty cycle and average compression rate can also be reduced. In this guidebook, the term pressure ratio (PR) is used to describe the air pressure after it has been expelled from the screws ($p_d$) divided by the air pressure just prior to the intake port of the compressor ($p_i$). Thus,

$$PR = p_d / p_i$$

**Mechanics.** The Mechanics section explains how the controlled variable(s) are physically manipulated.

**Energy Use.** There will also be a section on energy use for each control strategy. The principal instrument in this section is the Part Load Power curve. The graph indicates possible operating points as a solid line and with discrete points. Overall average power is indicated by a dotted line when it departs from actual operating points. A dashed line indicates the control mode's efficiency. Air flow rate out per horsepower input (cfm/hp) is a measure of efficiency. There will also be at least one formula presented in the section. The formula defines the power curve shown on the graph. In most cases, these formulas model specific curves or data provided by equipment manufacturers. Actual performance will, of course, vary.

**Applications.** The final section describes appropriate operating environments for the control strategy.

| THROTTLING CONTROL | | | |
|---|---|---|---|
| Minimum Storage Capacity | Low Load Efficiency | High Load Efficiency | Controlled Variable |
| Small | Poor | Good | Inlet Pressure, $p_i$ |

**Thermodynamics:** Throttling controls reduce the inlet pressure below atmospheric pressure (0 psig) by causing a partial vacuum to form at the compressor inlet. The outlet pressure will be affected, the inlet and outlet volumes and the discharge pressure will not change. In thermodynamic jargon, the pressure ratio increases and the volumetric compression ratio remains constant. The introduction to this section describes all of these terms.

**Mechanics:** In general, modulating controls are a treat for the finicky user because the compressor tries to maintain a constant discharge pressure instead of bouncing between a high and low set pressure. Throttling modulation works by starving the compressor of air. The mechanism itself is a butterfly valve or a slide valve that is mounted upstream of the compressor inlet, as shown in Figures 10 and 11. If the system pressure sensor perceives that the pressure is increasing (because plant demand has decreased below the system capacity), the modulating valve starts to close. This creates a partial vacuum at the compressor inlet. Consequently, the air entering the compressor is less dense and less air mass enters the compression chamber between the screws. The compressor delivers less air to match demand. The discharge port is always at system pressure. The location of the discharge port on the compressor casing defines the volume ratio, and different ratios are available for different pressure ranges. However, once it is machined, it cannot be changed.

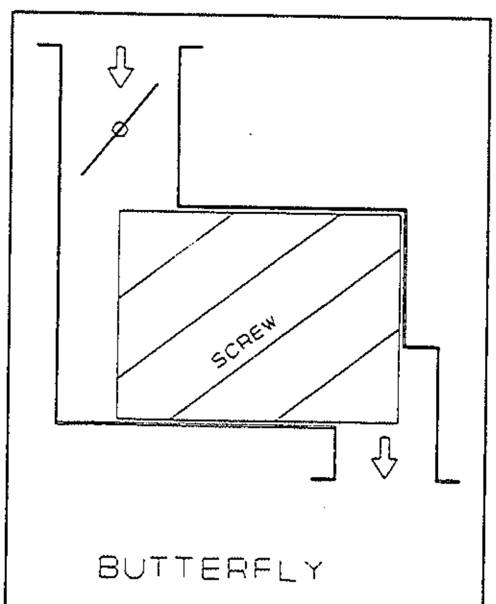


**Figure 10:** Butterfly Valve

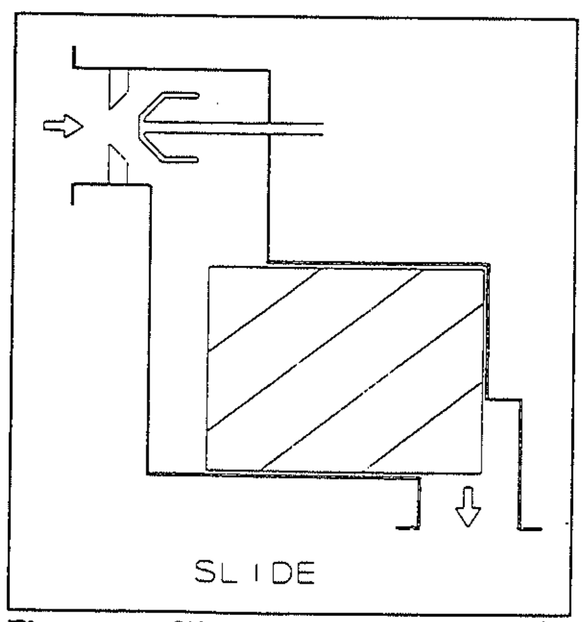


**Figure 11:** Slide Valve

In summary, a fixed volume of air is drawn into the compressor and the volume is always compressed by the same amount ($V_1/V_2$ = constant). The number of compression cycles per minute does not decrease. But the pressure ratio does change, and the mass flow rate of delivered air also changes.

**Energy Use:** Life would be easy if throttling controls were also efficient. Unfortunately, this mode is often not efficient. Because the compressor constantly works against system pressure at the discharge port, the motor never really gets a chance to relax. Part load efficiency is particularly poor during low demand periods. Sixty-eight percent of the full-load power is required at 0% capacity! The part load performance curve in Figure 12 shows the a linear relationship between power and capacity. The equation for part-load power is:

$$\%P = 68\% + 0.32 \times \%C$$

This mode of control can be efficient for high loads, because excessive cycling is avoided (see unloading control strategies described later).

The Part Load Performance curve indicates that the compressor can operate continuously at any point between 0% and 100% capacity.

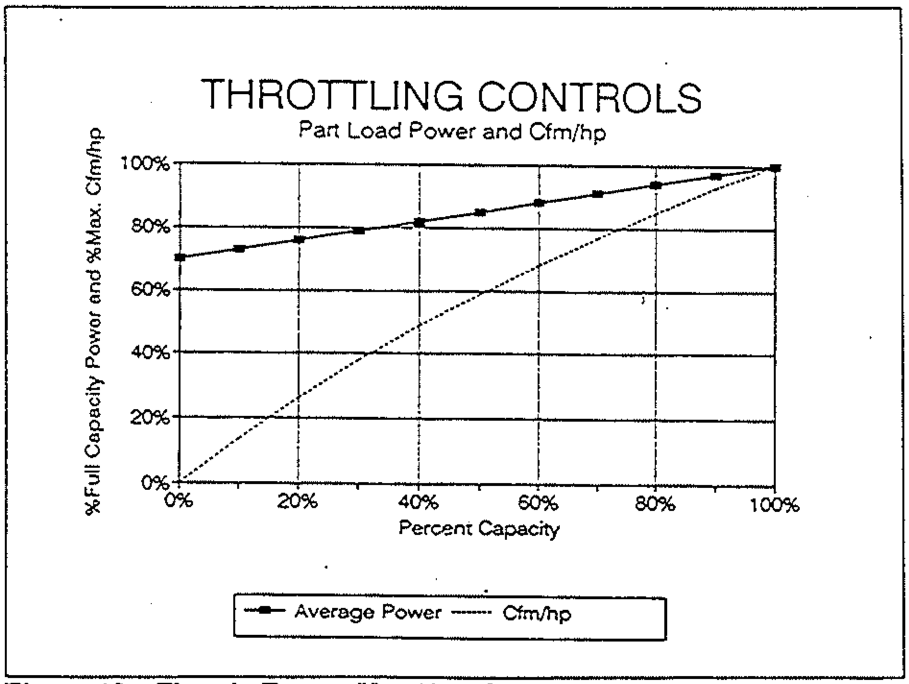


**Figure 12:** Throttle Energy Use (data from Rogers Machinery Company)

**Applications:** Throttling is desirable when over-all plant demand is high or erratic, when receiver size is small, or when the acceptable range for system pressure is small. Modulation-only control is a low-risk option because of mechanical simplicity, small pressure variation, and cycling is avoided. Consequently, it is a common control strategy. Throttling is not desirable if extended low load periods are expected.

| TURN VALVE CONTROL | | | |
|---|---|---|---|
| Minimum Storage Capacity | Low Load Efficiency | High Load Efficiency | Controlled Variable |
| Small | Poor | Excellent | Inlet Volume, $V_i$ |

**Thermodynamics:** The inlet volume is the controlled variable. Turn valves control the supply of compressed air by changing the volumetric compression ratio. The inlet pressure remains at atmospheric pressure and the pressure at the discharge port remains at system pressure, so the pressure ratio does not change. Since the compressor undercompresses the air, it essentially becomes a combination compressor-blower. The introduction to this section describes all of these terms.

**Mechanics:** Turn (or spiral) valve control is another form of modulation. Consequently, no minimum or maximum pressure settings are required. However, the mechanical similarity to throttling ends here. As shown in Figure 13, the "turn valve" itself is composed of a spirally threaded shaft and four or more discrete ports in the compression chamber wall. The shaft lies parallel to the rotors. When plant demand drops below full capacity, the shaft gradually rotates. This opens up some of the ports to atmospheric pressure. Air compression cannot begin until the section of air being rotated through the screws has past the last open port and there are no more escape routes.

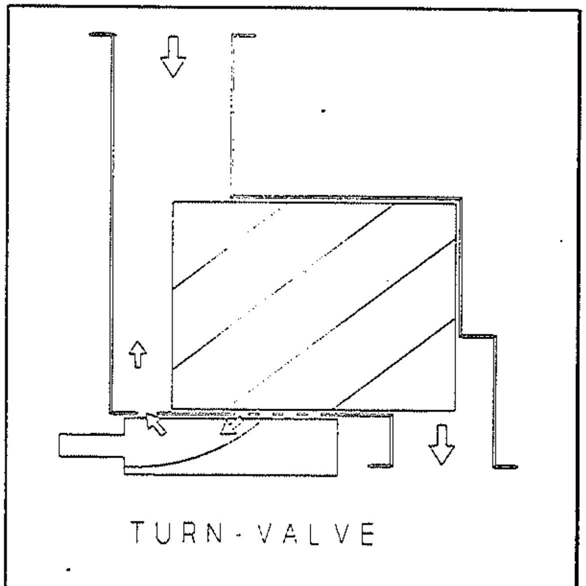

**Figure 13:** Turn Valve

Since part of the full load compression range is eliminated, the volumetric compression ratio is effectively reduced in order to reduce the air flow rate. Even though the outlet pressure of the trapped air leaving the screws actually is reduced, the "external" discharge pressure at the system port remains at system pressure. Consequently the effective pressure ratio remains constant.

In summary, the pressure ratio and the number of compression cycles per minute remain constant, but the volumetric compression ratio and the mass flow rate change.

**Energy Use:** This method is more efficient than throttling. However, since the compressor works against system pressure at all times, this is still a relatively energy-intensive control strategy at lower loads. The part-load power curve in Figure 14 shows good performance at high loads, but about 57% of full load power is still required at 0% capacity. If average capacity is known, the part-load power can be calculated from the following parabolic equation:

$$\%P = 57\% + .43 \times \%C^2$$

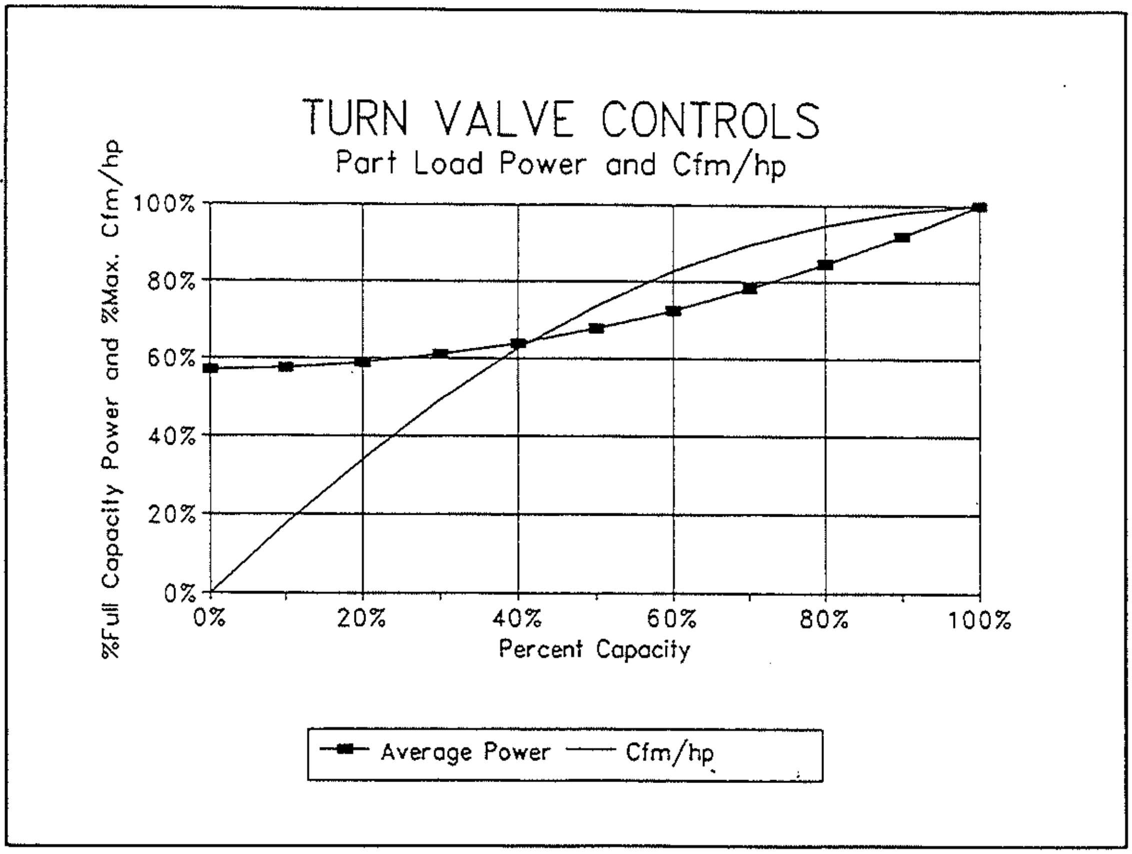


**Figure 14:** Turn Valve Energy Use, Approximated from Gardner Denver data

**Applications:** Turn valves are an effective control strategy when over-all plant demand is high or erratic, when receiver size must be small, or when the acceptable range for system pressure is small. Modulation is a low-risk option and consequently, a common control strategy. Though more efficient than throttling, turn valve control is not desirable if extended low load periods are expected.

| POPPET VALVE CONTROL | | | |
|---|---|---|---|
| Minimum Storage Capacity | Low Load Efficiency | High Load Efficiency | Controlled Variable |
| Small | Poor | Excellent | Inlet Volume, $V_i$ |

**Thermodynamics:** Inlet volume changes. Poppet valves control the supply of compressed air by changing the volumetric compression ratio. The inlet pressure remains at atmospheric pressure and the discharge pressure remains at system pressure, so the pressure ratio does not change. Since the compressor undercompresses the air, it essentially becomes a combination compressor-blower. The introduction to this section describes all of these terms.

**Mechanics:** Poppet valves certainly sound like fun. Functionally, they operate using the same principle as the turn valve: the volumetric compression ratio is reduced by opening discrete ports in the compression chamber walls, (see Figure 15). But instead of using a single rotating shaft, four or five pneumatic valves open and close to expose the ports and vent the air to the inlet which is at atmospheric pressure.

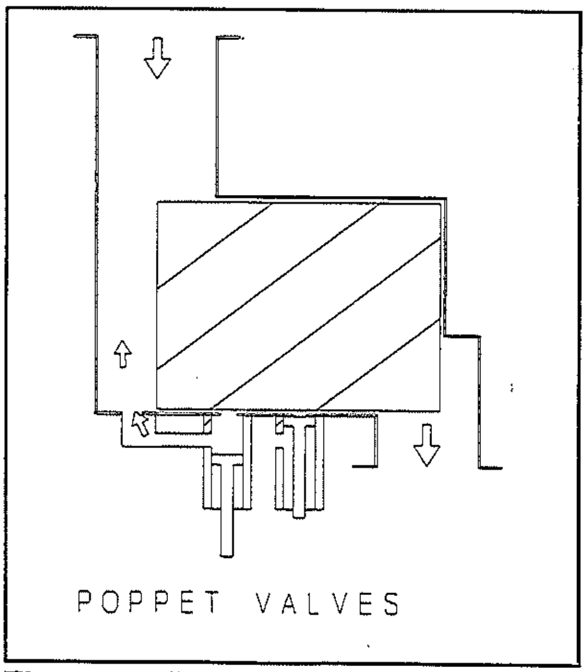


**Figure 15:** Poppet Valve

**Energy Use:** Unsuprisingly, the energy use for poppet valves is similar to turn valve control. The thermodynamics are the same; only the mechanics of implementation vary. Poppet valves are more efficient than throttling but the compressor works against system pressure. Consequently, poppet valves are a relatively energy-intensive control strategy. The part-load power curve in Figure 16 shows very good performance at high loads, but about 61% of the full load power is still required at 0% capacity. The power-capacity relationship can be approximated by the following parabolic equation:

$$\%P = 61\% + .39 \times \%C^2$$

Differences in modeled performance between poppet valves and turn valves should not be considered significant.

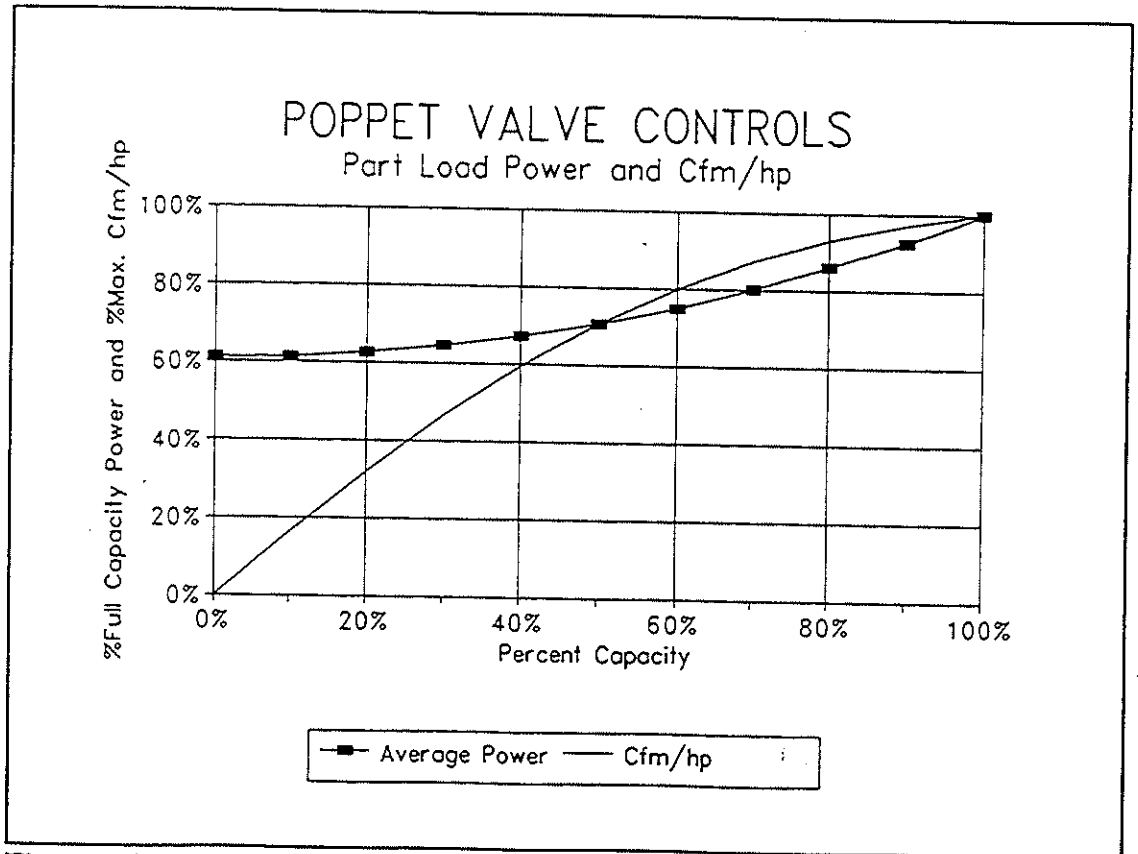


**Figure 16:** Poppet Energy Use, Approximated from LeRoi data

**Applications:** It must start to sound redundant, but suitable applications for poppet valve control are the same as those for other previously described modulation only controls.

| ON-OFF CONTROL | | | |
|---|---|---|---|
| Minimum Storage Capacity | Low Load Efficiency | High Load Efficiency | Controlled Variable |
| Large | Excellent | Excellent | Duty Cycle |

**Thermodynamics:** On-Off controls run the compressor at 100% capacity, or shut off it completely. Only the duty cycle changes.

**Mechanics:** On-off controls are typified by the gas-station compressor (finally, a different strategy than modulation). An air compressor with this type of control requires that a range of acceptable system pressure be tolerable. The compressor will run at 100% capacity, as shown in Figures 17 and 18, until the system pressure reaches the pre-set maximum. Then both the compressor and motor completely shut off. A check valve (CV) prevents the flow of air back through the compressor. At the time of shutdown, an unloading valve (UV) opens so that air at the discharge port is released to atmospheric pressure. The discharge pressure reduction makes it easier for the compressor to restart.

Once the compressor turns off, Figure 17 shows that high pressure air between the discharge port and the check valve will exhaust through a blowdown filter (BF). The filter acts as a muffler. Some control strategies instead will vent the air to atmospheric pressure at the inlet pipe, as shown in Figure 18, and use the inlet air filter (not shown) as a blowdown filter also. In either case, the reverse flow of air through the compressor is avoided. Once enough air is used that the system pressure downstream of the check valve drops to a set minimum pressure, the compressor and motor restart and run at full load.

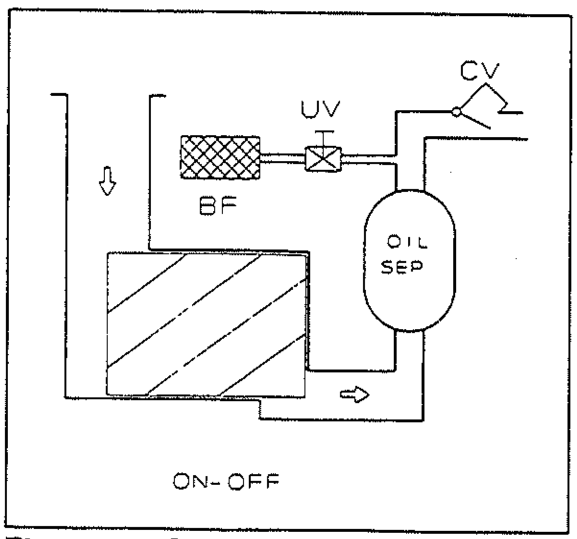

Figure 17: On-Off with Unloading Filter

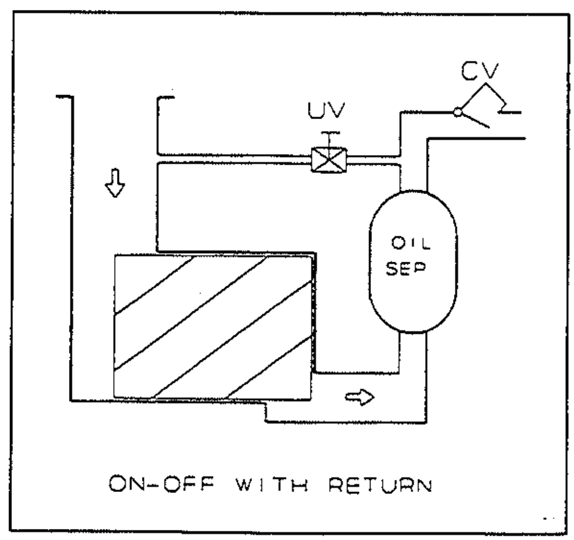

Figure 18: On-off with Return Line

Timers can be incorporated to reduce the number of starts, but this can adversely affect the operating pressure and should be used with caution.

Energy Use: This control strategy is actually the most efficient mode. Since a compressor operating in this mode only produces air while running at 100% capacity and never idles, performance approaches the "ideal," as shown in Figure 19. There will be modest losses because any compressed air that is upstream of the system pressure check valve will be lost once the compressor is shut down. For example, a system with that runs six minutes per cycle will likely have losses of less than three percent. If start-up losses are neglected, power consumption can be modeled by the simple relationship:

$$\%P = \%C$$

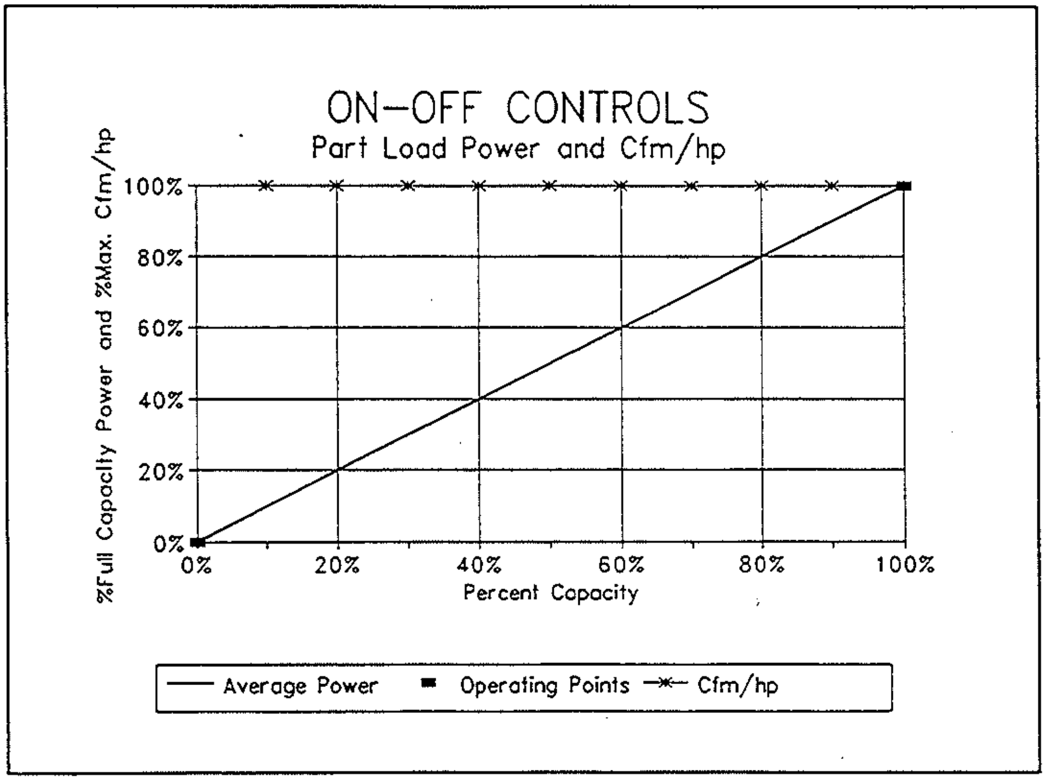


**Figure 19:** On-Off Energy Use

Applications: This type of control strategy works best when the user is confident that there will be long periods of either very high or very low use, and when the maximum and minimum pressures are not close together. Large receivers are important. Like automobile engine lubrication advertisements say, machinery experiences the most wear and tear during start-up. This method of control is not recommended if the compressor cycles more than once every six minutes.[6] A small plant with an occasionally used sandblaster would be an appropriate application for this control strategy.

| LOAD-UNLOAD CONTROL | | | |
|---|---|---|---|
| Minimum Storage Capacity | Low Load Efficiency | High Load Efficiency | Controlled Variables |
| Large | Average | Excellent | Inlet, Discharge Pressure |

**Thermodynamics:** Both inlet and discharge pressure are reduced when the compressor idles. The introduction to this section describes these terms.

**Mechanics:** Load-Unload controls on screw compressors allow the compressor to operate at only two points: fully loaded at 100% capacity and unloaded at 0% capacity. This strategy is similar to On-Off controls except that the motor and compressor never completely shut off. The compressor runs at full power until the system pressure increases to the maximum pressure. Then, an unloading valve at the compressor discharge side opens, and the air leaving the compressor is vented to a lower pressure. Figure 20 shows the controls in an unloaded mode. The most efficient controls use a small oil pump and vent the discharge all the way to atmospheric pressure. However, some manufacturers maintain a pressure of about 30 psig to circulate oil through the compressor while it is unloaded. In either case, a check valve prevents the back flow of air at system pressure. Simultaneously, a valve in front of the intake closes, preventing air from being drawn into the suction port. The butterfly valve shown does NOT modulate in this strategy; it is either fully open or fully closed. In the unloaded condition, the compressor does little work, because it is starved of air at the inlet (near -14 psig) and only working against reduced (0 or 30 psig) pressure at the outlet.

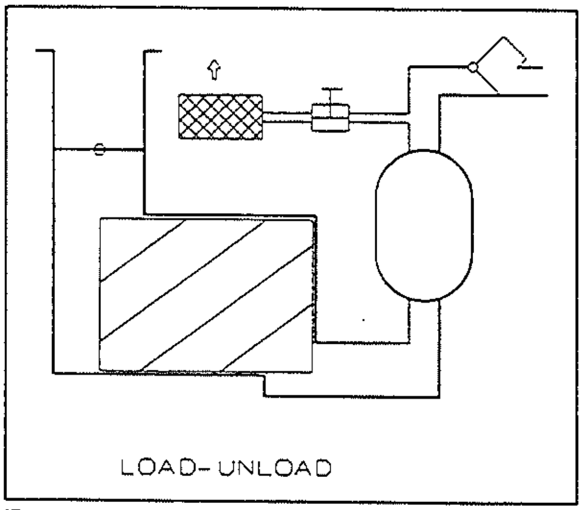


**Figure 20:** Load-Unload Control

**Energy Use:** When appropriate, this method of control has very good average energy use characteristics since it only produces air at 100% capacity and idles with low energy use at other times. There will be a small loss of energy each time the outlet blows down, because any compressed air preceding the check valve will be vented to attain a lower pressure. The simplest way to estimate energy use is to ignore these losses and those that may accrue as the intake valve opens and closes. This sounds rash, but the volume of air lost will be less than 2 $ft^3$ per cycle with most oil separators. If the compressor discharge pressure drops all the way to atmospheric pressure, the Average Percent Full Load Power consumption will be approximately:

$$\%P = 16\% + 0.84 \times \%C$$

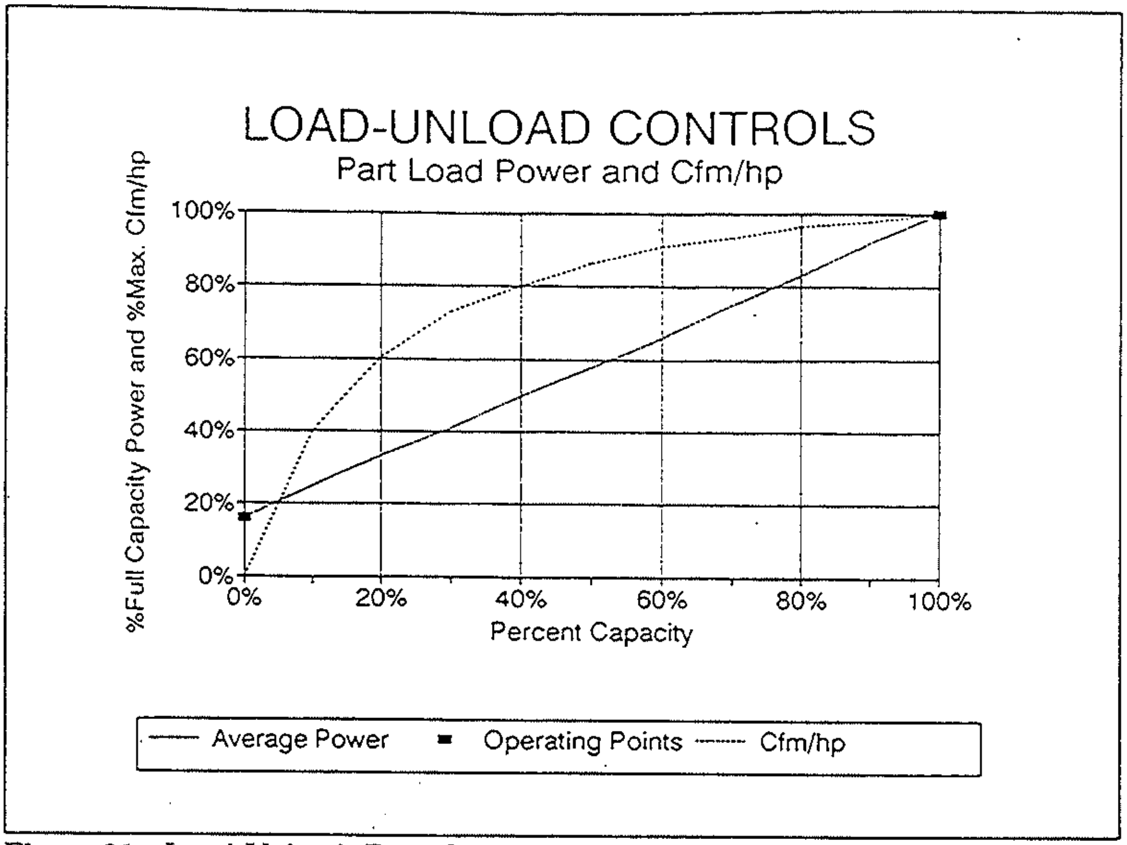


Figure 21: Load-Unload, Data from Rogers Machinery Company

The graph is for a compressor that is completely vented to atmospheric pressure. A partially vented compressor at 0% capacity will normally be near 25% of full load power. The capacity-power relationship will still be linear. Thus, the equation for a 30 psig sump pressure would be:

$$\%P = 25\% + 0.75 \times \%C$$

**Applications:** Load-unload control is most appropriate when conditions will not cause unloading too often, though it can operate with more unloading cycles than On-off controls can. An on-off controlled compressor would not be suited to restart every 2 minutes, for example, but a load-unload controlled compressor and motor could handle the cycling. A plant with a large air storage capacity and equipment without exacting pressure requirements is ideally suited for load-unload control. Many lumber mills fit this category because they have extensive piping networks and space to install large receivers.

| LOW-UNLOAD CONTROL | | | |
|---|---|---|---|
| Minimum Storage Capacity | Low Load Efficiency | High Load Efficiency | Controlled Variables |
| Medium | Fair | Good*<br>Excellent** | $p_i$, $p_d$<br>$V_i$, $p_i$, $p_d$ |

*Throttle + Unloading **Turn/Poppet + Unloading

**Thermodynamics:** During modulation, either the inlet pressure or the inlet volume ratio changes, depending on whether throttling or turn/poppet valves are used. During unloading periods, the inlet and outlet pressures are reduced, like with load-unload controls.

Mechanics: Low-Unload control represents a combination of Load-Unload control and modulation. The modulation may be a throttling valve, a turn valve or a poppet valve. It is recommended that those descriptions be read and understood before proceeding further.

Low-unload controls are designed to modulate during periods of high demand and unload if demand drops below a certain percentage of full load capacity. The unload point may be permanently pre-set by the manufacturer, (40% and 50% settings exist), or it may be manually adjustable, depending on the compressor manufacturer.

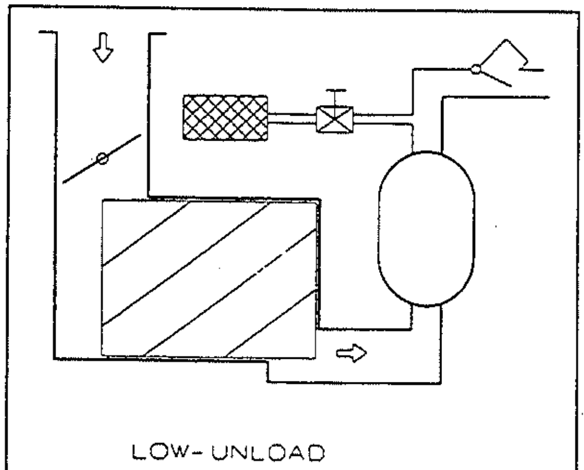

**Figure 22:** Low-Unload Control

Low-unload hardware looks similar to the load-unload control in the schematic diagram, but modulation is included with the low-unloading. With low-unloading there will also be a maximum and a minimum pressure. The compressor runs at 100% capacity and gradually increases the system pressure (assuming demand is less than 100% of capacity). However, before the system reaches the maximum desired pressure the inlet control starts to modulate. Modulation reduces capacity until it either balances compressed air demand with supply, or until the capacity drops to the set unloading point (% capacity), whichever comes first. If the unloading point is reached, the compressor drops to an unloaded idle condition, as described in the load-unload section, and waits there until system pressure drops to the minimum. At this point, the modulating valve fully opens, the blowdown valve closes, and the compressor returns to full capacity.

**Energy Use:** Unsuprisingly, the energy efficiency of low-unload controls falls between that of load-unload control and modulation-only control. Since the operating mode varies depending on the magnitude and regularity of the plant air demand, receiver size, pressure range, and unload point, it is not easy to make a simple mathematical model. However, as an example the following simplified form can be used. Assuming inlet throttling modulation is used, the unload point is set at 50%, the compressor completely unloads to atmospheric pressure, and unloading losses are ignored, energy use can be approximated as:

$$\%P = 16\% + 1.36 \times \%C \text{ (Ave. capacity} < 50\%)$$
$$\%P = 68\% + 0.32 \times \%C \text{ (Ave. capacity} >= 50\%)$$

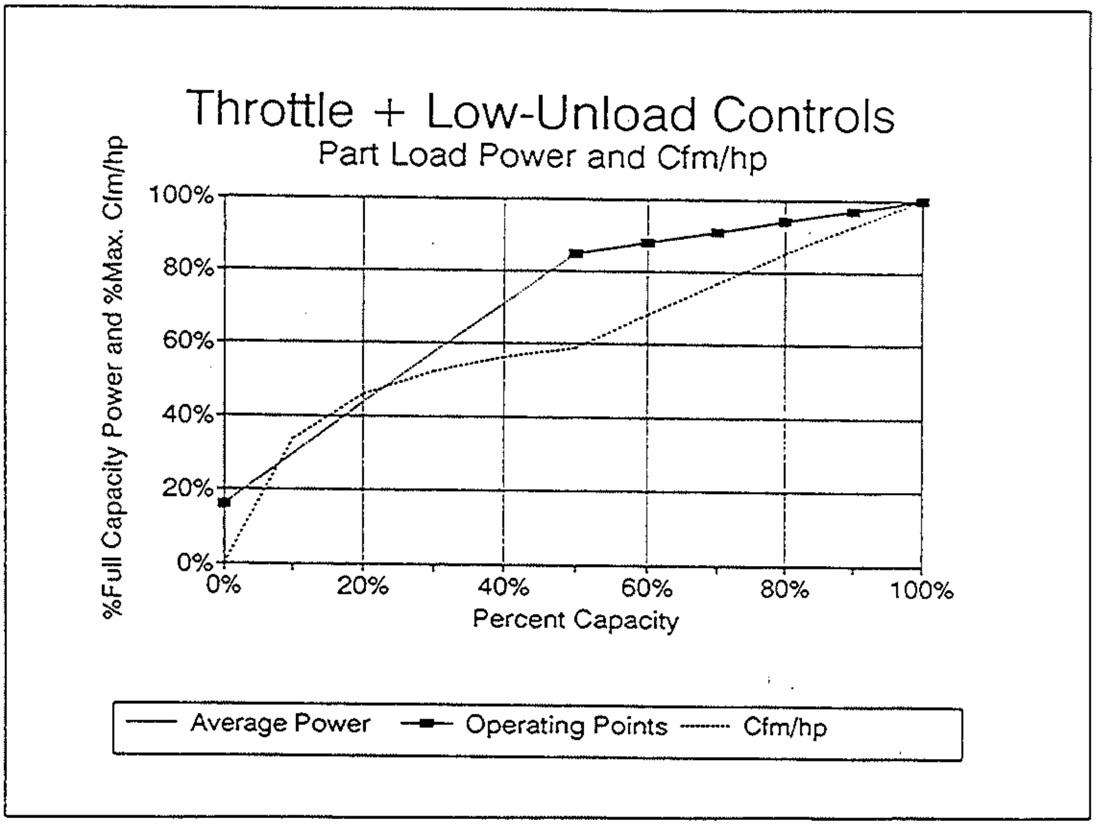


**Figure 23:** Throttle + Low-Unload Energy Use, Full Unloading

Or, with a turn valve, a 40% unload point, and 30 psig minimum sump pressure:

$$\%P = 25\% + 0.972 \times \%C \text{ (Ave. capacity} < 40\%)$$
$$\%P = 57\% + 0.43 \times \%C^2 \text{ (Ave. capacity} >= 40\%)$$

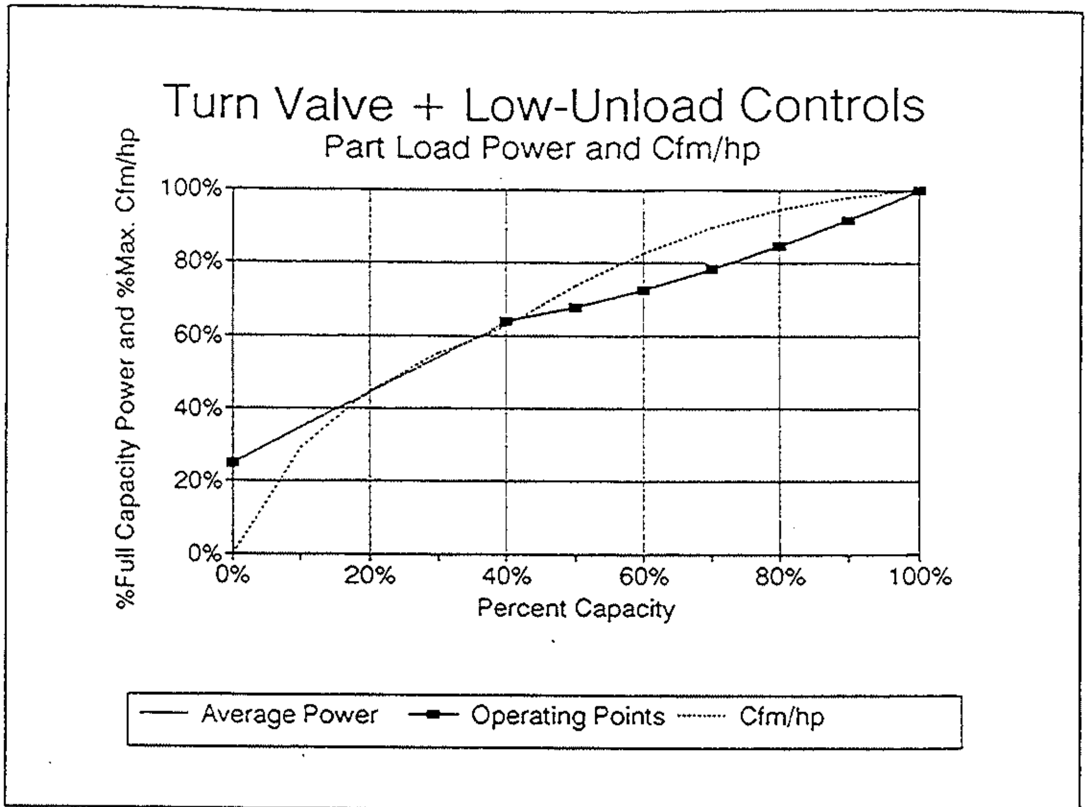


Figure 24: Turn Valve + Low-Unload Energy Use, Partial Unloading

Note: In cases where the unload point is adjustable, it is recommended that the unload point be increased as high as possible, 80% capacity for example, until the cycle time is a short as deemed acceptable for operation. A minimum unloaded time of 30 seconds under normal plant demand conditions is suggested. The energy savings can be seen graphically by looking at Figure 23 and then moving the unload point to the right. The total area under the curve is reduced, and additional savings are possible. Since spiral/turn/poppet valves are already efficient in the higher load region, available savings for this adjustment are less significant for compressors with this type of control.

**Applications:** Low-Unload control is a good compromise between modulation and load-unload. It does not outperform either of the other two modes if the operating conditions can be clearly defined as matching requirements of modulation or load-unloading. Low-unload control excels when load conditions vary over the course of a day. An example of appropriate application of low-unload control would be a plant where there is a steady high load during first shift, intermittent demand on second, and holding pressure for a fire system at night. In this case, the compressor would mostly modulate during the day, load-unload at night, and mix it up during the evening shift. Since this type of situation is common, this control strategy is frequently the preferred choice.

| VARIABLE SPEED DRIVE + MODULATING CONTROLS | | | |
|---|---|---|---|
| Minimum Storage Capacity | Low Load Efficiency | High Load Efficiency | Controlled Variables |
| Small | Fair | Excellent | Compression Rate and Inlet Pressure |

**Thermodynamics:** Only the compression rate changes until the minimum compressor speed is reached. At this point throttling begins.

**Mechanics:** A compressor system with a variable speed drive (VSD) controls the compressed air production rate by changing the rotational speed of the screws. When demand is high, the screws turn faster and displace more air per minute than when demand is low and rotation is slower. The minimum capacity (and speed) has a lower limit of between 25% and 50% capacity.[7] Once the screw drops below the critical speed, seals between the screws and either the cylinder walls or each other will begin to fail and the resulting leakage will prevent proper operation. Therefore a low load strategy must be included with VSDs. Either modulation or unloading can be used to drop capacity without further slowing the screws. This guidebook only considers modulation, because the biggest advantage VSDs seem to offer is that they offer modulation down to low loads while maintaining efficiency.

**Energy Use:** Like low-unload controls, there are two different operating modes. During periods of high demand, the VSD controls the modulation. If the average load drops below the minimum level that can be compensated for with the VSD, the compressor will stop reducing speed and reduce capacity further with either a butterfly, slide, turn, or poppet valve arrangement. An example situation would be a plant that has scaled back operation and has an oversized compressor, but has tight pressure requirements.

Using throttling and assuming 35% minimum VSD functional capacity as an example, the energy use equations are:

$$\%P = 35\% + 0.46 \times \%C \text{ (Ave. capacity} < 35\%)$$
$$\%P = 24\% + 0.76 \times \%C \text{ (Ave. capacity} >= 35\%)$$

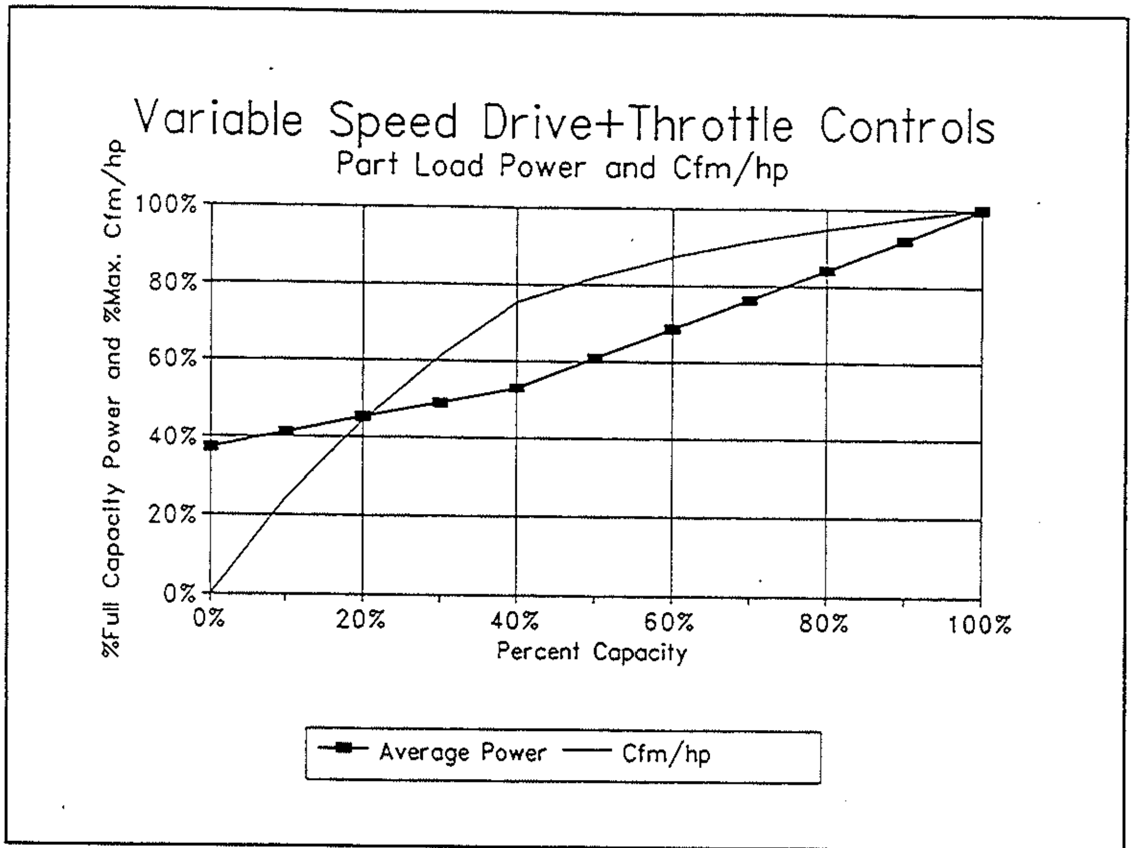


**Figure 25:** VSD with Throttle, modified from DOE bulletin CS/40520-T2

**Applications:** VSDs are the most expensive of all of the control options and are not typically offered by compressor manufacturers as a standard configuration. When combined with modulation, however, VSDs have the singular advantage of offering relatively high efficiency across the full capacity range with the convenience of full modulating control. VSDs would be appropriate when extended low demand periods are expected and a range of supply pressures is unacceptable.

## CONTROL STRATEGY SUMMARY

The following table summarizes headers for each control strategy. Efficiency values are provided to help quantify relative performance for part load conditions. They represent the percent of maximum possible cfm/hp required to compress air if demand operated uniformly between 0 and 50% load (low), and between 50 and 100% load (high).

| Control Strategy | Minimum Receiver Size | Low Load Efficiency | High Load Efficiency | C. V.+ |
|---|---|---|---|---|
| Throttling | Small | Poor 31% | Good 80% | $p_i$ |
| Turn Valve | Small | Poor 39% | Excellent 90% | $V_i$ |
| Poppet Valve | Small | Poor 38% | Excellent 88% | $V_i$ |
| On-off | Large | Excellent 100% | Excellent 100% | rate |
| Load-Unload | Large | Average 57% | Excellent 94% | $p_i$, $p_o$ |
| Low-Unload* (Throttle) | Medium | Fair 44% | Good 80% | $p_i$** $p_i$, $p_d$*** |
| Low-Unload* (Turn/Poppet) | Medium | Fair 41% | Excellent 90% | $V_i$** $p_i$, $p_d$*** |
| VSD+Throttle* | Small | Fair 48% | Excellent 92% | rate $p_i$ |

* Mode switching points are as described in the previous section.
** When modulating
***When unloading

Each control strategy has strengths and weaknesses. The job of the equipment purchaser is to determine which ones are most appropriate for the application being considered. Figure 26 shows the relative efficiency for most of the control strategies described above.

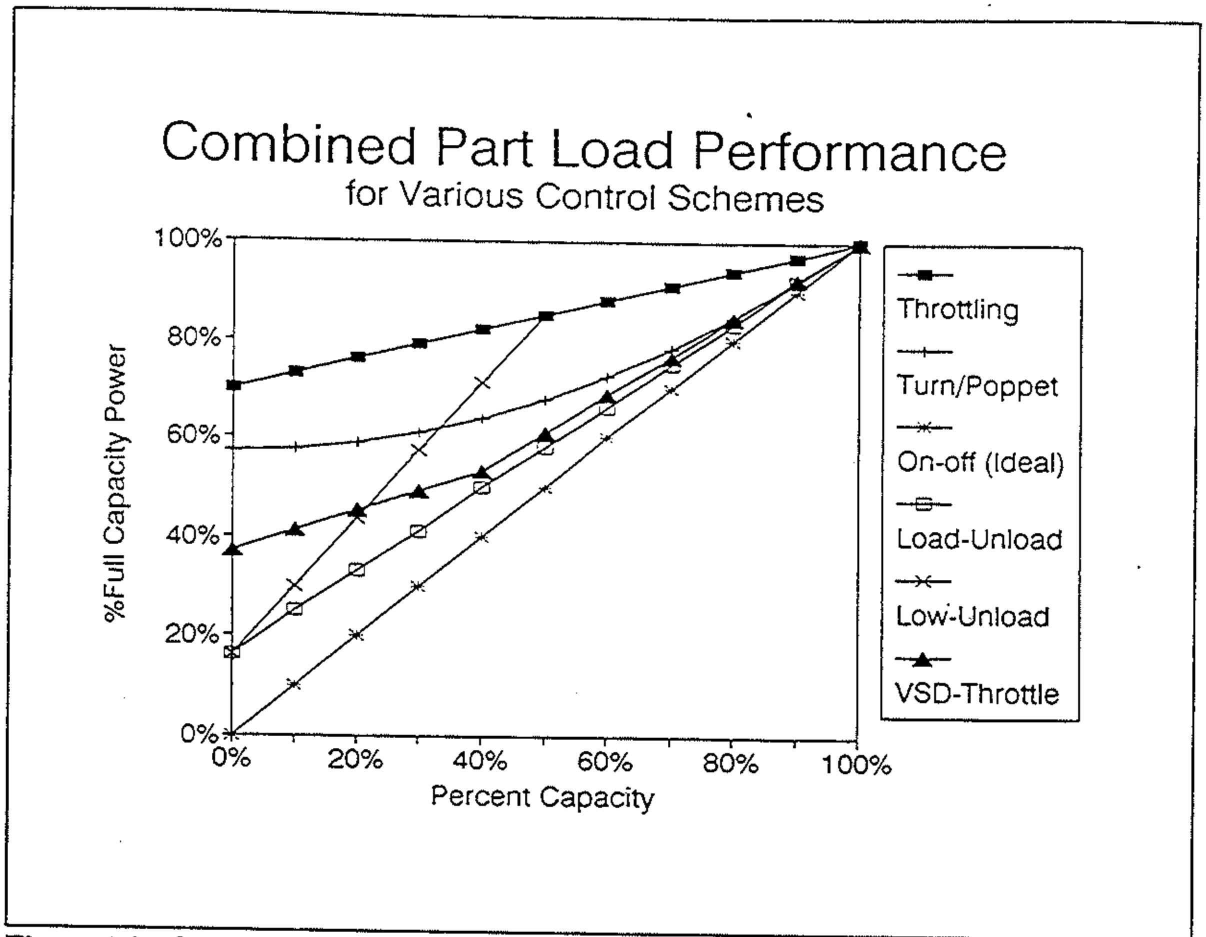


**Figure 26:** Combined Part Load Performance

If efficiency were the only issue, it would be simple to look at the graph, determine the most frequent load condition expected, and purchase a compressor with the most efficient controls available at that condition. Of course, extenuating circumstances affect every decision. Receiver capacity is important. If the maintenance department is understaffed, modulating compressors may merit extra consideration based on their simplicity. Or, if the staff is not highly trained, the issue of microprocessor-based controls becomes more important. Sometimes the local manufacturer's representative for a particular brand may have earned brand loyalty due to exceptional support in the past. Obviously, these issues do not show up in mathematical formulas.

Nonetheless, a compressor system will cost much more to operate over its lifetime than to buy. And it won't always run at full load, so part load efficiency must be considered an important decision-making criteria.

The decision-making tree shown in Figure 27 may help in the decision-making process. It is based on the assumption that energy efficiency is the most important issue. When using the tree, keep in mind that adding receiving capacity will almost always pay for its cost when part load conditions are expected and modulating control would otherwise be the only option. It also may be a worthwhile investment to buy a receiver to make load-unload operation possible when low-unload operation would otherwise be chosen.

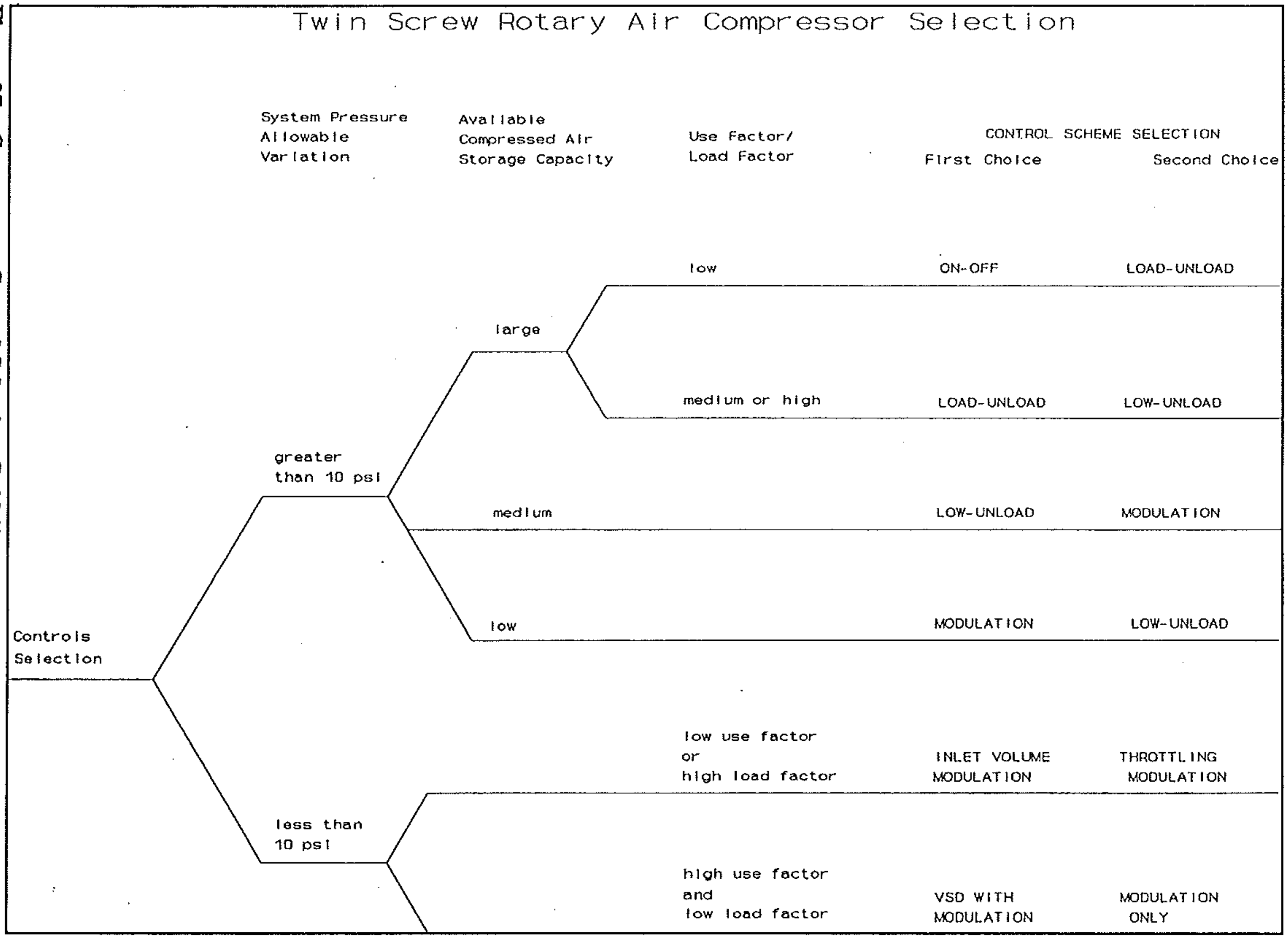


Figure 27: Compressor Control Selection Guideline

## A WORD ABOUT SEQUENCING

Compressor sequencing control is a whole subject in its own right, and several manufacturers offer elaborate microprocessor-based controls to operate multiple compressors together. The primary objective of sequencing is to deliver the proper quantity of air at the desired pressure. The secondary objective is to do this in an efficient manner. If you are not fortunate enough to have a magic black box to make decisions for you, the following tips can serve as guidelines:

- Use the compressor with the best part load efficiency characteristics as the "top" or "swing" compressor. For example, arrange the compressors so that modulation controlled compressors always run at full load or are off, and a reciprocating compressor or screw with unloading runs at part load to meet demand.

- Use compressors with the best full load cfm/hp as base compressors. Obviously, this rule will interact with the previous one if the compressor with the best part load control is also the most efficient compressor at full load.

- Meet demand requirements as closely as possible. For example, if you have a 50 hp,a 150 hp, and a 300 hp compressor with a load that can be met by running the smaller compressors together, use them rather than the 300 hp compressor alone, because the smaller compressors will run closer to full load and avoid poor part load performance by the large compressor.

- Sequence compressor use so that the fewest number of compressors actually operate at any given time. The previous recommendation gets priority to this one, but does not necessarily contradict it. For example, if you have 175 hp of plant air demand and have one 200 hp, and two 100 hp compressors available, energy consumption will normally be less if the single 200 hp compressor is used. This is because the volumetric efficiency (cfm/hp) is frequently better for larger compressors. This type of decision-making can be challenging as the number of available compressors increases.

- All of the above being stated, it is also healthy to ensure that all compressors are rotated for use regularly. Just like cars, compressors seem to be happiest when they are used at least occasionally.

- Do not operate more than one compressor at part load. Setting the maximum pressure on one compressor to be slightly lower than the others is an easy way to meet this objective. Two compressors operating at part load may disguise the fact that one of them could be turned off. Also, multiple compressors with unloading controls probably will not operate properly if their set pressure ranges overlap.

- Avoid starting all of the compressors at one time. It is hard on the distribution equipment.

## A WORD ABOUT MICROPROCESSOR-BASED CONTROL

Computerized controllers currently do not include actuating devices other than those already described. They do offer options such as performance monitoring and maintenance scheduling. More significant for this book, electronic devices offer logical options for part load control that are not otherwise available.

One manufacturer offers a controller that can switch from load-unload mode to throttling mode depending on demand. Another design calculates demand and directs the compressor to switch between load-unload and on-off control. Timers are also more likely to be incorporated when microprocessor-based control is used.

Compressor sequencers are often computer controlled when the desired sequencing logic cannot be simulated with pneumatic controls. While electronic controllers are not yet installed on all single compressor systems, their popularity is growing. More manufacturers are offering microprocessor controls as standard equipment, especially on large (>200 hp) horsepower systems.

## COMPRESSED AIR ENERGY CONSERVATION OPPORTUNITIES

There are basically three parameters that can be adjusted to reduce the average power required by an air compressor: required system pressure, amount of air required, and equipment efficiency. First, the effects of each parameter are described, and then a list of ideas to reduce energy use are offered.

### Reduce Air Demand

Compressed air is an expensive commodity. Any action taken to reduce the overall plant demand will save money. As a rule of thumb, screw compressors commonly require between 0.2 and 0.3 hp/cfm at 100-125 psig and full loaded.

Measures

**Fix leaks:** Air leaks are the pneumatic equivalent of leaving lights on. Leak repairs are generally a cost-effective use of time. Leaks are most easily found during breaks or when the shop is otherwise quiet. Ultrasonic detectors that can find leaks based on sound are available for less than $2,000. Plumbing connections, hose fittings, pressure regulators, line and control valves, valve packings, hoses, and pneumatic cylinders are all common criminals. For example: a 1/8" hole in a 100 psig air line will release 26 cfm and cost $763 /yr, based on a $0.02 /kWh energy cost, a $4.00 /kW-mo demand cost, two shift operation, and a 0.3 hp/cfm compressor efficiency. Other leak rates are shown below.[8]

| Hole Diameter | 1/64" | 1/32" | 1/16" | 1/8" | 1/4" | 1/2" |
|---|---|---|---|---|---|---|
| Leak Rate (cfm) | 0.406 | 1.62 | 6.49 | 26.0 | 104 | 415 |

**Engineered nozzles:** Perhaps the most common use of compressed air is the blowdown of dirty equipment or people. Engineered nozzles offer two main benefits: First, they can provide the same air velocity as an open hose with a significantly lower volumetric air flow rate, much like a water-saver shower head. Second, they often have quick-release grips, which means that air is only delivered for the instants it is needed. Washing your car certainly requires less water when a squeeze grip handle is used. The same applies for air use.

**Reduce branch system pressure:** If all equipment and processes that draw air from a branch of the main air supply line have minimum pressure requirements lower than the minimum system pressure, the air pressure can be dropped for the entire branch. This saves money in two ways: first, any leaks in that particular branch will lose less air compared to a higher line pressure; and second, the equipment uses no more air than is needed.

**Capacity-controlled regenerative dryers:** Regenerative dryers employ two tanks that contain desiccants, chemicals used to attract moisture from the air. The tanks alternate, with one tank drying air while the other is being reactivated. Reactivation is performed by sending clean dry air through the off-line tank and ejecting it. Normally regenerative dryers operate on a timer. However, since the regeneration process can use a considerable quantity of compressed air, it is beneficial to perform the regeneration only as often as necessary. Installing a moisture-sensing device instead of a timer to prevent unnecessary regeneration cycles and effectively reduce plant air demand.

**Isolate fire system:** If your fire system requires compressed air, then setting up a dedicated air line can save money by avoiding leaks that exist in the rest of the air system. Since leaks won't be fed during shutdown periods, substantial savings are possible.

## Reduce Required Discharge Pressure

As a rule of thumb, 1/2 % of full load power can be saved for every psi the discharge pressure can be decreased. Savings will be slightly less, about 0.4%, for two stage screw compressors because they are more efficient to begin with.[9]

### Measures

**Reduce minimum system pressure:** Set the minimum system pressure so that it delivers air at the minimum acceptable pressure level to the user. If the pulley ratio between the motor and compressor is also adjusted, this has a potential benefit of increasing compressor capacity as well. For example, a 150 hp compressor may be rated to deliver 620 scfm at 125 psig but it can deliver an additional 140 scfm by decreasing the discharge pressure to 100 psig and increasing the compressor speed.

**Reduce pressure drop across oil separator/dryer/filter:** Every obstruction to a straight path for compressed air leaving the compressor will drop the system pressure relative to the compressor discharge. A corroded separator element, clogged drying coils, a dirty drying filter, plugged or faulty automatic drain valves, or ignored manual liquid drain valves will cause an unnecessary pressure drop before the air ever gets to the receiver. To avoid this, check equipment and replace expendable parts according to scheduled maintenance. If there is a significant amount of equipment downstream of the compressor, you can install a differential pressure gage between the receiver and the discharge port of the compressor to make it easy to monitor the pressure drop. In most cases, the pressure should not drop by more than 5 psi (unless unloaded, of course).

**Install larger pipes:** There will always be a pressure drop between the compressor and the end user because of pipe friction. If the air lines are too small because of increased air use in an area (or perhaps low-bid contracting), the compressor will have to discharge air at an unnecessarily high pressure to deliver the desired pressure at the demand source. Large pipes also improve operations as described in other recommendations on local manifolds and increasing receiver capacity.

**Looped piping:** Air lines throughout the plant should form a closed loop with take-offs for individual areas. Looping effectively doubles pipe capacity in terms of response to demand. Consequently, the pressure drop due to pipe friction can decrease significantly. Looping has the additional benefits of balancing air lines and improving the efficiency contribution of remote receivers.[10]

**Local manifolds:** A local manifold in a work area acts as a mini-receiver for that area. This is beneficial because it helps minimize the effect of one user's air demand on other user's supply pressure if the two users are close together. This can save energy as well as provide more desirable working conditions because the first action the users will take to remedy low pressure problems is to march over to the maintenance shop and demand higher pressure air so he or she can get the job done.

**Reduce pressure at night:** Since high pressure air is more expensive than low pressure air, its is beneficial to drop the system pressure whenever there is no reason to maintain a high pressure. For example, if a day-shift-only piece of equipment requires 120 psig air and the machinery used for all three shifts only needs 90 psig air, then 10% (2/3 shifts x 30 psi x 0.5 %/psi) savings can be realized by dropping the system pressure when the day-shift equipment goes off-line. This is not necessarily the most practically implemented course of action, but it can be done.

## Equipment Related Opportunities

A diverse collection of actions can be taken to improve equipment efficiency and performance.

### Measures

**Install low-unload controls:** Since modulating-only controls can be so much less efficient than methods that employ unloading when capacity is low, there is often significant available savings from installing unloading controls on the existing compressor. For one manufacturer, low-unload controls can be installed for less than $1,500. As an added option on new equipment, the additional cost will likely be less. When appropriate and used as designed, payback time is commonly measured in months.

**Increase receiver capacity:** All compressors that unload or turn off experience cycling losses, as alluded to repeatedly in previous sections. Losses are primarily caused by the release of compressed air in the oil separator, compressor discharge pipe, and any other space upstream of the main check valve that precedes the aftercooler. Reduced efficiency during unloading and reloading also occurs, because the compressor is likely to operate briefly in a part load condition. On-off controls will endure potential life reduction and modest energy losses every time the motor restarts due to temporary high input current. Perhaps most importantly, increasing the air storage capacity can significantly help improve the applicability of the first measure described above. Adding air storage capacity can improve equipment performance and product quality by reducing the rate of change of supply pressure. For example, an airbrushing operation, can be very sensitive to quick pressure changes.

**Reheat air:** The delivery of compressed air is fundamentally an energy transfer process, little different than electricity. Thus, adding heat to the air increases its energy value. When considered from this perspective, conservation measures such as capturing heat energy from the compression or drying processes becomes quite understandable. There are many potential heat sources; pre-cooled oil from the oil separator sump and compressed air are the most commonly captured heat sources. However, waste heat from industrial processes other than the compressor system also can be considered as a source of energy for the compressed air. In a typical 100 psig system, 15%-20% of the rejected heat can be recovered as compressed air energy.[11] An additional benefit is that the relative humidity of the compressed air will be significantly lower - 8% compared to 100% relative humidity if the temperature is raised from 70°F to 160°F. Reheating is appropriate for many applications, but may be less cost-effective when air demand is very low compared to storage capacity, or if the receiver is located outside in a cool climate and the reheater must precede the receiver.

**Heat recovery:** If the heat energy from the air and oil cooling operations cannot be returned to the compressed air, you may be able to use the rejected heat to warm ambient plant air in the winter. One company makes a heat recovery unit that will thermostatically regulate the temperature of exhaust sent air to the plant at a comfortable level in the winter, and reject the hot air outdoors during warm weather conditions. Claimed savings is about 5.5 MMBtu/hp/year based on three shift operation.

**Install Air intake in cool location:** In seeming contrast to the above opportunities, it is beneficial to draw air into the compressor from the coolest possible location. Under atmospheric conditions, air becomes denser as temperature drops. Since the required pressure does not change, the compression ratio can be reduced without reducing the flow rate or discharge pressure of the compressed air. As a rule of thumb, you can save 1% of compressor demand for every 10°F that the inlet air temperature is reduced.[12]

**Efficient motors:** This is an easy one to understand. Since any 50 hp motor will deliver 50 hp to the shaft, it is obvious that you will save money if less energy is required by the motor to deliver that 50 hp. Many compressor manufacturers offer the option of specifying an energy efficient motor instead of a standard efficiency motor when purchasing a new compressor. The economic decision is easy if payback is considered relative to the life of the motor - always buy an energy-efficient motor - but the payback issue is not nearly as straightforward when payback time is measured in years. A simplified rule of thumb for a user with a $0.04 /kWh average energy cost is that the additional cost of a high-efficiency motor to pay for itself within three years if the compressor is used an average of 10 hours/day or more. The same logic can be used when replacing or rewinding a burnt out motor, but the numbers will vary. Replacing a working standard efficiency motor with a high efficiency motor is rarely a good investment. However, an easy way to save compressor energy savings with an efficient motor is to find an efficient motor of the same frame size and horsepower elsewhere in the plant that is not used as often as the compressor motor. Then, swap the motors. You have to be pretty lucky to find a match, but if possible, this action requires no capital expenditure.

**Efficient drive belts:** Forget this if the motor is directly coupled to the compressor. No belt can transfer the energy of the motor shaft to the compressor shaft with 100% efficiency. Standard V-belts lose most of their energy by slipping around the sheave. The friction causes heat generation and energy loss. There are two alternatives to standard V-belts. Notched V-belts fit on a regular pulley but are approximately 2% more efficient than standard V-belts (source). The notches help the belt bend around the pulley more easily and reduce slippage. They cost slightly more than regular belts, but the reduced slip, reduced heat generation, and better dissipation of heat that does get generated help notched belts last longer than standard belts. They are therefore a smart choice in many applications, including compressors.

The second alternative is installing a high torque drive. This is a more expensive option because high torque drives require special matched pulleys. They work more like a chain than a conventional V-belt, and slippage is eliminated. A high torque drive will be 4-8% more efficient than a standard V-belt and can be economical for compressors that have high operating hours.

**Clean intake filter:** It is always desirable to maintain a clean air filter at the compressor intake. An oily or clogged filter can reduce compressor capacity by causing a partial vacuum to form between the filter and the compressor intake. This could cause the unnecessary purchase of additional air compressors (see maintain throttle below). Some manufacturers include a vacuum gauge that indicates the pressure drop across the filter. You can also install a gauge yourself.

**Combine air lines:** If the plant currently uses two or more independently operating compressed air circuits operating at approximately the same system pressure, it is frequently beneficial to combine them into a single system with multiple sequenced compressors. Savings are especially high when the involved compressors typically operate at part load. Savings will be low if one of the loops requires near full capacity from its compressor.

**Increase unload point:** Unless the receiver is too small, load-unload type controls are typically more efficient than low-unload controls. This is because the power required for modulation is higher than the average power required when the compressor loads and unloads. Load-unload controls don't modulate at all while low-unload controls do. Therefore, if adjustable low-unload controls are set with a higher unload point, the compressor will modulate less often during each cycle. Furthermore, a higher unload point will cause the compressor operate in the more efficient cycling mode up to a higher percentage of full load capacity. The only notes of warning necessary here are that undersized receivers can cause the compressor to reload too soon at high loads, and that some vacuum switches used to measure capacity can be unpredictable if the unload point is set above 80%.

**Maintain modulating valve performance:** Screw air compressors are low maintenance, dependable pieces of machinery, but the modulating valves can gradually lose their accuracy without any obvious indication of deterioration. One consultant estimated that over 80% of all throttling valves fail to maintain their designed behavior.[13] If your compressor has a capacity gauge, you can judge throttle performance easily, by first opening a relief valve so that maximum compressor capacity is required and then intentionally valving off the compressor discharge completely. If the gauge does not range from 100% to 0% capacity, then the valve is not working properly (or the gauge has failed). The most disastrous energy cost from this problem occurs when plant demand appears to exceed the capacity of a single compressor so a second one is unnecessarily added. The capital cost isn't particularly pleasant either.

**Use blowers for low pressure applications:** Up to about 10 psig, blowers are a more efficient means of providing compressed air than by reducing plant air pressure down from 90+ psig to the desired pressure. The unnecessary compression and decompression costs money. This situation commonly occurs when a liquid requires non-mechanical agitation. It is much easier to tap a line off of an existing air line than to go to the trouble of purchasing a blower. However, using a blower is frequently more economical.

**Downsize at night:** Often, the main plant air compressor is used to maintain pressure in a dry fire system. If manufacturing stops after one or two shifts, a much smaller compressor can maintain pressure for the fire system without all the inefficiencies of low part load use. The same logic can apply if third shift demands are much lighter than first shift. For maximum savings, be sure to eliminate as many leaks as possible before sizing the small compressor. If the leak load is a large percentage of the total load, this opportunity won't work.

## BIBLIOGRAPHY


British Columbia. Hydroelectric Industrial Energy Management, *Efficient Compressed Air Systems: A Reference Guide for Positive Displacement Air Compressors, Capacity Controls, and Dryers*, Bulletin 30540, Vancouver, BC, undated.

Brown, Royce N., *Compressors: Selection and Sizing*, Gulf Publishing, Houston, 1986.

Carrol Hatch & Associates, *A Report to Bonneville Power Administration on Industrial Compressed Air Energy Efficiency* (draft report), Portland OR, July 1990.

Gardner-Denver Cooper Industries, *Electra-Saver Rotary Screw Air Compressor 100 to 500 hp*, 3rd edition, Bulletin 13-10-200, 1989.

Gibbs, Charles W., ed., *Compressed Air and Gas Data*, Ingersoll-Rand, New York, 1971.

LeRoi Division of Dresser Industries, Inc., *WE-Series Rotary Screw Compressors*, Bulletin LC-11-SS 12-86HG, Sidney, OH, 1986.

Novak, W. M., *Some Basic Measures for Conserving Energy in Compressed Air Systems*, Plant Engineering, February 19, 1976.

Oviatt, Mark D., and Richard K. Miller, *Industrial Pneumatic Systems: Noise Control and Energy Conservation*, Fairmont Press, Atlanta, 1981.

Pasternak, Lanny, Airflow Energy, Ltd., *Reducing Air Leaks*, presented at the Electric Ideas Workshop: Compressed Air Systems, Portland OR, December 12, 1991.

Sullair Corporation, *Sullair Operators Manual and Parts List: 100 hp series 25 Motor Driven Compressor*, Michigan City, IN.

Sullair Corporation, *Engineering Manual on Compressors*, Michigan City, IN, 1989.

Van Ormer, Henry, *Capacity Control Influences Power Cost for Your Plant's Rotary-Screw Compressors*, Power magazine, McGraw-Hill, December, 1976.

Varigas Research, Inc., *Compressed Air Systems: A Guidebook on Energy and Cost Savings*, Publication Number DOE/CS/40520-T2 (DE84008802) prepared for the U. S. Department of Energy, Office of Industrial Programs, under contract number AC03-81CS40520, Timonium, MD, March 30, 1984.

Wells, Lyle, Rogers Machinery Co., *Compressed Air Systems and Operational Savings Opportunities*, presented at the Electic Ideas Workshop: Compressed Air Systems, Portland OR, December 12, 1991.

Zurn Industries, *Compressed Air Data: A General Guide for the Selection and Comparison of Compressed Air Dryers, Separators, and Filters*, Form 411 ADV, Erie, PA, 1985.

## ENDNOTES


1. Frank Richards, Compressed Air: Practical Information Upon Air-Compression and the Transmission and Application of Compressed Air (New York: John Wiley & Sons, 1895), pp. 7-8.

2. Gardner-Denver-Cooper Industries, Electra-Saver Rotary Screw Air Compressor, 100-500 hp, 13-10-200, (1989), p. 3, and LeRoi Division of Dresser Industries, WE Series Rotary Screw Compressors, (Sidney, OH: 1986), p.6.

3. Sullair Corporation, Engineering Manual, (Michigan City, IN: Sullair, 1991), performance curves. Also taken from Charles W. Gibbs, ed., Compressed Air and Gas Data, (New York: Ingersoll-Rand, 1971), p.16-4.

4. William O'Keefe, Air Compressors, Power Magazine, June, 1977, p. S-11.

5. Eugene Avallone and Theodore Baumeister III, eds., Marks' Standard Handbook for Mechanical Engineers, 9th edition, (New York: McGraw-Hill, 1986), p.4-10.

6. O'Keefe, p. S-7.

7. Based on a data from bulletin DOE/CS/40520-T2, USDOE Office of Scientific and Technical Information, Technical Innovation Center.

8. Mark D. Oviatt and Richard K. Miller, Industrial Pneumatic Systems: Noise Control and Energy Conservation, (Atlanta: Fairmont Press, 1981), 64.

9. Sullair Corporation, Sullair Series 32/25 200-600 hp, Bulletin E953, 1989, p.4. Also from Sullair Engineering Manual performance curves.

10. Lyle Wells, Compressed Air Systems, presentation at The Electric Ideas Workshop: Compressed Air Systems; Opportunities for Energy and Cost Savings, December 12, 1991.

11. Walter M. Novak, Some Basic Measures for Conserving Energy in Compressed Air Systems, Plant Engineering (reprint of article), February 19, 1976, p.4.

12. According to Mark D. Oviatt and Richard K. Miller, Industrial Pneumatic Systems: Noise Control and Energy Conservation, (Atlanta: Fairmont Press, 1981), p. 49, the savings will be about 1% power per 5°F. This estimate is based solely on the increasing inlet air density. However, compressor must work harder to compress the denser air. Therefore, the net effect on power is clower to 1% savings per 10°F. Interview with Lyle Wells, Rogers Machinery Co., November 12, 1992.

13. B.C Hydro, Efficient Compressed Air Systems: A reference guide for positive displacement air compressors, capacity controls, and dryers, Vancouver, BC, p.18.