AN ABSTRACT OF THE THESIS OF

Eric G. Bessey for the degree of Master of Science in Mechanical Engineering presented on May 14, 2001. Title: Operation and Maintenance Procedures for Improving Compressed Air System Efficiency.

Abstract approved: Redacted for Privacy

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Air compressors are a significant industrial energy user and therefore a prime target for industrial energy audits. The project goals were to develop a software tool, AIRMaster, develop a methodology for performing compressed air system audits, and conduct field audits to refine the methodology and assess savings potential from six common Operation and Maintenance (O&M) measures. AIRMaster and supporting manuals are designed for general auditors or plant personnel to evaluate compressed air system operation with simple instrumentation during a short-term audit. AIRMaster provides a systematic approach to compressed air system audits, analyzing collected data, and reporting results. AIRMaster focuses on inexpensive Operation and Maintenance measures, such as fixing air leaks and improving controls, that can significantly improve performance and reliability of the compressed air system, without significant risk to production.

An experienced auditor can perform an audit, analyze collected data, and produce results in 2-3 days. AIRMaster reduces the cost of an audit, thus freeing funds to implement recommendations. AIRMaster proved to be a fast and effective tool. In seven audits AIRMaster identified energy savings of 4,056,000 kWh, or 49.2% of annual compressor energy use, for a cost savings of $152,000. Total implementation costs were $94,700 for a project payback period of 0.6 years. Available airflow increased between 11% and 51% of plant compressor capacity.

Operation and Maintenance Procedures for Improving Compressed Air System Efficiency

by

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A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented May 14, 2001
Commencement June 2001

Master of Science thesis of Eric G. Bessey presented on May 14, 2001

APPROVED:

Redacted for Privacy

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Eric G. Bessey, Author

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1. INTRODUCTION

1.1 Background

Air compressors are a significant industrial energy user, and therefore a prime target for energy audits. Based on analysis of energy audit reports from 125 northwest plants, air compressors account for an average 10% of total plant energy use (1). Furthermore, air compression is inefficient, with much of the compressor power dissipated as heat. Thus, even minor improvements in system operation, control strategies, and efficiency can yield large energy savings. Many industrial plants have significant air leaks, or inappropriate uses of compressed air. Because the cost to compress air is high, reducing compressed air losses to system leaks and inefficient uses of air can also produce energy and cost savings.

1.2 Project Goals

The project purpose set five primary goals:

1. Develop a software tool to estimate savings from O&M improvements. AIRMaster is a spreadsheet-based software program that estimates existing and proposed compressed air system energy use and costs.

2. Assess savings from six common Energy Efficiency Measures (EEMs). These measures were chosen because they are O&M measures commonly recommended during energy audits and include:

   - **Reduce plant air leaks**. Determine proposed airflow profiles based on leak reduction and fixed airflow adjustments.

- **Adjust manual staging (no sequencer)**. Adjust pressure control ranges on modulating compressors to avoid multiple compressors operating inefficiently at partload.

- **Use unloading controls**. Install or adjust existing unloading controls with optional automatic shutdown timer to improve partload efficiency. This measure requires adequate receiver capacity to avoid unloading cycle times less than two minutes.

- **Reduce system pressure**. Reduce system pressure to reduce compressor power. Compressor discharge pressure is reduced in order to minimize power required to compress air and system airflow requirements. Care must be taken to ensure that critical end uses have adequate pressure.

- **Sequence compressors**. Sequence compressors to turn compressors on and off automatically, as needed, and to allow changing the sequence order to balance wear.

- **Reduce run time**. Turn off compressors that are not needed at specified times. Compressors that would otherwise operate to feed leaks are turned off.

3. Develop a methodology and manual to perform compressed air system audits: to collect data and to analyze compressed air systems.

4. Validate the tool and methodology from field audits. Seven plants were audited to refine and develop the methodology as well as assess the savings potential of the EEMs.

5. Improve O&M cost estimation. Use audit results to determine the savings potential of the EEMs.

The audits should use only simple instrumentation during a relatively short time. The focus was on Operation and Maintenance (O&M) measures because these measures typically have low capital costs, quick paybacks, and low risks.

1.3 Contents

Chapters 2 through 4 describe analysis methods used by AIRMaster to analyze data collected during the compressed air system audit. Refer to the glossary when definitions of terms are needed. This methodology covers the following topics:

- Single and multiple compressor analysis
- Airflow control strategies
- Operating pressure ranges-multiple compressor control
- System operating profiles
- Power, energy, and savings calculations
- Energy Efficiency Measures

Chapter 5 describes features and capabilities of the analysis tool, AIRMaster. Specific software operating instructions can be found in User's Manual for AIRMaster (2). AIRMaster evaluates potential Operation and Maintenance (O&M) measures to maximize the performance of existing compressed air systems. O&M measures are those that typically can be carried out by O&M personnel, and generally entail low capital costs, few operating risks and quick paybacks.

Chapter 6 summarizes procedures and result for seven field audits The purpose of the audits were to refine AIRMaster and methodology as well as assess the savings potential and implementation cost estimation of six common Operation and Maintenance measures. See Case Studies: Compressed Air System Audits Using AIRMaster (3) for full descriptions of each audit.

Five appendices support the body of the thesis. They include nomenclature used in the analysis methodology, application and barriers for each EEM, an EEM cost guide, and a glossary of terms.

2. AIRFLOW CONTROL

2.1 Airflow Control Strategies

This section includes different airflow control strategies and multiple compressor control. Mathematical formulas that model power and airflow are given for different airflow control strategies. These formulas are the basis for calculating compressor power given system airflow requirements. Refer to the glossary and Appendix A as needed.

This methodology includes three airflow control strategies used to match part load compressor output to system requirements: modulation, flow/no flow, and low-unload. Compressor part load operation is modeled using normalized power versus airflow profiles, as shown in Figure 1.

2.1.1 Modulation

There are two types of modulation: throttle and variable displacement. Airflow is controlled by the position of the throttle or variable displacement device which is proportional to discharge pressure within the proportional modulation pressure range. The proportional modulation pressure range is the difference between the full load discharge pressure (the minimum discharge pressure, PMIN) and the no load discharge pressure (the maximum discharge pressure, PMAX). This range is generally fixed for compressors with mechanical pressure regulators, but may be variable for compressors that use pressure transducers with electronic control.

In general, when discharge pressure is low, either the throttle is wide open or the variable displacement device is fully closed, resulting in full air delivery. If airflow is less than the capacity of the compressor, discharge pressure will increase until PMIN is reached. At this point, the throttle will begin to close or the variable displacement device will begin to open, reducing airflow from the compressor. Modulation continues until compressor airflow matches plant air requirements and discharge pressure stabilizes. If no air is required from the compressor (for example, another compressor can meet airflow requirements), discharge pressure will continue to increase and modulation will continue until PMAX is reached and no air flows from the compressor. At this point the throttle is completely closed or the variable displacement device is completely open. If pressure drops below PMAX, the compressor will begin to modulate again.

2.1.1.1 Throttling

Throttling is a form of inlet modulation accomplished by a butterfly or slide valve, and is typically found on rotary screw compressors. Airflow is reduced by creating a partial vacuum at the compressor inlet by closing a butterfly or slide valve. The result of this control strategy is a linear reduction in power with airflow (4). Part load performance will fall on a straight line drawn between the full load and no load operating points. An example is illustrated in Figure 1 with no load power ($\%P_{nl}$) at 68% of full load power.

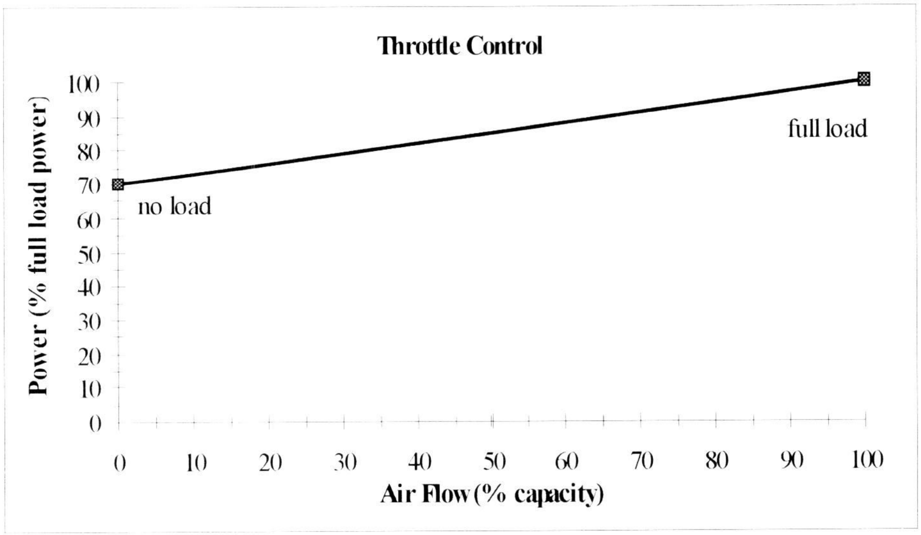


Figure 1: Performance Profile for Throttle Control

For a given compressor load, airflow expressed as a percentage of compressor capacity (%C) can be calculated from power expressed as a percentage of full load power (%P) using the following formula:

$$\%C = \frac{\%P - \%P_{nl}}{100\% - \%P_{nl}}$$

Given airflow, power can be calculated using the following formula:

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

2.1.1.2 Variable Displacement

Variable displacement is the other form of modulation used on rotary screw compressors. Variable displacement may be achieved through the use of turn, spiral, or poppet valves. As air requirements decrease, the turn or spiral valve rotates, allowing intake air to escape to atmospheric pressure through ports in the compression chamber walls, shortening the effective rotor length and displacement. The volumetric compression ratio and airflow are reduced, resulting in a nearly quadratic reduction of power with airflow (5) as shown in see Figure 2. Similarly, poppet valves open to allow intake air to escape through the compressor housing, reducing airflow.

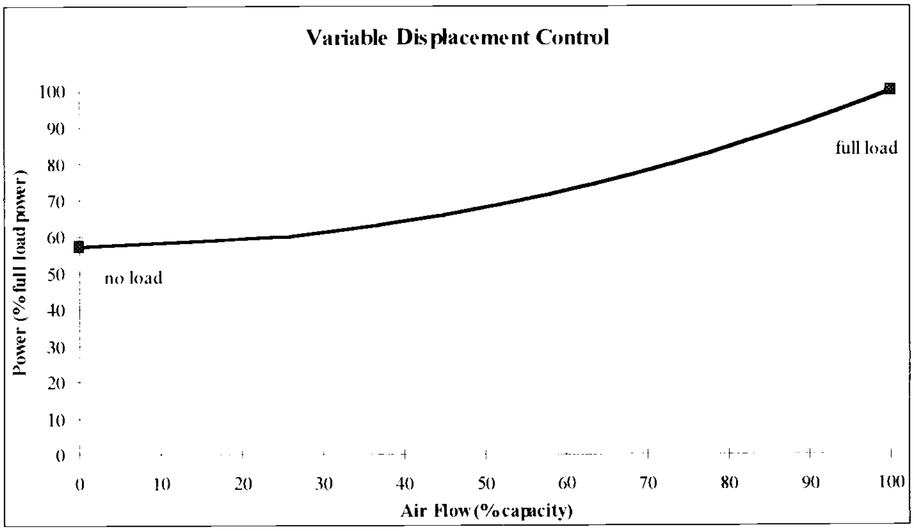


Figure 2: Performance Profile Variable Displacement Control

For a given compressor load, airflow can be calculated from power using the following formula:

$$\%C = \sqrt{\frac{\%P - \%P_{nl}}{100\% - \%P_{nl}}}$$

Given airflow, power can be calculated using the following formula:

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

2.1.2 Flow/No Flow

The three types of flow/no flow controls are: load-unload, on-off, and multi-step.

2.1.2.1 Load-Unload

Load-unload controls on rotary screw and reciprocating compressors allow the compressor to operate at two points: full load and no load (unloaded). The compressor operates at full load until the system reaches the maximum discharge pressure (PMAX) at which time the compressor unloads.

An unloading valve at the compressor discharge of a rotary screw compressor vents the oil separator and sump to a lower pressure. Compressors with an oil pump vent to atmospheric pressure, while other compressors vent to some other pressure that is greater than atmospheric, but lower than system, pressure. A check valve prevents system air from leaking back through the compressor. Simultaneously, a valve at the intake of a rotary screw compressor closes to prevent air from being drawn into the intake.

For reciprocating compressors, intake valves remain open to prevent pressure buildup in the cylinders. Air drawn into a cylinder is pushed back out to the atmosphere. A check valve prevents system air from leaking back through the compressor.

No modulation occurs with load/unload controls. The compressor reloads when system pressure drops to the minimum discharge pressure (PMIN). Typical pressure ranges (PR = PMAX - PMIN) are 10 psi to 25 psi depending on how sensitive end uses are to pressure variation and cycle time (see "Use Unloading Controls" in Appendix B).

No load power is reduced because the compressor discharge pressure is less than system pressure. Average power is modeled as a straight line with average airflow between full and no load. Figure 3 shows this with no load power (unloaded) at 17 percent of full power. The dashed lines indicate the compressor never actually operates between full load and no load.

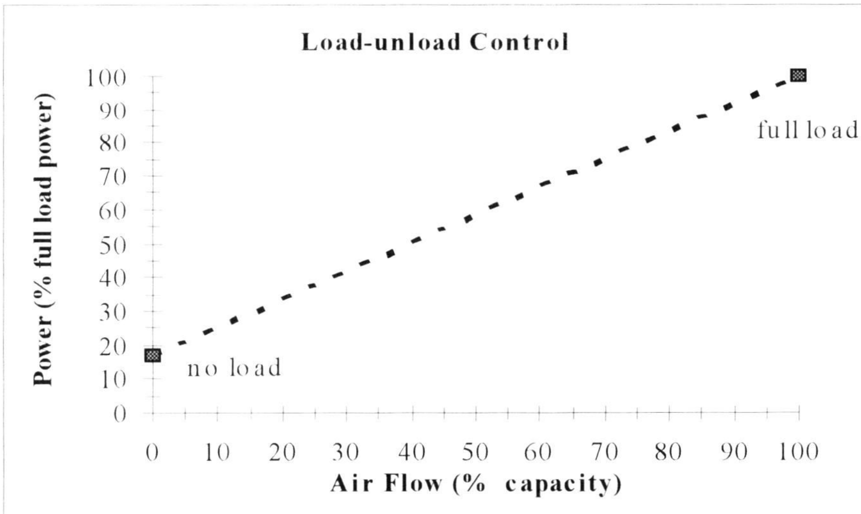


Figure 3: Performance Profile for Load-Unload Control

For a given compressor load, average airflow can be calculated from average power using the following formula:

$$\%C = \frac{\%P - \%P_{nl}}{100\% - \%P_{nl}}$$

Given average airflow, average power can be calculated using the following formula:

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

These formulas are identical to those for throttle control.

2.1.2.2 On-Off

On-off control is similar to load-unload control and is found primarily on reciprocating compressors. The compressor operates at full load until PMAX is reached, at which time the motor turns off. An unloading valve opens allowing the air in the compressor to vent. This makes it easier for the compressor to restart. A check valve prevents system air from leaking back through the compressor. When system pressure drops to PMIN, the compressor turns back on. Typical pressure ranges are 10 psi to 25 psi depending on how sensitive end uses are to pressure variation and cycle time (see "Use Unloading Controls" in Appendix B).

On-off control is more efficient than load-unload control because the compressor consumes no energy at no load. This strategy is also modeled as a linear reduction in average power with average airflow (Figure 4).

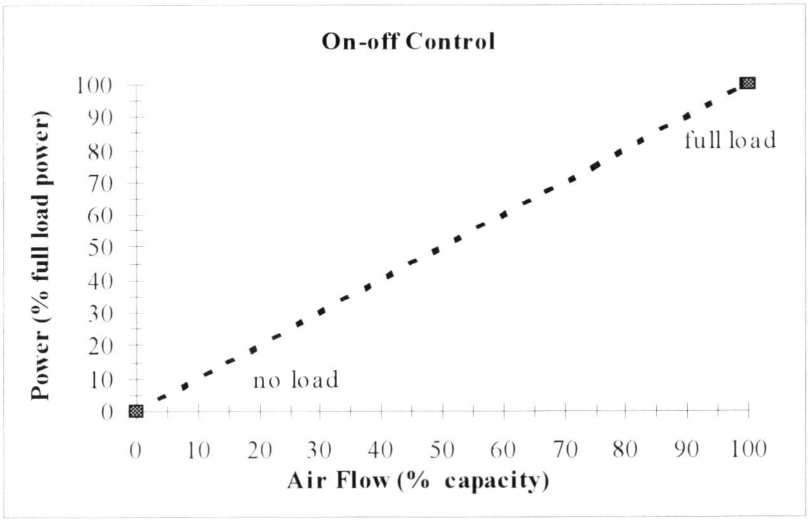


Figure 4: Performance Profile for On-Off Control

Since no power is required when no air is delivered, average airflow equals average power as shown below.

$$\%C = \%P$$

2.1.2.3 Multi-Step

Multi-step control is found only on reciprocating compressors. Reciprocating compressors with multiple pistons, either single or double acting type, reduce capacity by opening intake valves or chambers. Individual cylinders or banks of cylinders (usually two at a time) unload to provide different airflow delivery. For example, a six cylinder might unload two cylinders at a time to produce the following possible airflow delivery: 0%, 33%, 67%, and 100% of the compressors capacity. Pressure ranges can be kept narrower than with other flow/no flow controls (approximately 2 psi between steps).

Multi-step control is not a true flow/no flow control type. However, the part load performance of a compressor with multi-step control is modeled the same as a compressor with load-unload control: power as a straight line with airflow. The compressor operates at full load, no load, and one or more intermediate loads (see Figure 5).

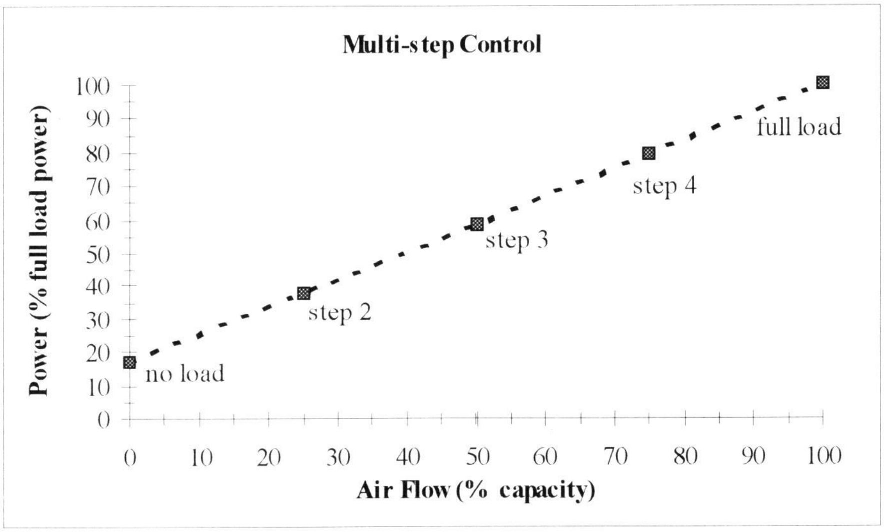


Figure 5: Performance Profile for Multi-Step Control

For a given compressor load, average airflow can be calculated from average power using the following formula:

$$\%C = \frac{\%P - \%P_{nl}}{100\% - \%P_{nl}}$$

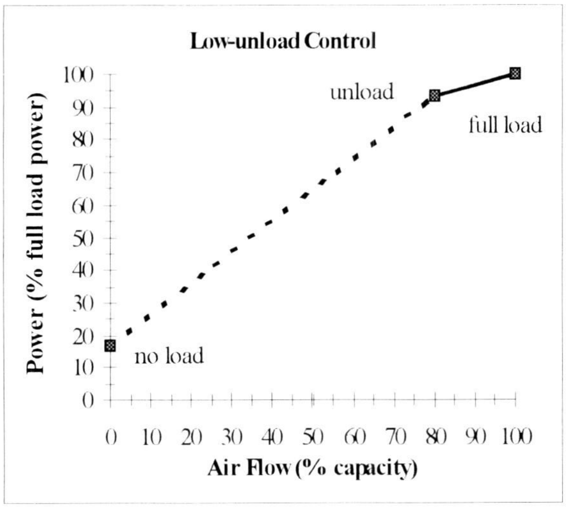
Given average airflow, average power can be calculated using the following formula:

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

These formulas are identical to those for throttle and load-unload controls.

2.1.3 Low-Unload

This control strategy is a combination of modulation and load-unload controls, and is found only on rotary screw compressors. Modulation may be either throttle or variable displacement. Compressors operate at full load until the full load discharge pressure is reached, then begin to modulate to match system air requirements. If airflow requirements are above the unload point, the compressor will modulate to this airflow, where it will remain. If air requirements are below the unload point, discharge pressure will continue to increase and the compressor will modulate until PMAX (corresponding to the unload point) is reached, at which time the compressor will unload. An unloading valve opens allowing the air in the compressor to vent. A check valve prevents system air from leaking back through the compressor. Reloading occurs when system pressure drops to PMIN. The unload point may be adjustable or permanently set by the manufacturer. If the unload point is set at 100% of capacity, the control behaves as load-unload control. Typical pressure ranges are 10 psi to 25 psi depending on how sensitive end uses are to pressure variation and cycle time, and if the compressor is cycling (see "Use Unloading Controls" in Appendix B). Figure 6 shows part load performance for compressors with unload points set at 80% and 40% of compressor capacity respectively.



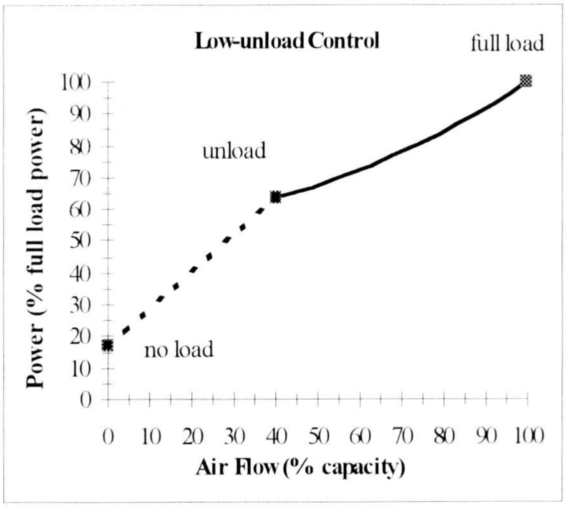


Figure 6: Performance Profiles for Throttle and Variable Displacement Modulation with Low-Unload Control

Modeling for airflow between full load and the unload point is the same as previously described for the appropriate modulation control. Compressor power is modeled as a straight line with airflow between no load and unload. Average airflow is found from average power according the following formulae:

$$\%C = \frac{\%P - \%P_{nl}}{\%P_{ul} - \%P_{nl}} \times \%C_{ul} \qquad (\text{avg. } \%C < \%C_{ul})$$

$$\%C = \left[(\%P - 100\%) \times \frac{100\% - \%C_{ul}}{100\% - \%P_{ul}} + 100\% \right]^{\frac{1}{n}} \qquad (\text{avg.} \%C \geq \%C_{ul})$$

Given average airflow, average power can be calculated using the following formulae:

$$\%P = \frac{(\%P_{ul} - \%P_{nl})}{\%C_{ul}} \times \%C + \%P_{nl} \qquad (\text{avg. } \%C < \%C_{ul})$$

$$\%P = \left(\%C^{n} - 100\%\right) \times \frac{100\% - \%P_{ul}}{100\% - \%C_{ul}} + 100\% \qquad (\text{avg.}\%C \geq \%C_{ul})$$

where,

n = 1 for throttle control.

n = 2 for variable displacement.

2.2 Operating Pressure Ranges-Multiple Compressor Control

Compressors may be staged or sequenced so they will delivering air in a predictable order. For example, a system may have a 1000 acfm, a 500 acfm, and a 100 acfm compressor. The operator may wish to have the 1000 acfm compressor begin delivering air first. This machine would act as the "lead" compressor. The operator may then want the 500 acfm compressor to deliver air after air requirements increase beyond the lead compressor's capacity. Finally, the operator may want the 100 acfm compressor to deliver air, acting as the trim machine. Also, the operator may want the order in which the compressors deliver air to vary over the operating period. All of this can be accomplished by staging or sequencing the compressors properly. This is done by setting pressure regulators, pressure switches, or sequence order.

This section describes the staging or sequencing of compressors so the auditor may understand how AIRMaster analyses multiple compressor systems. Depending on compressor control strategies, either staging or sequencing describes how multiple compressors are controlled. There are fundamental differences between staging and sequencing, so first a description of both is necessary so the auditor will understand which is applicable to the compressed air system under study. In either case, one or more compressors may use an automatic shutdown timer that turns off a compressor after it has operated at no load for a specified amount of time. Automatic shutdown timers are usually found only on compressors with unloading controls, however some manufacturers offer them on modulating-only compressors with electronic control.

Staging refers to the order in which compressors deliver air according to their pressure range. Staging applies to compressed air systems with compressors not controlled by an automatic sequencer and use fixed pressure control settings. If compressors are controlled by an automatic sequencer, then staging does not apply and the following definition for sequence is used.

Sequence refers to the order in which compressors are brought “on line” (compressors are either turned on or reloaded to deliver air) according to a programmed automatic sequencer, or pressure settings for compressors with unloading or on-off controls. Refer to the definition of staging, above, for compressed air systems not controlled by an automatic sequencer.

These definitions are simplified ones, and although there are exceptions, they reduce the complexity of user input when using AIRMaster. Following are detailed descriptions of staging and sequencing, and include examples.

2.2.1 Staging

The full load discharge pressure (PMIN) and pressure range (PR) for each compressor are important when staging multiple compressors. The PMINs dictate which compressors will be in lead, second and third positions, and so on. With staged compressors, system pressure remains constant for a given system airflow. Any given system airflow can be met by finding a system pressure where the sum of each compressor’s contribution matches the requirement, as shown in the following examples.

For example. consider three 1,000 acfm compressors with a system airflow requirement of 1,500 acfm. The compressors in Figure 7 have non-overlapping pressure ranges, resulting in nonoverlapping, staged operation; system pressure equals 103 psig. The compressors in Figure 8 have overlapping pressure ranges, resulting in overlapping, staged operation; system pressure equals 111 psig. The compressors in Figure 9 have identical pressure ranges, resulting in simultaneous modulation; system pressure equals 113 psig.

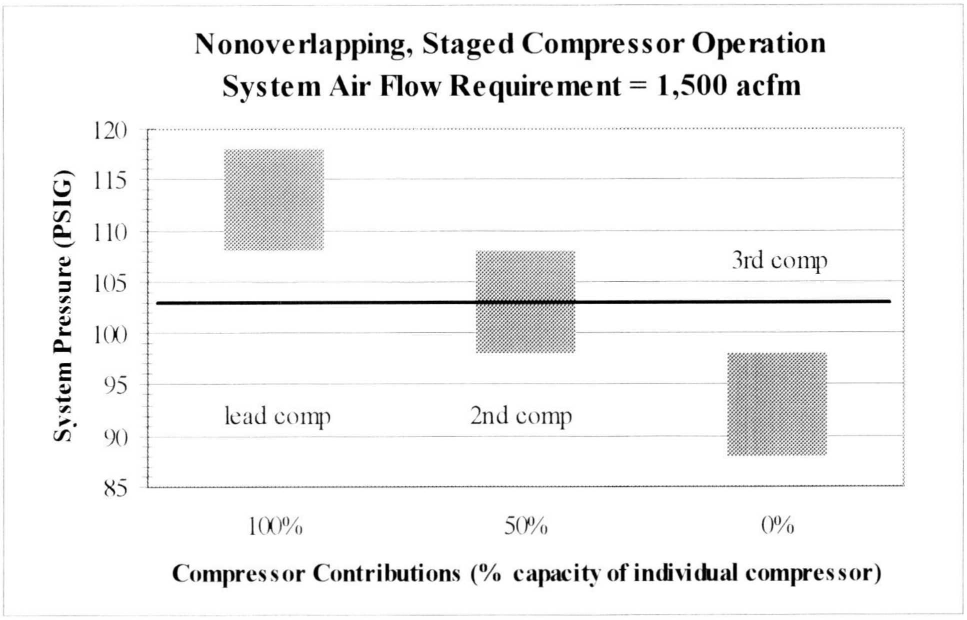


Figure 7: Compressors with Nonoverlapping Staged PRs, System Pressure Equals 103 psig

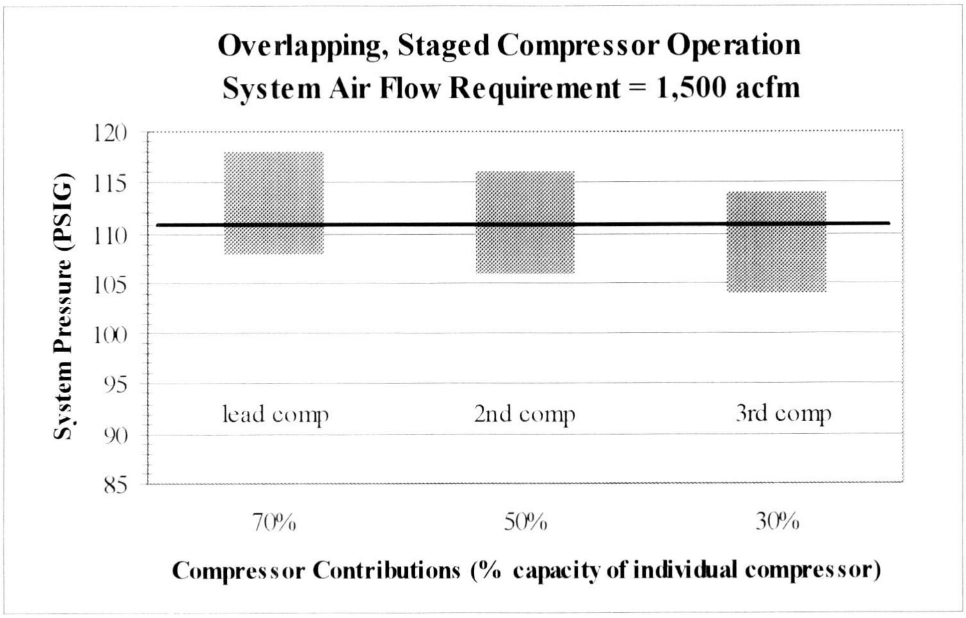


Figure 8: Compressors with Overlapping, Staged PRs, System Pressure Equals 111 psig

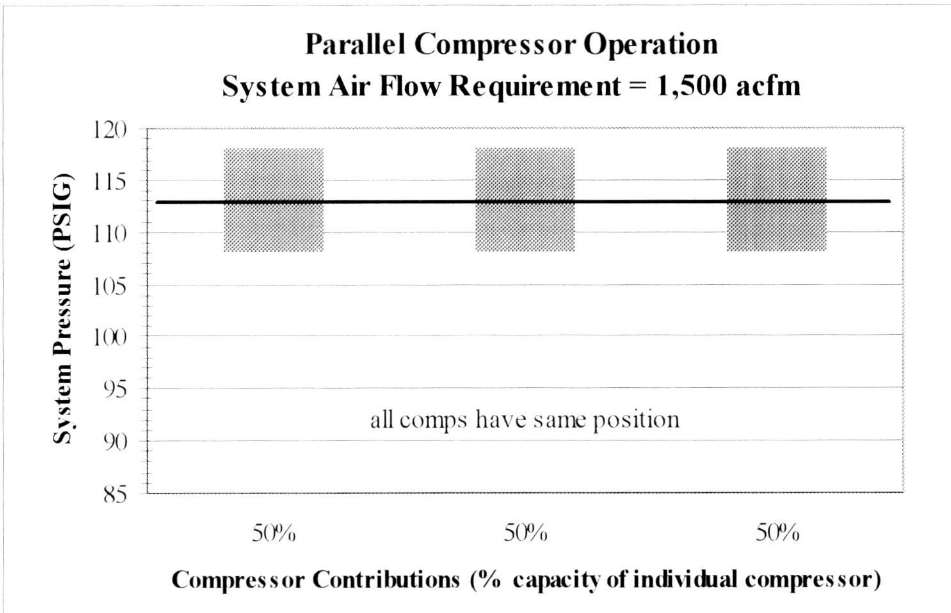


Figure 9: Compressors with Identical PRs, System Pressure Equals 113 psig

2.2.2 Sequencing

Sequence order (lead, second, third, and so on) is dictated by minimum discharge pressure settings for each position. Airflow requirements that can be met by the lead compressor alone will leave the second and third compressors unloaded. The lead compressor will cycle within its pressure range. Other compressors remain unloaded or off because system pressure never drops to the other compressors' minimum discharge pressure (pressure where another compressor comes on line). If airflow requirements increase, system pressure will drop to the second compressor's minimum discharge pressure, and the second compressor will reload and deliver air. The second compressor will cycle and the lead will remain at full load. An exception to this is if minimum discharge pressures and pressure ranges for compressors are the same. This results in simultaneous cycling and is an exception not handled by AIRMaster.

Compressors controlled by an automatic sequencer behave the same except the order is programmable, and may vary throughout the schedule. Automatic shutdown timers are used to turn off unloaded compressors after a specified amount of time. Control strategies that turn off unneeded compressors are most efficient.

Figure 10 illustrates sequenced compressors with an average system airflow requirement of 1,500 acfm. In this case, the lead compressor operates at full load, the compressor in second position cycles within its pressure range, and the third compressor is unloaded or off if equipped with an automatic shutdown timer.

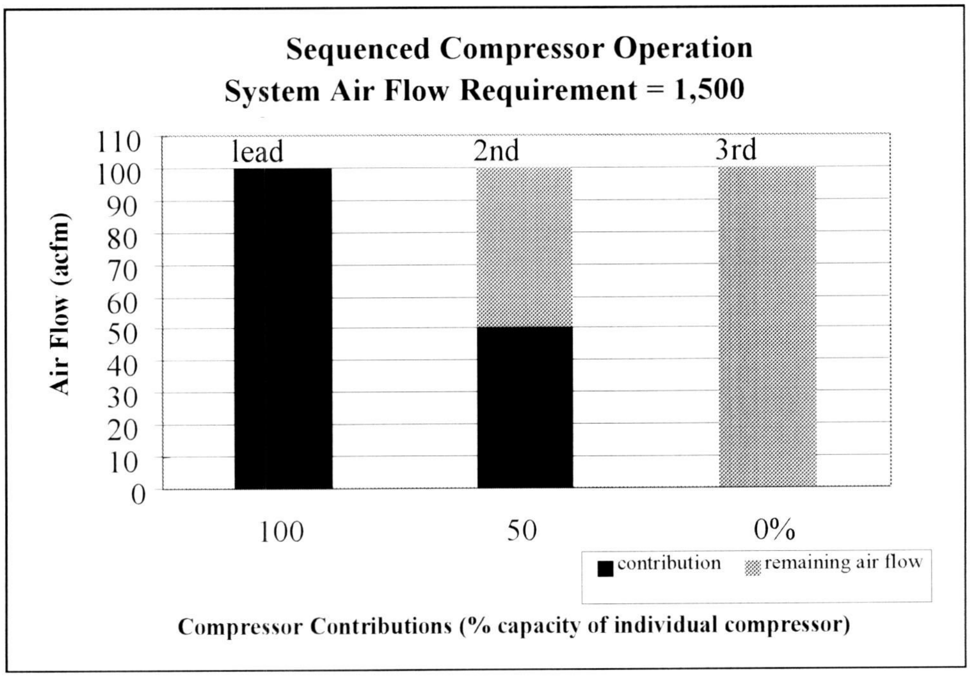


Figure 10: Sequenced Compressor Operation

Table 1 below summarizes the examples of staging and sequencing for a system airflow requirement of 1,500 acfm.

Airflow Distribution				
Corresponding Figure Reference	**System Pressure (psig)**	**Lead Compressor (acfm)**	**2nd Compressor (acfm)**	**3rd Compressor (acfm)**
Figure 7	103	1,000	500	0
Figure 8	111	700	500	300
Figure 9	113	500	500	500
Figure 10	varies	1,000	500	0

Table 1: Airflow Distributions for Staging and Sequencing Examples

3. OPERATING PROFILES

3.1 System Operating Profiles

3.1.1 Airflow and Power Profiles

Typical daytypes are used to model plant air use. A daytype is a 24 hour period representing a typical operating day, such as a production weekday, maintenance day, or weekend day (see the section on Daytypes in the User's Manual for AIRMaster (2) for more details). AIRMaster accepts up to four daytypes and an annual schedule of occurrence for each daytype. Hourly averages of airflow or power (collected from the field) are entered for each compressor and daytype. If current and voltages are entered, AIRMaster calculates power in kilowatts based on entered values, motor power factor and phase (see the Electrical Calculations section for power calculation if current and voltage are measured).

AIRMaster uses previously defined compressor performance profiles to calculate corresponding airflow or power. If airflow is entered, corresponding power for each compressor, hour and daytype is calculated. If power is entered, corresponding airflow is calculated using the appropriate formula based on compressor control strategy. Compressors operating at no load (delivering no air to the system) will be assigned no load power. Compressors turned off will be assigned zero power.

System airflow and system power profiles are created for each daytype. To create system airflow profiles, each compressor's airflow is weighted by its capacity compared to system capacity for each hour and daytype. For example, a 200 acfm compressor operating at 25% of capacity (50 acfm) and a 100 acfm compressor operating at 100% of capacity (100 acfm) would have a system airflow of 50% of system capacity [(50 + 100)/(200 + 100)]. Power for each compressor is added for each hour to create system power profiles. Examples of system airflow and power profiles for a daytype are shown in Figures 11 and 12 respectively.

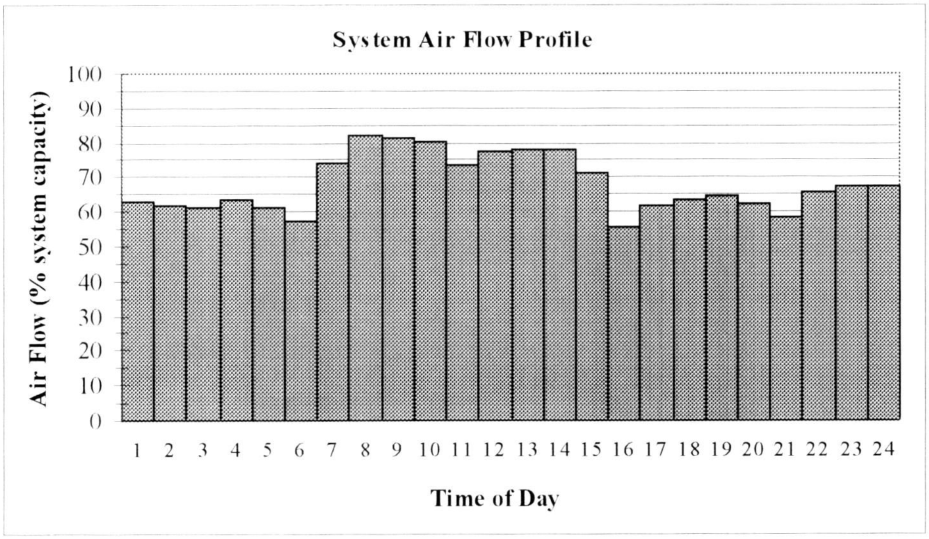


Figure 11: System Airflow Profile for a Weekday

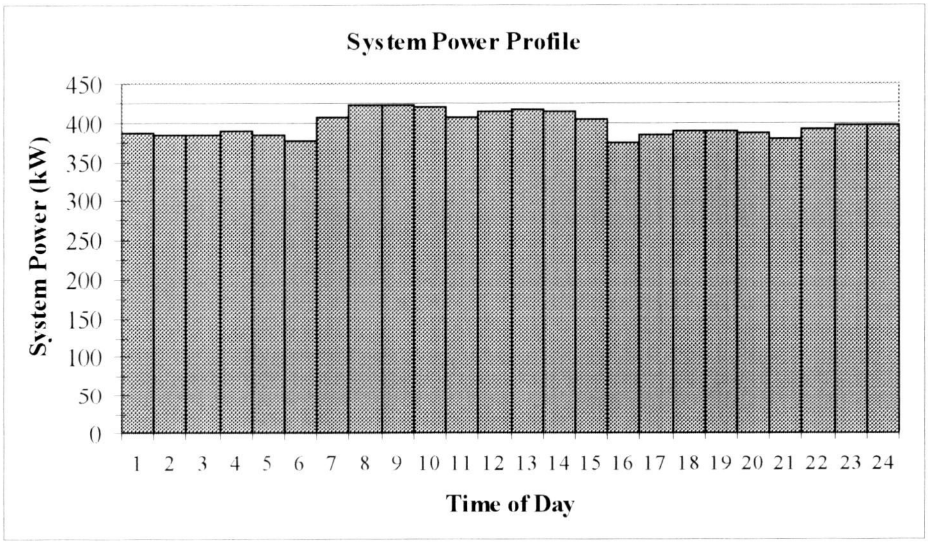


Figure 12: System Power Profile for a Weekday

3.1.2 Daytype Operating Schedules

Besides airflow or power contributions, operating schedules for each daytype must be entered. For each hour, enter an operating schedule indicating which compressors are on, along with their staging or sequencing order.

AIRMaster constructs compressor operating schedule profiles for each daytype based on user input. An example daytype operating schedule is shown in Figure 13.

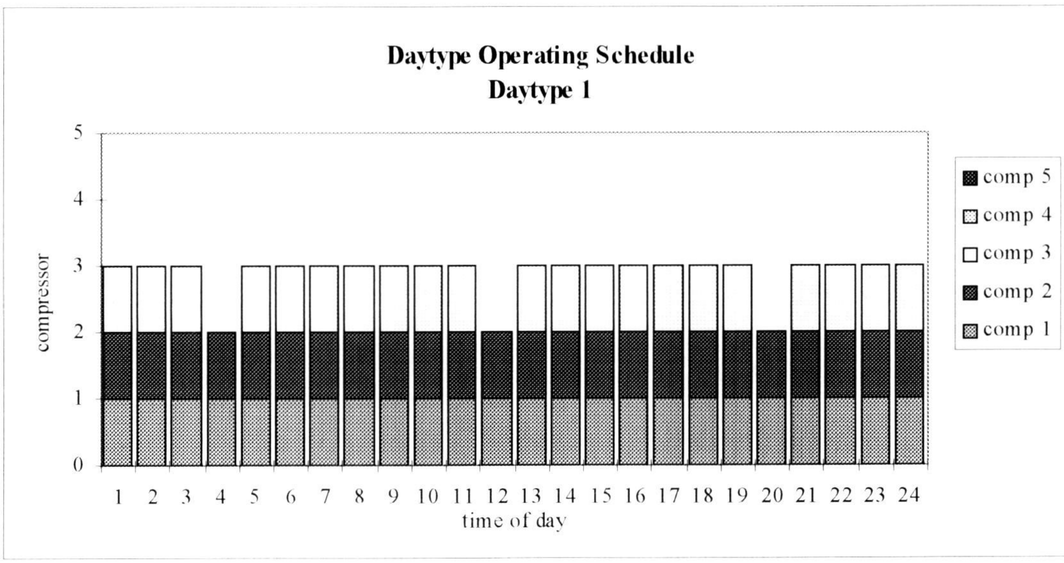


Figure 13: Daytype Operating Schedule

3.2 Airflow Calculations

Airflow (C) in acfm can be calculated by multiplying airflow by compressor capacity (C_{fl}).

$$C = \%C \times C_{fl}$$

Airflow expressed as a percentage of compressor capacity can be calculated by dividing airflow in acfm by compressor capacity by compressor capacity.

$$\%C = \frac{C}{C_{fl}} \times 100\%$$

3.3 Electrical Calculations

3.3.1 Power

Power meters are available and will measure three phase power in kilowatts directly. If a power meter is not available, power can be calculated based on voltage and amperage measurements. An average of all three line-to-line voltages and amperages should be used. Power is based on average voltage (V), average amperage (A) and motor power factor.

Motor power factor depends on motor size and load. Load is represented by percentage of full load amperage (%FLA), which is the average measured amperage divided by nameplate full load amperage. Nameplate full load amperage must be adjusted if measured average voltage differs from nameplate voltage. The following formula can be used to calculate percent full load amperage.

$$\%FLA = \frac{A \times V}{\text{nameplate full load amperage} \times \text{nameplate voltage}}$$

where,

A = average measured current: amps

V = average measure voltage: volts

Motor power factor is determined using Figure 14 (6).

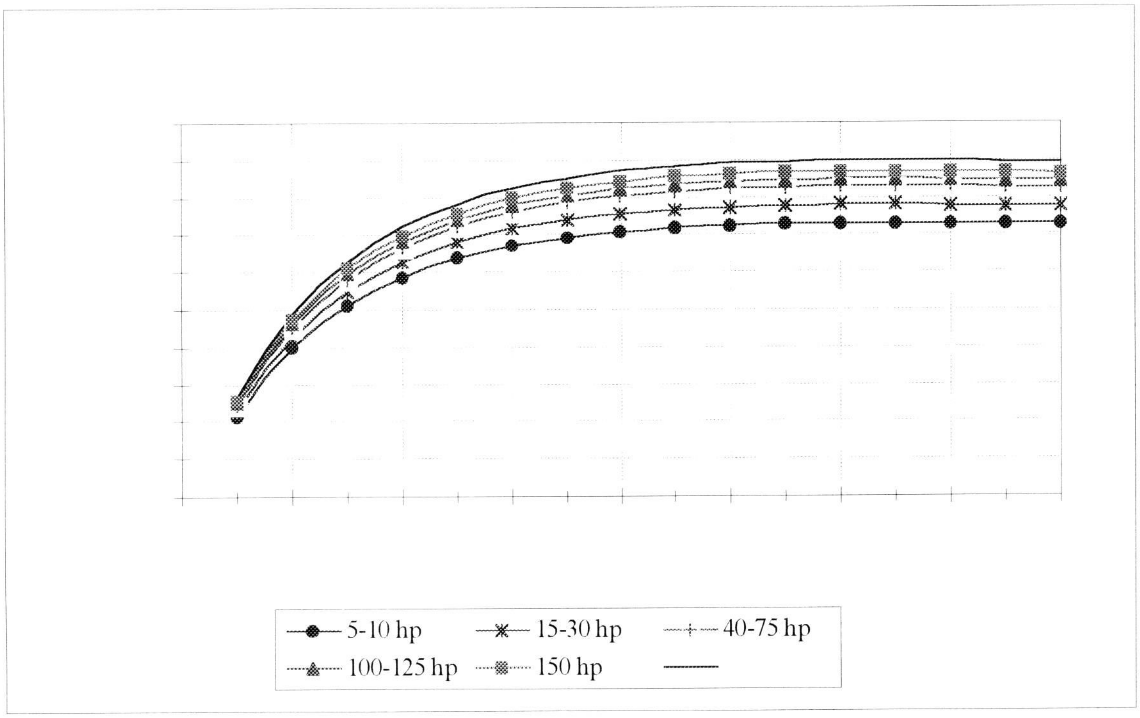


Figure 14: Motor Power Factor

Power (P) in kilowatts for a three phase motor in kilowatts is found from:

$$P = \frac{V \times A \times \text{power factor}}{1{,}000}$$

where,

power factor = cosine of the phase shift between current and voltage: %

Average power for a compressor that is delivering an average airflow between unload and no-load (compressor is cycling) is easiest using a power meter. Average power is found by monitoring the compressor over several cycles. If a power meter isn't available, alternative methods may be used. Refer to <u>Audit Manual for AIRMaster</u> (7) for details.

Another way is to calculate power based on an assumed average airflow and appropriate formula according to compressor control strategy. Power (P) in kilowatts for a given percentage of full load power (%P) is then calculated based on full load power.

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

AIRMaster assumes full load motor efficiency (η_{fl}) for loads above 25% of full load motor power. Efficiency corrections are made for loads below 25% of full load power. Below 25% of full load, motor efficiency losses (%losses@25%P) for a standard totally enclosed fan cooled induction motor are practically constant. Power is therefore calculated as:

$$P = \%P \times P_{fl} \times \eta_{fl}/\eta_{pl}$$

where partload efficiency for motor loads below 25% (η_{pl}) is:

$$\eta_{pl} = \frac{\%P}{\%P + \%losses@25\%P} \times 100\%$$

and,

$$\%losses@25\%P = \frac{25\%}{(\eta_{25}/\eta_{100})_{stndrd}} \times \frac{1}{\eta_{fl}} - 25\%$$

The quotient $(\eta_{25}/\eta_{100})_{stndrd}$ was calculated using a standard 100hp totally enclosed fan cooled induction motor (6).

$$(\eta_{25}/\eta_{100})_{stndrd} = \frac{91.6\%}{92.4\%}$$

Therefore, partload efficiency for motor loads less than 25% of full load is

$$\eta_{pl} = \frac{\%P}{(\%P + 25.22/\eta_{fl} - 25)} \times 100\%$$

If the load is given, then power expressed as a percentage of full load power may be calculated by dividing the measured load by full load power.

$$\%P = \frac{P}{P_{fl}} \times 100\%$$

3.3.2 Energy

Energy (E) in kilowatt-hours for a given power (P) is calculated as power times operating hours (H).

$$E = P \times H$$

3.3.3 Savings

Demand savings (DS) for a given operating condition after implementing an EEM is calculated as existing peak demand minus proposed peak demand. Existing and proposed peak demands are determined by locating the hour with greatest power of all daytypes. Existing peak demand may occur on a different hour than proposed peak demand. For example, if equipment is turned off during the existing peak demand time, the demand may drop below that of another time. This methodology assumes that plant peak demand coincides with compressor peak demand.

DS = existing peak demand - proposed peak demand

Energy savings (ES) are likewise calculated as existing energy minus proposed energy.

$$ES = \text{existing energy} - \text{proposed energy}$$

3.4 Economic Calculations

Demand cost savings (DC) are based on demand savings and are calculated as:

$$DC = DS \times \text{Demand Charge} \times \text{Months per year}$$

Months per year is the number of months the demand savings apply to. AIRMaster assumes this value is 12 and is fixed.

Annual energy cost savings (ES) is calculated as:

$$EC = ES \times \text{Energy Charge}$$

Demand and energy charges are average values and may be obtained from the plant's electric utility. Total annual cost savings (CS) is the sum of demand cost savings and energy cost savings.

$$CS = DC + EC$$

Simple payback period (PB) is determined by dividing the implementation cost (IC) by the annual cost savings for a particular EEM.

$$PB = \frac{IC}{CS}$$

4. ENERGY EFFICIENCY MEASURES

4.1 Analysis Order

Energy Efficiency Measures (EEMs) are analyzed in the order specified. Each EEM uses proposed operating conditions, such as proposed system airflow profiles, daytype operating schedules, and control strategies, from the previous EEM. For example, if the "reduce system pressure" EEM is analyzed after "reduce plant air leaks," then analysis for the "reduce system pressure" EEM will be based on operating conditions after analyzing for "reduce plant air leaks." This prevents savings from being double counted.

Except for item 2, AIRMaster can analyze EEMs in any order. Analyzing makes adjusting manual staging moot. The provided default order is shown below.

1. Reduce plant air leaks. Fixed airflow reductions, such as shutting of an air end use, can also be applied.

2. Adjust manual staging (no sequencer). This applies to systems whose compressors are equipped with modulating-only or unloading controls and where an automatic sequencer is not used. This EEM must be analyzed before running "sequence compressors" EEM.

3. Use unloading controls. Be sure unloading controls are available for the compressors. This EEM can be analyzed even if only one compressor has unloading controls available. This EEM can be used for compressors already equipped with unloading controls.

4. Reduce system pressure.

5. Sequence compressors.

6. Reduce run time.

4.2 Summary Tables

Existing and proposed operating conditions are included in the summary of each EEM in AIRMaster. Airflow and power are averaged by daytype over the hours in which at least one compressor is turned on. For example, if compressors are turned on eight hours in a day, then airflow and power is averaged only over the operating eight hours. Totals for operating hours and energy are provided and are the sums of all daytypes. Total power is the peak hourly demand found in all daytypes. Refer to Table 2 for an example of existing and proposed conditions for an EEM. Existing peak demand does not necessarily occur during the same daytype as the proposed peak demand. All EEMs assume each daytype occurs at least once during each of 12 consecutive months. Values are zero for daytypes not used.

Savings are calculated as the difference between existing and proposed conditions for each daytype, and are included in the savings summary. Energy, demand, and cost savings (energy plus demand savings) are calculated based on utility rate schedules. Totals for operating hours and energy are provided and are the sums of all daytypes. Total demand is the difference between existing and proposed peak demands. Refer to "Savings" in the Electrical Calculations section and the Economic Calculations sections for formulas used to calculate savings.

Existing Conditions					
Operating Conditions	Air Flow ($\%C_s$)	Power ($\%P_s$)	Power (kW)	Operation (hours)	Energy (kWh)
Weekdays	82.5%	94.4%	296.6	6,000	1,779,600
Weekends	51.1%	55.3%	173.7	800	138,960
daytype 3	0.0%	0.0%	0.0	0	0
daytype 4	0.0%	0.0%	0.0	0	0
Total		96.8%	304.1	6,800	1,918,560

Proposed Conditions					
Operating Conditions	Air Flow ($\%C_s$)	Power ($\%P_s$)	Power (kW)	Operation (hours)	Energy (kWh)
Weekdays	70.5%	90.6%	284.5	6,000	1,707,000
Weekends	39.1%	51.4%	161.5	800	129,200
daytype 3	0.0%	0.0%	0.0	0	0
daytype 4	0.0%	0.0%	0.0	0	0
Total		93.0%	292.1	6,800	1,836,200

Savings Summary						
Demand Charge:	$4.00/kW-mo.		**Energy Charge:**		$0.02500 /kWh	
	Demand (kW)	Demand ($)	Operation (hours)	Energy (kWh)	Energy ($)	Cost Savings
Weekdays			6,000	72,600	$1,815	$1,815
Weekends			800	9,760	$244	$244
daytype 3			0	0	$0	$0
daytype 4			0	0	$0	$0
Total	12.0	$576	6,800	82,360	$2,059	$2,635

Table 2: EEM Summaries

AIRMaster constructs an EEM savings summary table (see Table 3) using the total savings from each EEM and includes: peak demand, demand cost, energy, energy cost, and total cost savings. Also included in the EEM savings summary table is energy savings percent, implementation cost, and payback period. Energy savings percent for each EEM is its contribution to the total savings and is calculated as the EEMs energy savings divided by total energy savings. Implementation cost must be entered by the user. For example, unloading controls prices vary by manufacturer and model. Some tips are given in Appendix C: EEM Cost Guide. Simple payback is calculated as the implementation cost divided by the total cost savings for each EEM.

EEM Savings Summary										
Audit File:										
Demand Charge: $4. /kW-mo. Energy Charge: $0.02500 /kWh										
EEM #	EEM	Peak Demand kW	Demand $	Energy kWh	Energy $	% Energy Use	Cost Savings	Implementation Cost	Payback Years
1	**Reduce Leaks**	12.1	$579	82.130	$2.053	13.5%	$2.632	$1.000	0.4
2	**Manual Staging**	5.7	$274	38.172	$954	6.3%	$1.228	$100	0.1
3	**Unloading Controls**	33.1	$1.591	289.713	$7.243	47.6%	$8.834	$2.400	0.3
4	**Reduce Pressure**	28.4	$1.365	167.612	$4.190	27.6%	$5.555	$50	0.0
6	**Reduce Run Time**	0.0	$0	28.333	$708	5.0%	$708	$200	0.3
*	**Maximum Savings**	79.3	$3.809	605.960	$15.148	100.0%	$18.957	$3.750	0.2

Table 3: EEM Savings Summary

4.3 Analysis Procedures Common to All EEMs

By monitoring compressor power or airflow during various plant operating loads and the leak load, average power or airflow for each load and compressor is obtained. If power is measured, it is converted to percentage of full load power (%P) for each compressor. If airflow is measured in acfm, it is converted to percentage of capacity (%C) for each compressor. Corresponding airflow or power for all loads compressors is calculated according to compressor control strategies (see Figures 1 through 6). Refer to Chapter 2 for required information, explanation of compressor control strategy, part load characteristics, and formulas for calculating airflow or power. Existing operating conditions are included in the Existing Conditions table (see Table 2).

Proposed system airflow for all operating periods is apportioned among the compressors according to control strategies and daytype operating schedules (see Figures 7 through 10 and 13). Proposed power (%P) for each compressor is calculated for each plant operating load based on proposed airflows (%C) using formulas in Chapter 2.

Proposed system operating conditions and calculated savings are summarized in the Proposed Conditions and Savings Summary tables (see Table 2). Savings are determined by comparing existing and proposed operating conditions.

4.4 Reduce Plant Air Leaks

4.4.1 Introduction

Compressing air is inefficient, with as much as 90% of compressor power being dissipated as heat. Therefore, leaks can be expensive. Compressor loads are monitored during various operating conditions. This information is used to estimate how much of the compressed air is lost to leaks, and how much these leaks cost.

This EEM assumes only one leak load. However, multiple leak loads are possible if a portion of the plant is valved off during an operating period. Multiple copies of AIRMaster may be used to model multiple leak loads. Airflow delivered by available compressors is changed by reducing compressed air leaks throughout the plant and by making fixed airflow adjustments. Fixed airflow adjustments may include adding or removing equipment requiring compressed air. Such adjustments may increase or decrease airflow delivered by the compressors. In the case of increasing plant airflow requirements, the motive to fix leaks becomes clear. By reducing leaks, the need to purchase or turn on another compressor may be eliminated. In most cases however, plant personnel will reduce leaks to a proposed level, thereby reducing the airflow required of the compressors.

While system airflow and power profiles (see Figures 11 and 12) are changed by reducing leaks or making fixed airflow adjustments, daytype operating schedules (see Figure 13) remain unchanged. Typically, the largest savings are achieved by reducing air leaks to a point where a compressor can be turned off. However, a compressor cannot be turned off with this EEM, unless the compressor possesses an automatic shutdown timer that will turn off a compressor operating at no load. If system airflow profiles are reduced to where a compressor will operate at no load, one of the following EEMs may be used to turn the compressor off should be considered: "reduce run time," "use unloading controls," or "sequence compressors."

4.4.2 Anticipated Savings

Proposed savings are based on fixing air leaks and making fixed airflow adjustments throughout the plant. Existing plant airflow ($\%C_{ep}$) requirements for all operating periods are determined by subtracting existing leak airflow ($\%C_{el}$) from existing system airflow ($\%C_{es}$).

$$\%C_{ep} = \%C_{es} - \%C_{el}$$

Existing leak airflow percentage of peak plant airflow ($\%L_e$) is calculated as existing leak airflow divided by existing plant airflow during peak production ($\%C_{epp}$).

$$\%L_e = \frac{\%C_{el}}{\%C_{epp}} \times 100\%$$

Plant airflow during all periods may be changed by adding or removing air using equipment from the compressed air system. For example, plant personnel may decide to replace pneumatic cylinders with hydraulic ones. This would reduce plant airflow requirements. Adding equipment such as high pressure air nozzles, would increase plant airflow requirements.

Proposed plant airflow requirements ($\%C_{pp}$) are calculated by adding fixed airflows (FAF) to existing plant airflows for appropriate periods. Fixed airflows ($\%C_{faf}$) are calculated as the equipment airflow in acfm divided by system capacity (C_s).

$$\%C_{faf} = \frac{FAF}{C_s} \times 100\%$$

If no fixed airflow adjustments are made, proposed plant airflow requirements are equal to existing plant airflow requirements. Fixed airflows are positive when adding equipment and negative when removing equipment.

$$\%C_{pp} = \%C_{ep} + \%C_{faf}$$

Leaks are reduced by decreasing the value of leak airflow percentage of peak plant airflow from $\%L_e$ to a proposed amount, $\%L_p$. A default value of 30 percent of system capacity for $\%L_p$ is recommended, but may be changed. This is only a target; it may be difficult to repair leaks to this exact number. For example, a 10 percent target may be appropriate for light duty production in a clean environment. If leaks are already at an acceptable level, $\%L_p$ may be set equal to $\%L_e$.

Proposed compressor airflow to support proposed leaks ($\%C_{pl}$) during proposed peak production ($\%C_{ppp}$) is calculated using the following formula:

$$\%C_{pl} = \%C_{ppp} \text{ x } \%L_p$$

Proposed system airflow ($\%C_{ps}$) for all operating periods is calculated as proposed plant airflow requirements plus proposed leak airflow.

$$\%C_{ps} = \%C_{pp} + \%C_{pl}$$

Proposed power (%P) for each compressor is calculated for each plant operating load. Proposed airflow profiles are apportioned among the compressors according to proposed staging and savings are calculated. Refer to section 4.3 for further details.

4.5 Adjust Manual Staging (no sequencer)

4.5.1 Introduction

System efficiency can be improved by staging compressors to minimize the energy required to deliver a required airflow. In many cases, two compressors operating at part load will be staged, allowing one compressor to operate at full load and the other at part load, resulting in lower energy use. This is particularly true if a compressor uses unloading controls so that a modulating-only compressor can operate at full load, its most efficient operating point. If staging results in one compressors operating at no load, then that compressor can likely be turned off. Refer to Adjust Sequencing or Staging in Appendix B for tips on how to stage compressors for efficient operation.

This EEM may be analyzed before any EEM, but not after Sequence Compressors. Compressors are staged according to full load pressures and pressure ranges (see Chapter 2). Staging may be changed by altering full load pressures of available compressors, and in some cases, pressure ranges, which are typically fixed for a given compressor.

While system power profiles are changed, system airflow and operating schedules remain unchanged in this EEM. A compressor operating at no load will not turn off unless equipped with an automatic shutdown timer. One of the following EEMs should be considered to turn compressors off: "reduce run time," "use unloading controls," or "sequence compressors."

4.5.2 Anticipated Savings

After compressor staging is adjusted, full load power for each compressor is recalculated based on proposed staging. Proposed full load power (P_{pfl}) is altered by one half percent of existing full load power (P_{fl}) per psi of full load pressure change (8) as shown in the formula below.

$$P_{pfl} = P_{fl} \times (100\% + 0.5\% \times \text{full load pressure change})$$

System airflow profiles remain unchanged and are apportioned among the compressors according to proposed staging and savings are calculated. Refer to section 4.3 for further details.

4.6 Use Unloading Controls

4.6.1 Introduction

Compressors are most efficient when operating at capacity. With airflow modulation, efficiency decreases as airflow decreases. Power remains high because compressors must work against system pressure, even when no air is delivered. Unloading controls allow the compressor discharge to blow down to a lower pressure, reducing no load power. Part load performance is most efficient when the unload point is set at 100 percent of compressor capacity, provided adequate receiver volume is present. See Refer to Use Unloading Controls in Appendix B for tips. The unload point setting may depend on the manufacturer. See Figures 3 through 7 for typical performance profiles.

This EEM should be considered if some compressors don't have unloading controls and a sequencer is planned. Unloading controls may be adjusted or added if they are available for the compressor. Automatic shutdown timers are often an available option with unloading controls, and save energy by turning off unneeded compressors.

Compressors with unloading controls are staged or sequenced according to daytype operating schedules and pressure settings. Unless controlled by an automatic sequencer, each compressor's position remains the same, that is, the lead compressor is always lead compared to other compressors. This is because pressure switch settings that determine which compressor is in lead position, which is in second position, and so on, are typically not adjusted routinely throughout the plant operating period.

While system power profiles are changed, system airflow profiles and daytype operating schedules remain unchanged. A compressor operating at no load will automatically be turned off only if an automatic shutdown timer is installed.

4.6.2 Anticipated Savings

Adding unloading controls or adjusting existing controls to unload at the highest point possible can improve system efficiency. Load-unload (or low-unload with unload point set at 100 percent of compressor capacity) are more efficient than low-unload with an unload point set below 100 percent of compressor capacity (refer to Figures 3 and 6 in Chapter 2) provided there is adequate receiver volume. Not all manufacturers offer load-unload controls, or it may not be possible to set the unload point at 100 percent of compressor capacity with low-unload controls. Depending on system requirements, unloading controls may not be appropriate. Refer to Use Unloading Controls in Appendix B.

Once low-unload controls have been installed, average power will be reduced when average airflow is below the unloading point (compressor cycles to meet airflow requirements). For some compressors, a maximum unload point ($\%C_{ul}$) of 95% of compressor capacity is possible for a starting point; different unloading points will affect savings. For example: compare Figures 3 and 6 for an average flow of 50%C. The unload point may have to be lower depending on system requirements (see Use Unloading Controls in Appendix B). Power corresponding to the proposed unload point ($\%P_{ul}$) is calculated using the appropriate formula (see Chapter 2) and is located in the Proposed Conditions table (Table 2).

4.7 Reduce System Pressure

4.7.1 Introduction

Reduce average compressor discharge pressure to minimize power required to compress air. Reducing system pressure will also reduce airflow supplied to end uses and leaks, further reducing compressor power. The amount by which pressure may be reduced depends on system requirements. Refer to Reduce System Pressure in Appendix B for tips. Care must be taken to ensure that critical end uses have adequate pressure. While system airflow and power profiles are changed, operating schedules remain the same.

4.7.2 Anticipated Savings

Reducing system pressure will reduce full load power by approximately one half percent per psi reduction (8). Reducing system pressure will reduce power and save energy. Proposed full load is power calculated as:

$$P_{pfl} = P_{fl} \times (100\% - 0.5\% \times \text{pressure drop in psi})$$

Also, end uses and leaks will use less air at lower pressure, thereby reducing system airflow profiles. Proposed system airflow ($\%C_{ps}$) for all operating periods is calculated as existing system airflow ($\%C_{es}$) multiplied by proposed average system absolute pressure (proposed average system gauge pressure (p_p) + atmospheric pressure (p_a)) divided by existing average system absolute pressure (existing average system gauge pressure (p_e) + p_a). A good rule of thumb is airflow will be reduced by ¾% per psi pressure reduction, but AIRMaster uses the calculation below (9). All pressures are in pounds per square inch.

$$\%C_{ps} = \%C_{es} \times \frac{(p_p + p_a)}{(p_e + p_a)}$$

Proposed system airflow profiles are apportioned among the compressors according to proposed conditions and savings are calculated. Refer to section 4.3 for further details.

4.8 Sequence Compressors

4.8.1 Introduction

System efficiency can be improved by sequencing compressors to minimize energy required to deliver desired system airflow. In many cases, two compressors operating at part load will be sequenced, allowing one compressor to operate at full load and the other at part load. This is particularly true if a compressor uses unloading controls so that a modulating-only compressor can operate at full load, its most efficient operating point. Refer to Adjust Sequencing or Staging in Appendix B for tips on how to sequence compressors for efficient operation. While this EEM may be applied to compressors with any control strategy, it is usually considered after analyzing the "use unloading controls" EEM.

Unloading compressors without an automatic sequencer depends on pressure switch settings to determine which compressor is in lead position, which is in second position, and so on. These settings are typically not adjusted routinely. An automatic sequencer allows for more complicated sequencing, such as rotating compressors to even wear. Automatic shutdown timers are frequently an option with automatic sequencers that saves energy by turning off unneeded compressors.

Individual compressor control strategies remain unchanged. Compressors are sequenced by changing daytype operating schedules (see Chapter 2). Sequence order for each hour and daytype is entered. AIRMaster suggests a default order based on existing operating schedules that may be accepted or changed. Compressors may also be turned off during desired times with this EEM, although an automatic shutdown timer will do this automatically if installed. While daytype operating schedules and system power profiles are changed, system airflow profiles remain unchanged.

4.8.2 Anticipated Savings

System airflow profiles remain unchanged and are apportioned among the compressors according to proposed sequence (see Figure 10). Proposed power (%P) for each compressor is calculated for each plant operating load based on proposed airflows (%C) using formulas in Chapter 2 for given control strategies. Proposed system operating conditions and calculated savings are summarized in the Proposed Conditions and Savings Summary tables (Table 2).

System airflow profiles are apportioned among the compressors according to proposed sequencing and savings are calculated. Refer to section 4.3 for further details.

4.9 Reduce Run Time

4.9.1 Introduction

Compressors operating at part load use between 16% and 100% of full load power depending on load, compressor type, model, and control. Shutting off the compressor when no air is required will save energy. Automatic shutdown timers will turn off compressors that operate at no load, but not those that are only serving to feed leaks during non-production times.

Usually this EEM is analyzed after running other EEMs. This is because other EEMs may present periods when one or more compressors can be turned off. Turning off compressors when not needed will reduce power and save energy. Refer to Reduce Run Time in Appendix B and operating schedules to determine when compressors can be turned off.

While daytype operating schedules and system power profiles are changed, system airflow profiles remain the same.

4.9.2 Anticipated Savings

Compressor power is saved by shutting off the air compressor during times when compressed air is not needed, such as lunch time or weekends, or when compressors are operating at no load. A timer could be installed to shut off and restart compressors at the appropriate times. The timer should be programmed to restart the compressor approximately five minutes before production restarts to restore system pressure if necessary.

System airflow profiles are apportioned among the compressors according to proposed sequencing. Refer to section 4.3 for further details.

5. ANALYSIS TOOL

5.1 Overview

AIRMaster is a software package to help industrial plant personnel, professional auditors and utility customer service representatives maximize the performance of existing compressed air systems (10). Toward this end, AIRMaster has focused on the most important Operation and Maintenance (O&M) measures in the auditors arsenal. O&M measures are those that can typically be carried out by O&M personnel, and generally entail low capital costs, few operating risks and quick paybacks.

5.2 AIRMaster Features and Capabilities

AIRMaster is a spreadsheet-based software program that models the operation of compressed air systems. AIRMaster lets auditors simulate both existing and modified system operation, and potential future modifications. Results in tabular and graphical form can be used to generate a report. Descriptions and user instructions for AIRMaster software can be found in the User's Manual for AIRMaster (2). Information entered into AIRMaster comes from data collected during a compressed air system audit. Refer to the Audit Manual for AIRMaster (7) for audit instructions and forms used to collect AIRMaster information. Refer to Chapter 2 though Chapter 4 of this thesis for analysis methods and theory behind AIRMaster's development.

To assist industrial energy auditors, AIRMaster is able to model several types of systems that may be encountered. For systems with only one air compressor, a simpler approach can be taken. AIRMaster can model partload system operation with up to five interconnected oil-flooded single-stage rotary screw and reciprocating compressors operating simultaneously with varying control strategies and independent operating schedules. Centrifugal are not modeled precisely with AIRMaster, but can be approximated by modeling as a rotary screw compressor with low-unload controls.

AIRMaster allows analysis of six Energy Efficiency Measures (EEMs). An EEM is an opportunity where the system is altered to improve system efficiency and save energy. Economical savings are calculated based on average electrical utility rates. The six EEMs available for analysis are (refer to the glossary as needed):

- **Reduce plant air leaks**. Determine proposed system airflow profiles based on proposed leak airflow and fixed airflow adjustments.

- **Adjust manual staging (no sequencer)**. Adjust proportional modulation pressure ranges on modulating-only compressors to alter compressor staging.

- **Use unloading controls**. Install or adjust existing unloading controls with optional automatic shutdown timer.

- **Reduce system pressure**. Reduce average system pressure by a specified amount.

- **Sequence compressors**. Sequence compressors possessing unloading controls, or install an automatic sequencer. An automatic shutdown timer is optional.

- **Reduce run time**. Turn off compressors which are not needed at specified times.

Implementation of each EEM depends on available equipment for the compressed air system being audited. Refer to the Appendix B for items to consider when analyzing a measure.

5.3 Single Air Compressor Analysis

Analysis is greatly simplified for single air compressor systems. The auditor may perform this analysis using data collected and a hand held calculator. This becomes particularly easy when the plant operates at only a few loads. For example, a plant operating 350 days per year may operate at constant production load for 8 hours a day, have a 1 hour lunch break, and be down the remaining 16 hours. AIRMaster can still be useful in this case because it will perform all pertinent calculations. Refer Appendix D for examples of EEMs that may be used for single air compressor systems. Hand or AIRMaster calculations may be produced and the results entered in the EEMs. The EEMs may then be included in a compressed air O&M report. Analysis for multiple compressor systems and different operating schedules is considerably more complex, and so AIRMaster is recommended to analyze such systems.

6. COMPRESSED AIR SYSTEM AUDITS

6.1 Audits

Seven field audits were conducted to refine AIRMaster and methodology as well as assess the savings potential and implementation cost estimation of six common Operation and Maintenance measures (11).

6.1.1 Plant Selection

The plants that met the selection criteria were chosen for the study either by participant utility nomination or by responses to project promotions. Seven plants in a variety of industries were selected:

1. Bakery
2. Sawmill
3. Millworks plant
4. Metal fabrications plant
5. Foundry 1
6. Foundry 2
7. Electronics manufacturer

6.1.2 Preaudit (1/2 day)

The preaudit portion of the audits consisted of four parts and required roughly half a day. These are outlined below.

6.1.2.1 Utility Bill Analysis

Annual electric bills and electricity rate schedules were collected from the participating utility prior to the audit. Utility information was used to determine the percentage of plant annual plant energy used by compressors and to calculate cost savings.

6.1.2.2 Power Metering

Compressor power was monitored by the electric utility for approximately two weeks for each plant using recording three-phase power meters.

6.1.2.3 Compressed Air System Description

General compressed air system components and specifications were discussed and recorded. A plant layout was also requested, showing the compressed air system, and an equipment list with key compressed air end-uses.

6.1.2.4 Interview

Each audit was preceded with an interview with plant personnel, either by phone or in person. Information came from plant personnel, typically from two to four people per plant.

6.1.3 Compressed Air System Audit (1 day)

The audit usually requires one full day and may be performed when the plant is operating, when the plant is down, or a combination of the two. For example, compressor loads and distribution line pressures during production times must be measured while the plant is operating. However, measuring compressor performance is best accomplished when the compressor can be valved off and operated at full and no load without disturbing production.

Also, detecting leaks is easier and safer when the plant is quiet. An auditor can get close to, and even inside of, production equipment when it is off without interfering with production personnel and equipment operation. Best results were achieved by conducting a portion of the audit during production times, and completing the remainder of the audit after the plant shut down, such as at night or evening.

6.1.3.1 Introductions

The audit team first meets with plant personnel to introduce each other, and to develop the plan for the day. Plant maintenance personnel and auditors discussed operational concerns and methods for collecting compressor nameplate and performance information. Following the meeting the team was guided on a plant tour, in which key components and their locations were identified, as well the general plant layout and production process.

6.1.3.2 System Component Specifications

Information on the compressor, motor, control types and settings, and accessories were recorded. This information included motor nameplate data, compressor type and model numbers, and accessories such as aftercoolers and dryers.

6.1.3.3 Operating Schedules

The audit methodology uses typical days for annual schedules. A set of 24-hour periods with a common operating schedule would constitute one typical daytype. For example, weekdays might be one daytype, while weekends and holidays might be another. Daytypes are based on descriptions given by plant personnel. Using measurements from the two weeks power monitoring and information from operators, hourly averages for each daytype were determined. Figure 15 shows an hourly profile of airflow for a weekday.

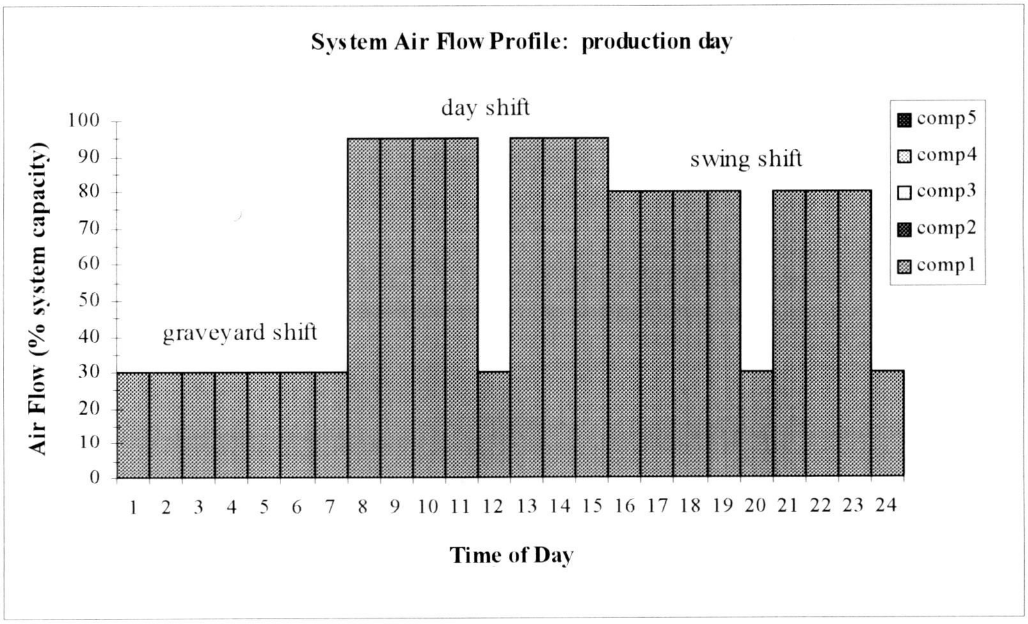


Figure 15: Hourly Airflow

6.1.3.4 Compressor Performance

Compressor performance profiles for part load operation were established from power measurements, or used compressor manufacturer's performance specifications as a default. Compressor power at four key performance points were measured: no load (fully modulated); no load (unloaded, with controls installed); full load; and unload point (for compressors with low-unload controls). From the performance profiles, air use is calculated for hourly power averages entered in the operating schedules.

6.1.3.5 Pressure Measurements

Air pressures were measured at end uses using a pressure gauge with a quick-release air hose fitting, when possible. Otherwise, existing pressure gauges in the air distribution system were used. Pressure measurements were used to determine compressor staging for multiple compressor systems and the feasibility of reducing system operating pressures.

6.1.3.6 Leak Detection

An ultrasonic leak detector was used to identify compressed air system leaks. Most leak detection was done during non-production periods. Maintenance personnel charged the compressed air system and the auditors inspected such elements as flexible air hoses, fittings, pneumatic cylinders, and other end-uses for leaks. When production equipment was not operating, leaks were easier to detect because noise levels were lower. It also was easier to inspect equipment without safety hazards or interfering with plant personnel and production.

6.1.3.7 Exit Interview

All audits ended with a meeting with plant personnel. Potential recommendations were discussed, to be sure they are feasible, and report delivery schedules were determined. Remaining questions by plant personnel were answered.

6.1.4 Analysis (1-2 days)

6.1.4.1 AIRMaster

Field data were entered into the AIRMaster software, which then calculated energy and power use for all compressors. The analysis required roughly one to two days. AIRMaster evaluates the following EEMs:

1. **Reduce plant air leaks.** Airflow is reduced by repairing compressed air leaks throughout the plant and by making fixed airflow adjustments. These adjustments reduce inefficient air uses by eliminating "planned leaks," such as part or people cooling.

2. **Adjust manual staging.** Adjust pressure setpoints on compressors to alter compressor staging. For example, the primary compressor might operate alone, until a second compressor is needed, rather than have two compressors operating at partload.

3. **Use unloading controls.** Unloading controls are an optional control feature for oil-flooded twin-screw compressors that can easily be added. Some compressors already had unloading controls, and only required simple adjustments to improve efficiency, further increasing the effectiveness of the measure.

4. **Reduce system pressure.** Reduce average system pressure by a specified amount. Reducing system pressure will reduce the pressure difference across each system compressor, thereby reducing compressor power. The amount of pressure reduction depends on system requirements and current operating pressures.

5. **Sequence compressors.** Sequencing controls can operate two or more compressors in a programmed or optimized manner to allow the most efficient compressors to meet each air requirement, and turn unneeded compressors off. Compressors are sequenced using unloading controls, or by installing an automatic sequencer.

6. **Reduce run time.** Turn off compressors that are not needed. For example, turn off compressors that are only supplying air leaks.

6.1.4.2 Report

The report was sent to the manufacturer and other partners in the project as soon as possible. In theory this should be within two weeks. In practice, more time was spent modifying and improving AIRMaster to better analyze the situations and conditions that were encountered, so the reports often took a month to complete. A sample report is included in the Analysis Methodology Manual for AIRMaster (12).

6.1.4.3 Followup

The report cover letter states that the manufacturer will be contacted within a couple of weeks to make sure that they understand the analysis and recommendations, and to offer various types of assistance. Assistance might include referrals to state and utility financial assistance programs, including cost sharing, shared savings, loans, rebates, and tax credits, and to equipment manufacturers, vendors, or consultants.

6.2 Summary

Results of the seven Compressed Air System audits are summarized in this section.

6.2.1 Compressors

Each of the seven plants audited had either two or three compressors. Table 4 shows compressor type, model, horsepower, capacity, system pressure and compressor control type for each plant. Average compressor power and capacity per plant and per compressor are also shown. Power measurements at no load, full load, and unload points were used to create compressor operating profiles and are also shown.

Each of the plants had oil-flooded, twin screw compressors. None had reciprocating compressors. Plant total horsepower and capacity ranged from 150 hp and 706 acfm for the electronics plant to 500 hp and 2,491 acfm for the sawmill. System and compressor operating pressures were around 100 psig for most of the plants.

Compressor Summary Table										
Audit	Compressor Manufacturer	Model Number	Power hp	Capacity scfm	System Press. psig	Compressor Controls	No-Load Power kW	Unload Power kW	Full-Load Power kW
Bakery	Quincy NW	QNW1-360	75	357	115	throttle	37.7	N/A	63.9
	Quincy NW	QNW1-360	75	357	115	throttle	0.0	53.4	64.3
Sawmill	Quincy NW	QNW1500	300	1,489	111	throttle	167.3	N/A	279.0
	Quincy NW	QNW1000	200	1,002	111	throttle	107.3	N/A	176.2
Millworks Plant	Quincy NW	QNW490	100	504	101	throttle	54.3	N/A	84.6
	Quincy NW	QNW490	100	503	101	throttle	55.1	N/A	84.8
Metal Fabrication Plant	Quincy NW	QNW490	100	496	100	load-unload	20.5	92.4	92.4
	Quincy NW	QNW490	100	496	100	load-unload	20.0	90.3	90.3
	Quincy NW	QNW490	100	496	100	load-unload	21.8	95.8	95.8
Foundry 1	Quincy NW	QNW1000	200	1,001	105	throttle	105.0	N/A	176.0
	Quincy NW	QNW740	150	762	105	low-unload	27.9	105.0	130.0
Foundry 2	Quincy NW	QNW1-500	100	496	100	low-unload	18.2	72.4	92.9
	Quincy NW	QNW1-500	100	500	100	low-unload	16.9	69.8	88.5
Electronics Manuf.	GardnerDenver	ECH-QJD	50	234	123	throttle	27.9	N/A	46.5
	GardnerDenver	ECH-QJD	50	234	123	throttle	27.6	N/A	46.3
	Quincy NW	QNW1-240	50	234	123	throttle	28.4	N/A	47.2
	Total		1,850	9,161			735.9		1,658.7
	Average/Comp.		116	573			46.0		103.7
	Average/Plant		264	1,309	108		105.1		237.0

Table 4: Audit Total Savings Summary

6.2.2 Electricity Use

Cost savings for each EEM were based on energy and demand costs provided by the utility serving each of the plants. Table 5 shows compressor and plant electricity use and utility rates for the seven audits.

Energy costs. Energy and demand charges used for estimating cost savings were averaged with tiered, seasonal, or time of day rates. Annual energy and demand costs for each plant from utility bills were shown either as average, actual, or tail block depending on which were saved.

Plant electricity use. Total annual plant electrical energy use was calculated from electric bills.

Compressor electricity use. AIRMaster calculated total annual compressor energy use.

Percent plant energy. Percentage of total plant electricity used by air compressors.

The percent plant energy per audit is the annual compressor electricity use divided by the total use for each plant. Total Percent Plant Energy is the total compressor electricity use for all seven audits divided by the total plant electricity use. Average plant values are the totals divided by the number of plants (seven), except for the Average/Plant energy, which is the simple average.

As Table 5 shows, compressors account for a significant portion of plant electricity use, ranging from 8.3% to 33.3%, with an average of 14.7%. Total compressor energy use ranged from 650,144 kWh for the electronics plant to 2,699,518 kWh for the sawmill. Thus, even minor modifications to the compressed air systems have high potential for significant energy savings.

Utility Summary					
Audit	Demand Cost $/kW-mo	Energy Cost $/kWh	Total Plant Electricity Use kWh	Compressor Electricity Use kWh	Percent Plant Energy
Bakery	$4.35	$0.0237	4,234,800	677,842	16.0%
Sawmill	$3.46	$0.0333	15,894,000	2,699,518	17.0%
Mill Work	$4.35	$0.0237	6,432,040	831,951	12.9%
Metal Fabrication	$4.30	$0.0361	3,358,193	1,119,044	33.3%
Foundry 1	$4.30	$0.0361	12,758,324	1,062,167	8.3%
Foundry 2	$3.86	$0.0349	10,458,000	1,201,419	11.5%
Electronics	$4.35	$0.0237	2,842,800	650,144	22.9%
Total			55,978,157	8,242,085	14.7%
Average/Plant	$4.14	$0.0302	7,996,880	1,177,441	17.4%

Table 5: Utility Summary

6.2.3 Total Savings

Using the data collected in the field audits and the subsequent analyses, the estimated total energy and cost savings for the seven audits are shown in Table 6. Implementation cost is primarily O&M labor and material costs, and typically includes only minor capital cost. The Payback period is the total implementation cost for the project divided by the total annual cost savings.

Audit recommendations in Table 6 show that the plants could achieve high-energy savings with low implementation costs and therefore short payback periods. The average compressor energy savings for implementing all recommended measures was 49.2%. Implementation costs were low compared to cost savings yielding an average payback of 0.6 years.

Audit Total Savings Summary								
Audit	EEM Description	Demand kW	Energy kWh	Percent * Savings	Cost Savings	Implementation Cost	Payback Years
Bakery	Reduce Leaks	34.3	172.904	25.0%	$5.888	$814	0.1
	Unloading Controls	1.8	48.004	7.0%	$1.231	$4.060	3.3
	Reduce Pressure	3.0	22.847	3.4%	$699	$1.849	2.6
	Maximum Savings	39.1	243.755	35.4%	$7.818	$6.723	0.9
Sawmill	Reduce Leaks	246.0	1.600.438	59.3%	$63.461	$24.655	0.4
	Unloading Controls	0.9	250.449	9.3%	$8.369	$1.200	0.1
	Reduce Run Time	0.0	70.516	2.6%	$2.346	$200	0.1
	Maximum Savings	246.9	1.921.403	71.2%	$74.176	$26.055	0.4
Millwork	Reduce Leaks	12.0	59.436	7.1%	$2.036	$3.667	1.8
	Unloading Controls	29.1	279.001	33.5%	$8.132	$11.550	1.4
	Maximum Savings	41.1	338.437	40.6%	$10.168	$15.217	1.5
Metal Fabrication	Reduce Leaks	53.6	342.609	30.6%	$15.136	$9.815	0.7
	Maximum Savings	53.6	342.609	30.6%	$15.136	$9.815	0.7
Foundry 1	Reduce Leaks	42.1	240.215	22.5%	$10.846	$20.911	1.9
	Unloading Controls	8.0	140.033	13.2%	$5.468	$200	0.0
	Maximum Savings	50.1	380.248	35.7%	$16.314	$21.111	1.3
Foundry 2	Reduce Leaks	44.2	450.362	37.0%	$17.764	$14.938	0.8
	Unloading Controls	9.0	37.514	3.0%	$1.725	$200	0.1
	Maximum Savings	53.2	487.876	40.0%	$19.489	$15.138	0.8
Electronics	Reduce Leaks	2.1	17.444	2.7%	$525	$425	0.8
	Reduce Run Time A	0.0	102.992	15.8%	$977	$0	0.0
	Reduce Pressure	11.4	69.072	10.6%	$2.247	$0	0.0
	Unloading Controls	8.4	50.669	7.8%	$1.648	$200	0.1
	Reduce Run Time B	16.9	101.400	15.6%	$3.299	$0	0.0
	Maximum Savings	38.8	341.577	52.5%	$8.696	$625	0.1
Audit	Total	522.8	4.055.905	49.2%	$151.797	$94.684	0.6
Average	/ Plant	74.7	579.415	49.2%	$21.685	$13.526	0.6

Table 6: Audit Total Savings Summary
* The Percent Savings is the energy saved by a measure divided by annual compressor use.

6.2.4 EEM Savings

Table 7 shows total energy and cost savings, and average percentage of compressor energy saved for four standard EEMs considered during the seven audits. Percent savings and payback were averaged only for the four EEMs that were primary audit recommendations.

6.2.4.1 Reduce Leaks

Each of the plants audited could realize significant energy and cost savings by fixing air leaks in their distribution system and at end uses. Savings from fixing air leaks were greater than from other EEMs for the seven audits as a whole, saving 35% of compressor energy with a payback period of 0.7 years.

6.2.4.2 Unloading Controls

Installing or using unloading controls was the second most frequently recommended EEM, and was recommended at each of the seven plants audited except for the metal fabrication plant that already used unloading controls. Savings for unloading controls were 9.8% with a payback of 0.7 years.

6.2.4.3 Reduce Pressure

Reducing system pressure was recommended twice. At the bakery modifications to the distribution system were required for implementation while the electronics plant required modification of a single process that required a higher pressure than the rest of the end uses.

6.2.4.4 Reduce Run Time

It was recommended that compressors be manually turned off when they would not otherwise turn off automatically by timers at two of the plants. This occurred because the compressor was still operating when not required for production, only to feed leaks.

6.2.4.5 Manual Staging

Manual staging was not recommended at any of the plants audited because the plants did not benefit significantly after other measures were implemented.

6.2.4.6 Sequence Compressors

Sequence compressors was recommended at three plants as an alternative to other EEMs. Therefore, the measure was written as an Other Measure Considered (OMC) at three of the plants audited: the bakery, sawmill, and millworks plants. If distribution system leaks were reduced to recommended levels, and other recommended EEMs were implemented, then the plants would not have benefited from sequencing compressors. Sequencing compressors often required implementing other O&M measures, such as installing unloading controls, that were included in other EEMs. For example, when the sawmill reduces leaks to recommended levels, plant operators are able to shut off one of the two compressors and a sequencer is not needed. However, if leaks are not reduced to recommended levels, or air use increases, then those plants would benefit from sequencing compressors.

EEM Total Savings Summary						
	Occurrence	Energy	Percent	Cost	Implementation Payback	
EEM	Rate	kWh	Savings	Savings	Cost	Years
Reduce Leaks	100%	2,883,408	35.0%	$115,656	$75,225	0.7
Unloading Controls	86%	805,670	9.8%	$26,573	$17,410	0.7
Reduce Pressure	28%	91,919	1.1%	$2,946	$1,849	0.6
Reduce Run Time	28%	274,908	3.3%	$6,622	$200	0.1
Total		4,055,905	49.2%	$151,797	$94,684	0.6

Table 7: EEM Total Savings Summary

6.2.5 Planned Leaks

Reducing leaks included eliminating "planned" leaks such as using compressed air for cooling or cleaning work-in-process. These and other inefficient end-uses are treated analytically the same as other "unplanned" leaks. Table 8 shows the four plants in which eliminating planned leaks was recommended. Savings and costs for the planned leaks are included in the "reduce leaks" EEM in the case studies and the Savings Summary Table. Table 8 shows savings for eliminating the planned leaks only. Each of the planned leaks was an end-use activity or task that could be accomplished more efficiently by other means. For example:

Efficient nozzles. Cleaning crews at the sawmill used three to four-foot lengths of straight 3/8 inch tubing without a nozzle at the end for blow down and cleaning. The tubes connected directly to flexible air hoses. The recommendation was to replace the straight tubing with efficient nozzles with hand actuated valves .

Dedicated vacuum pump. Millworks plant operators had a worktable that held furniture parts in place for sanding using a vacuum generated by venturis that used compressed air. A dedicated vacuum pump instead of using compressed air to create a vacuum was recommended.

Low pressure blower. Metal fabrication plant operators used compressed air nozzles to cool brazed parts. The air was reduced from the plant pressure of 100 psig to 15 psig before the nozzle supply line. A rotary lobe blower to provide 15 psig air for the cooling nozzles was recommended.

Burner fans. The burners used to pre-heat ladles at foundry 1 used compressed air for combustion air. Plant personnel were considering switching to thermostatically controlled burners with squirrel cage fans to provide combustion air. The cost and energy savings for using fans instead of compressed air to provide combustion air was estimated.

Open traps. Because of moisture in the compressed air distribution system, operators at Foundry 2 had moisture traps throughout the plant. All the traps were left slightly open at all times to prevent them from filling up with water and because plant maintenance personnel did not trust drains to operate properly. The open traps produced air leaks. A refrigerated air dryer to remove moisture from plant air, eliminating the need to leave traps open was recommended. The recommendation is not included in Table 8 because the airflow through the traps was not quantified.

Planned Compressed Air Leaks					
Audit #	Leak Description	Energy kWh	Cost Savings	Implementation Cost	Payback Years
Sawmill	Efficient Nozzles	400,109	$15,865	$40	0.0
Millwork	Dedicated Vacuum Pump	36,242	$1,277	$1,350	1.1
Metal Fab.	Low Pressure Blower	270,863	$12,049	$9,000	0.8
Foundry 1	Burner Fans	35,686	$3,334	$20,000	6.0
	Average	114,264	$5,553	$14,953	2.6

Table 8: Planned Compressed Air Leaks

6.2.6 Other Measures Considered

Besides alternatives to recommended EEMs, OMCs include recommendations in addition to the six basic EEMs (Table 9). OMCs are plant specific. These additional measures were considered but not recommended because either the payback period is too long, part of the recommendation was included in another EEM, or there was insufficient information to estimate savings accurately.

Other Measures Considered	
OMC Description	Audits
Increase Pipe Diameter	Bakery
Remove Oil Separator	Bakery
Sequence Compressors	Bakery, Sawmill, Millwork
Use Small Compressor for Packaging	Metal Fabrication
Vent Compressor Room to Outside Air	Metal Fabrication
Turn Off Cooling Tower	Metal Fabrication
Reduce Compressor Cycling	Metal Fabrication
Adjust Auto Shutdown Timer	Metal Fabrication
Separate Compressor for Sand Transport System	Foundry 1

Table 9: Other Measures Considered

6.2.7 Other Benefits

Most investments in energy efficiency consider only energy savings in calculating economic payback. There are, however, other "non-energy" benefits of efficiency that often affect the decision to implement these measures:

More available air. Reducing airflow lost to leaks, both planned and unplanned, and pressure loss in the distribution system will increase airflow available to tools and equipment.

Avoid buying new compressor. With more available air, capital and operating costs of a new compressor to meet growing demand for air may be delayed or reduced.

Extend equipment life. Reducing compressor loads, turning compressors off when not needed, and sequencing them to even out wear will generally extend equipment life.

Higher reliability. Improving maintenance generally increases efficiency and reduces equipment failure rates.

Environmental benefits. Saving energy and increasing equipment life reduces greenhouse gas emissions.

6.3 Conclusions

Compressed air is significant. Total compressor horsepower ranged from 150 to 500 horsepower per plant. Air compressors accounted for between 8.3% and 33.3% of annual plant electricity use with an average of 14.7%. Thus, even minor improvements to compressed air systems and operation have a high potential for reducing compressor and therefore plant electrical energy use and costs.

AIRMaster. The AIRMaster software program and supporting manuals and methodology were developed and tested during the project. AIRMaster estimates energy and cost savings for six simple O&M measures. The program and audit methodology were easy to use during a short term audit.

The software and manuals were further developed and refined during the course of seven field audits. Results from the audits helped to improve cost estimation and evaluate the savings potential from six common Energy Efficiency Measures.

Audit results. Total estimated savings for the seven audits were 4,056,000 kWh, or 49.2% of compressor electricity use, for a cost savings of $151,800. Peak demand could be reduced by 524 kW. Reducing Leaks saved an estimated 35%; Unloading Controls, 10%; Reduce Run Time, 3%; and Reduce System Pressure, 1% of annual compressor energy. Implementation costs were low compared to cost savings, yielding short payback periods. Total implementation costs were $94,700 for a project payback period of 0.6 years.

Other benefits. Besides energy and cost savings, there are other benefits to a compressed air system audit. Manufacturers can increase air available to equipment and tools by reducing leaks, and delay or avoid the capital and operating costs of buying a new compressor. Unloading Controls, Reducing Run Time, and Reducing Pressure can increase equipment life, improve reliability, and reduce maintenance costs.

In conclusion, significant opportunities exist to improve compressed air system efficiency and reliability with low cost O&M measures.

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APPENDICES

Appendix A: Nomenclature

The following are descriptions of variable used in formulas given in the analysis methodology. Where applicable, units are also given. Also see the glossary.

A = average measured current: amps

$\%C$ = Percentage of compressor capacity at any load.

$\%C_{el}$ = Existing leak airflow requirement expressed as a percentage of system capacity.

$\%C_{ep}$ = Existing plant airflow requirement (plant load), expressed as a percentage of system capacity.

$\%C_{epp}$ = Existing peak plant airflow requirement expressed as a percentage of system capacity.

$\%C_{es}$ = Existing system airflow (plant + leak load), expressed as a percentage of system capacity.

= $\%C_{ep} + \%C_{el}$.

$\%C_{faf}$ = Fixed airflow adjustment expressed as a percentage of system capacity.

$\%C_{fl}$ = Percentage of compressor capacity at full load: 100%.

$\%C_{nl}$ = Percentage of compressor capacity at no load: 0%.

$\%C_{pl}$ = Proposed leak airflow requirement expressed as a percentage of system capacity.

$\%C_{pp}$ = Proposed plant airflow requirement expressed as a percentage of system capacity.

$\%C_{ppp}$ = Proposed peak plant airflow requirement expressed as a percentage of system capacity.

$\%C_{ps}$ = Proposed system airflow (plant + leak load), expressed as a percentage of system capacity.

$\%C_s$ = Percentage of system capacity at any load.

$\%C_{ul}$ = Percentage of compressor capacity at the unload point:

20%-100% of compressor capacity.

C = Airflow at any load: acfm.

C_{fl} = Compressor capacity (full load): acfm.

C_s = system capacity: acfm.

DC = Demand cost savings: $.

DS = Peak Demand savings: kW.

E = Energy: kWh.

EC = Energy cost savings: $.

ES = Energy savings: kWh.

%FLA = Percentage of motor full load amperage.

FAF = fixed airflow adjustments.

H = Operating hours: hrs.

IC = Implementation cost: $.

$\%L_e$ = Existing leak airflow divided by peak plant airflow

= $\%C_{el} / \%C_{ep}$.

$\%L_p$ = Proposed leak airflow divided by peak plant airflow:

10% - 30% of peak plant airflow.

n = Order of part load performance equation
= 1 for throttle modulation, or
= 2 for variable displacement.

%P = Percentage of full load power at any load.

$\%P_{fl}$ = Percentage of full load power at full load: 100%.

$\%P_{nl}$ = Percentage of full load power at no load.

$\%P_s$ = Percentage of system full load power at any load.

$\%P_{ul}$ = Percentage of full load power at the unload point.

P = Power at any load: kW.

p_a = Atmospheric pressure: psia.

PB = Simple payback period: years.

p_e = Existing average system gauge pressure: psig.

P_{fl} = Full load power: kW.

Pmax = Maximum discharge pressure.

Pmin = Minimum discharge pressure.

P_{nl} = No load power: kW.

p_p = Proposed average system gauge pressure: psig.

PR = Abbreviation for pressure range.

P_{ul} = Unload point power: kW: 16% - 70% of full load power.

V = average measure voltage: volts

Appendix B: EEM Application and Barriers

Application for and barriers to implementing EEMs are organized by EEM type.

Reduce Plant Air Leaks

Application

- Qualified personnel should repair air leaks in the plant during non-production periods.
- Plant leak checks should be made on a regular basis.
- Many leaks are from faulty fittings, lines, valves, hoses, and pneumatic rams or cylinders.
- Inappropriate uses such as equipment or personnel cooling can be reduced or eliminated.

Barriers

- Pneumatic ram or cylinder rebuild kits and labor can cost several hundred dollars, depending on the size and location of the leak.
- Fixing air leaks requires plant down time.
- After identifying locations of air leaks, it may be possible to valve off sections of the compressed air system allowing partial plant operation while other sections are being repaired.
- Cost of fixing air leaks depends on location, such as height or underground.
- Follow safety standards when repairing leaks.
- Fixing air leaks is not a one-time, but a continuous maintenance task.

Use Unloading Controls

Application

- Plant airflow requirements vary considerably, e.g., full load one shift, half load the next.

- Plant is down for break times, but air pressure needs to remain at a minimum level for continuously running equipment.

- At least one compressor operates at part load.

Barriers

- Although unloading controls save energy, consider cycle losses, a wider pressure range, and adding receiver capacity. Each time the compressor unloads, compressed air in the oil separator and sump is lost. These losses are small if the cycle is not too short. A minimum cycle time of two minutes if recommended for compressors with, load-unload, or low-unload control. Several things affect cycle time. The wider the pressure range (PR = PMAX - PMIN), the longer the cycle time. However, a system with a tight pressure tolerance may not allow a wide pressure range. Air storage capacity is a major influence. Large receivers increase cycle time because it takes the compressor longer to fill the system network and it takes longer for end uses to drain the system network. Receiver capacity may need to be added to increase cycle time, which will increase implementation cost.

- Cycle times also vary with plant airflow. Typically, the shortest cycle time can be found when a compressor cycles to deliver and average of 50 percent of its capacity. It is this cycle time that is most critical with respect to cycle losses.

- Compressors with on-off control have similar cycle losses to load-unload controls. Also, starting is hard on an electric motor, therefore cycle time greater than ten minutes is recommended.

- For airflow requirements above the unload point, a compressor will modulate to meet the load and remain there, keeping system pressure constant. The unloading set point may have to be lowered so that pressure sensitive equipment won't experience the wide pressure range from cycling. Savings will be reduced, but may be necessary.

Reduce System Pressure

Application

- Reduce pressure to minimum requirement.

- Save more by isolating systems requiring lower pressure, e.g., fire suppression system). Capital costs for purchase of a second compressor, plumbing, hardware, and labor could quickly be recovered by cost savings.

- Lower pressure will reduce air loss to leaks, which will increase savings although this is not easily quantified.

- Careful assessment of pressures at end uses is important. Pressure drops in the air distribution system reduce pressure at end uses. Improving the air distribution system by closing loops and using larger pipes will improve system performance while allowing the compressor to operate at lower power.

- Measure pressure at end uses to check for adequacy.

Barriers

- Lowering pressure below the minimum requirement may result in equipment failure.

- Plant down time is required to replumb distribution systems.

- High capital costs of replumbing distribution systems may reduce cost effectiveness of reducing pressure.

Reduce Run Time

Application

- Reduce runtime whenever compressor feeds only leaks.

- Use a smaller compressor for periods of low air requirements, e.g., fire suppression system at night, and shut off the larger compressor.

- Turn off unloaded compressors.

Barriers

- Recovery time may be long depending on receiver size and air leaks. Allow adequate start up time to restore system pressure.

- Keep the number of motor starts to a minimum to prevent excess wear. Therefore, short break periods should not be considered.

Adjust Sequencing or Staging

Application

- More than one compressor is required.
- Consider an automatic sequencer for systems with varying loads.
- Sequence or stage compressors to minimize energy required to meet air requirements.

Barriers

- Sequencers can be capital equipment ($2,000 to $20,000).
- Plant down time is required to install a sequencer.
- System air use profile is needed to program sequencer.
- Tight pressure range requirements may not allow sequencing or staging.

Compressors may be sequenced or staged in any order, as long as there is enough air to supply plant requirements. The sequence or staging may be controlled by an automatic sequencer, pressure settings or simply a plant operator or timer turning on and off needed compressors at different operating times. Different sequence orders, although offering the same airflow, may place different demands on the electrical system. This is particularly true when the compressors are different in size. Here are a few tips to follow when sequencing compressors:

- Use the compressor with the best part load efficiency as the "lag" 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 control runs at part load to meet airflow requirements.

- Use compressors with the best full load cfm/bhp as base compressors. This tip will interact with the previous one if the compressor with the best part load efficiency is also the most efficient compressor at full load.

- Meet demand requirements as closely as possible. For example, if there are 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 so 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 there is 175 hp of plant air requirements and there are 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. As with most equipment, compressors should be used at least occasionally.

- Do not operate more than one compressor at part load. For modulating-only compressors, this can be achieved easily by setting the maximum discharge pressure of one compressor slightly lower than the minimum discharge pressure of another compressor. For compressors with unloading controls, this can be achieved by setting the maximum discharge pressure of one compressor slightly less than the maximum discharge pressure if another compressor. 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 pressure ranges are identical.

- Avoid starting all of the compressors at one time, particularly if plant voltage sags as a result.

Appendix C: EEM Cost Guide

This guide provides implementation cost estimates for the six EEMs.

Reduce air leaks. Implementation cost estimation is expected to improve with this study. Because implementation costs for the "reduce leaks" EEM vary drastically from plant to plant depending on the condition of the distribution system and types of end uses, leak repair costs must be estimated according to total repair costs for leaks detected when inspecting the air distribution system. When conducting audits, ask plant maintenance personnel about their leak repair methods. including:

- **General repair methods.** Do maintenance personnel prefer to rebuild or replace leaking components?

- **Component costs.** Does the plant have any lists of part or rebuild kit costs for common compressed air system components?

- **Repair times.** How long do maintenance personnel estimate to repair each general type of leak?

- **Labor rates.** What is the cost per labor hour for maintenance personnel, including total costs as seen by the plant?

Preferred repair methods may vary from plant to plant, such as whether maintenance personnel prefer to replace, or rebuild leaking components. For example, maintenance personnel at a plant with mostly small bore cylinders may prefer to replace a leaking air cylinder, while maintenance personnel at a plant with many large bore cylinders will likely prefer to rebuild leaking cylinders.

Actual vendor prices for specific parts are the most accurate means of determining replacement part or rebuild kit costs. Ask maintenance personnel to provide vendor list prices for compressed air system components if possible. Prices from a different supplier or manufacturer may also be used to estimate repair or replacement costs, if price data for a specific product is not available.

Often plant maintenance personnel can give a general estimate of the time required to repair a type of leak, such as time to rebuild an air cylinder. After identifying leaks, ask plant personnel about time requirements to fix general types of leaks, such rebuild a cylinder, replace a leaking hose or replace a leaking regulator. Rounding time estimates to quarter hour increments is usually sufficient. Labor cost is the product of the labor time and labor cost per hour. The total cost is the sum of the labor and replacement divided by repair cost. The total of all repair costs is the estimated implementation cost to reduce air system leaks.

Reduce air pressure. Implementation costs associated with this EEM include cost of resizing distribution pipe and labor to adjust compressor pressure settings.

Compressor sequencing. Implementation cost for electronic compressor sequencers is based on units capable of sequencing up to four air compressors. Different models are available ranging from \$2,000 to \$20,000. Cost includes sequencer and installation. The less expensive models require programming by the user based on estimated air use to specify compressor sequence for each time period. The more expensive model uses flow meters installed for a length of time to measure airflow. Airflows, operating schedule and compressor sizes are entered into the sequencer. The sequencer then decides which compressors should run to meet air requirements. The less expensive sequencer will reduce the payback period. Most systems require that the compressors have the ability to unload. If compressors do have this ability and it is required, unloading controls will have to be added. See "unload controls" entry below for implementation cost.

Unload controls. Implementation cost includes controls, plumbing, and labor. Factory installation cost approximately \$500 while retrofits cost approximately \$1,200. If a sequencer is purchased, unloading control are a necessity since the sequencer loads and unloads compressors as needed. Receiver capacity space may need to be added to have cycle times greater than two minutes. Receiver capacity costs approximately \$3.50/gallon for 150 psig pressure rating. Labor to install a receiver is approximately \$500. This is based on 16 hrs. at \$30/hr.

Reduce run time. Implementation cost includes a simple dial type timer with installation and is approximately $200. Implementation cost can be avoided if plant personnel are depended upon to turn off the compressor. Timers are generally more dependable and simpler to program than people. Payback period for a timer is typically short.

Implementation Cost Summary

Reduce air leaks	Cost varies with size and type of leaks
Reduce air pressure	Cost of resizing distribution pipe if necessary
Compressor sequencing	$2,000-$20,000 + unloading controls as needed
Unload controls	$700 for unloading controls only
	$500 for automatic shutdown timer
	$1,200 as a total
Reduce run time	$200 for a mechanical timer clock

Appendix D: EEMs for Single Air Compressor Systems

The following are examples of four Energy Efficiency Measures that may be used for single compressor audits. Each has example numbers and calculations that should be changed to fit a particular single compressor audit. They can be completed using field data and a hand held calculator, and included in a final report. Formulas for several calculated values may be found in the Electrical Calculations and Economic Calculations sections of the body of this manual. Appendix B: EEM Application and Barriers of the body of this manual should be consulted for tips on each EEM. AIRMaster uses the same calculation methods and may be used to perform all calculations if desired. Refer to Glossary and Nomenclature section as needed. The four Energy Efficiency Measures include:

- **Reduce plant air leaks.** Determine proposed system airflow profiles based on proposed leak airflow and fixed airflow adjustments.
- **Use unloading controls.** Install or adjust existing unloading controls with optional automatic shutdown timer.
- **Reduce system pressure.** Reduce average system pressure by a specified amount.
- **Reduce run time.** Turn off compressors that are not needed.

Adjust manual staging (no sequencer) and sequence compressors EEMs are not included since they require multiple compressors. An accurate representation for most multiple compressor systems is complex. AIRMaster is recommended for multiple compressor system. The single compressor EEMs may be analyzed in any order. An example order is:

1. Reduce Plant Air Leaks
2. Reduce System Pressure
3. Use Unloading Controls
4. Reduce Run Time

In any case the existing conditions for each EEM are taken as the proposed conditions of the previously analyzed EEM. The first EEM uses the current system operating conditions.

Reduce Plant Air Leaks

Recommended Action

Reduce compressed air leaks throughout the plant. By reducing leaks to 30% ($\%L_p$) of peak plant air requirements, the amount of air compressed during peak production will be reduced by approximately 20%. These reductions will reduce power and save energy.

Summary			
Energy Savings (kWh)	Cost Savings	Implementation Cost	Payback (years)
47,158	$1,448	$2,000	1.4

Table 10: Reduce Plant Air Leaks Summary

Background

Compressing air is inefficient, with as much as 90% of compressor power being dissipated as heat. Therefore, leaks can be expensive. Compressor loads are monitored during various operating conditions. This information is used to estimate how much compressed air is lost to leaks, and how much leaks cost.

Compressor power at no load, full load, and unload point (if applicable) is measured. By monitoring compressor power during various plant operating loads, an average power for each load is obtained. Plant operating loads may include various production and maintenance loads. These values are then converted to percentage of full load power of the compressor (%P). Airflow (%C) at these points is calculated using the appropriate formula. Refer to Chapter 2 for required information, explanation of compressor control strategy, part load characteristics, and formulas for calculating airflow. See the Compressor Summary table for required information.

Equipment and Operating Conditions

The compressor listed in the Compressor Summary table supplies compressed air. Power measurements (see Electrical Calculations section for power calculation if amperage and voltage are measured) are taken at up to three plant operating loads and are recorded in the Compressor Summary table. Power is also measured during a time when the plant is down (such as lunch time) to obtain the leak load. (*Note: this EEM assumes only one leak load. However, multiple leak loads are possible if a portion of the plant is valved off during an operating period*). From this, plant airflow requirements are calculated for each load using the equations in Chapter 2.

Existing system operating conditions and schedules for the air compressor are tabulated in the Existing Conditions table. Operating hours may be associated with the leak load if, for example, the compressor supplies air that supports leaks during break time. Total operating hours and energy are the sums of the individual operating periods. Total power is the peak demand of all operating periods. A single compressor will probably never operate at no load (except during the no load power test when the plant is valved off) because all compressed air systems leak.

Compressor Summary			
Manufacturer	Quincy Northwest	**Capacity (ACFM)**	435 ACFM
Model	QNW410	**System pressure (psig)**	100 psig
Type	rotary screw	**Control strategy**	throttle
Hp	100 hp	**Unload capacity (%C)**	N/A
		Proposed leak (%L)	30 %C

	voltage			amperage			power	operation
	A-B	B-C	A-C	A	B	C	(kW)	(hours)
no load power							56.0	0
unload power							N/A	N/A
leak load							66.7	0
plant loads (1)							83.4	5,475
(2)							80.4	1,460
(3)							78.8	1,460
full load power							86.4	0

Table 11: Reduce Plant Air Leaks Compressor Summary

Anticipated Savings

Proposed savings are based on fixing air leaks throughout the plant. Existing plant airflow ($\%C_{ep}$) requirements for all operating periods are determined by subtracting existing leak airflow ($\%C_{el}$) from existing system airflow ($\%C_{es}$), and are shown in the Proposed Conditions table.

$$\%C_{ep} = \%C_{es} - \%C_{el}$$

Existing leak airflow percentage ($\%L_e$) is calculated as existing leak airflow divided by existing plant airflow during peak production ($\%C_{epp}$).

$$\%L_e = \frac{\%C_{el}}{\%C_{epp}} \times 100\%$$

Plant airflow during all periods also may be changed by adding or removing air using equipment from the compressed air system. For example: plant personnel may decide to replace pneumatic cylinders with hydraulic ones. This would reduce plant airflow requirements. Adding equipment such as high pressure air nozzles, would increase plant airflow requirements.

Proposed plant airflow requirements ($\%C_{pp}$) are calculated by adding fixed airflows (FAF) from existing plant airflow for appropriate periods. Fixed airflows ($\%C_{faf}$) must be represented as a percentage of system capacity, and are calculated as the equipment airflow in ACFM divided by system capacity (C_s).

$$\%C_{faf} = \frac{FAF}{C_s} \times 100\%$$

If no fixed airflow adjustments are made, proposed plant airflow requirements are equal to existing plant airflow requirements. Fixed airflows are positive when adding equipment and negative when removing equipment.

$$\%C_{pp} = \%C_{ep} + \%C_{faf}$$

For this plant it is reasonable to expect no more than the proposed leak percent ($\%L_p$ given in the Compressor Summary) to satisfy leaks during proposed peak airflow. A default value of 30% of system capacity for $\%L_p$ is recommended, but may be changed. This is only a target; it may be difficult to repair leaks to this exact number. For example, a 10% target may be appropriate for light duty production in a clean environment. Proposed compressor airflow to support proposed leaks ($\%C_{pl}$) during proposed peak production (refer to plant load (1) in the Proposed Conditions section of Table 12 for the value of $\%C_{ppp}$) is calculated using the following formula:

$$\%C_{pl} = \%C_{ppp} \text{ x } \%L_p$$
$$= 55\% \text{ x } 30\%$$
$$= 16.5\%$$

Proposed system airflow ($\%C_{ps}$) for all operating periods is calculated as proposed plant airflow requirements plus proposed leak airflow.

$$\%C_{ps} = \%C_{pp} + \%C_{pl}$$

Proposed power (%P) is calculated for each plant operating period based on proposed airflows using formulas in Chapter 2 for the compressor. Proposed system operating conditions are summarized in the Proposed Conditions table.

Formulas for calculating savings are given in the Electrical Calculations and Economic Calculations sections of the body of this manual. Demand and energy savings are summarized in the Savings Summary table. Total demand savings are the demand savings from the peak production period.

Existing Conditions					
Operating Conditions	Air Use (%C)	Power (%P)	Power (kW)	Operation (hours)	Energy (kWh)
no load	0 %	64.9 %	56.0	0	0
unload point	N/A	N/A	N/A	N/A	N/A
leak load	35 %	77.2 %	66.7	0	0
plant loads (1)	90 %	96.5 %	83.4	5,475	456,615
(2)	80 %	93.0 %	80.4	1,460	117,384
(3)	75 %	91.2 %	78.8	1,460	115,048
full load	100 %	100.0 %	86.4	0	0
Total			83.4	8,395	689,047

Proposed Conditions					
Operating Conditions	Air Use (%C)	Power (%P)	Power (kW)	Operation (hours)	Energy (kWh)
no load	0 %	64.9 %	56	0	0
unload point	N/A	N/A	N/A	N/A	N/A
leak load	17 %	70.7 %	61.1	0	0
plant rqmnt. (1)	55 %				
(2)	45 %				
(3)	40 %				
plant loads (1)	72 %	90.0 %	77.8	5,475	425,955
(2)	62 %	86.5 %	74.7	1,460	109,062
(3)	57 %	84.7 %	73.2	1,460	106,872
full load	100 %	100.0 %	86.4	0	0
Total			77.8	8,395	641,889

Savings Summary						
Demand Charge: $4.00 /kW-mo.				**Energy Charge:** $0.025 /kWh		
	Demand (kW)	Demand ($)	Operation (hours)	Energy (kWh)	Energy ($)	Cost Savings
leak load	5.6	$0	0	0	$0	$0
plant loads (1)	5.6	$269	5,475	30,660	$767	$1,036
(2)	5.6	$	1,460	8,322	$208	$208
(3)	5.6	$	1,460	8,176	$204	$204
Total	5.6	$269	8,395	47,158	$1,179	$1,448

Table 12: Reduce Plant Air Leaks Operating Conditions

Implementation Cost

The implementation cost (IC) for reducing the leaks to 30% ($\%L_p$) above peak plant operation air requirements is estimated as:

$$IC = \$2{,}000$$

The cost savings (CS) will pay for the implementation cost in 1.4 years (IC/CS).

Use Unloading Controls

Recommended Action

Install or adjust low-unload controls on the air compressor to reduce average power energy use.

Summary			
Energy Savings (kWh)	Cost Savings	Implementation Cost	Payback (years)
50,990	$1,385	$1,200	0.9

Table 13: Use Unloading Controls Summary

Background

Screw compressors are most efficient when operating at capacity. With airflow modulation, efficiency decreases with airflow. Power remains high because the compressor must work against system pressure, even when no air is delivered. Low-unload controls allow the compressor discharge to blow down to a lower pressure, reducing no load power. Part load performance is most efficient when the unload point is set at 100 percent of compressor capacity (this operation is identical to load-unload operation). How high the unload point can be set may depend on the manufacturer.

Compressor power at no load, full load, and unload point (if applicable) is measured. By monitoring compressor power at up to three operating plant loads, an average for each load is obtained. Plant operating loads may include various production and maintenance loads. These values are then converted to percentage of full load power of the compressor (%P). Airflow (%C) at these points is calculated using the appropriate formula. Refer to Chapter 2 for required information, explanation of compressor control strategy, part load characteristics, and formulas for calculating airflow. See the Compressor Summary table for required information.

Equipment and Operating Conditions

Compressed air is supplied by the compressor listed in the Compressor Summary table. Power measurements (see Electrical Calculations section for power calculation if amperage and voltage are measured) are taken during various plant operating loads, and are recorded in the Compressor Summary table. From this, system airflow requirements are determined for each load using appropriate formulas in Chapter 2.

Existing system operating conditions and schedules for the air compressor are summarized in the Existing Conditions table. Total operating hours and energy is the sum of the individual operating periods. Total power is the peak demand of all operating periods.

Compressor Summary			
Manufacturer	Quincy Northwest	**Capacity (ACFM)**	435 ACFM
Model	QNW410	**System pressure (psig)**	100 psig
Type	rotary screw	**Control strategy**	throttle
Hp	100 hp	**Unload capacity (%C)**	N/A

	voltage			amperage			power	operation
	A-B	B-C	A-C	A	B	C	(kW)	(hours)
no load power							56.0	0
unload power							N/A	N/A
plant load (1)							83.4	5,475
(2)							80.4	1,460
(3)							71.3	1,460
full load power							86.4	0

Table 14: Use Unloading Controls Compressor Summary

Anticipated Savings

Once low-unload controls have been installed, average power will be reduced when average airflow is below the unloading point (compressor cycles to meet airflow requirements). For the compressor, a maximum unload point ($\%C_{ul}$) of 95% of compressor capacity is recommended for a starting point; different unloading points will affect savings. Adjusting the unload point might cause the compressor to short cycle, an undesirable condition. The unload point may have to be lower depending on system pressure sensitivity (Use Unloading Controls in Appendix B of this manual). Power corresponding to the proposed unload point ($\%P_{ul}$) is calculated using the appropriate formula (see Chapter 2) and is located in the Proposed Conditions table.

System airflow for all levels of plant operation remain the same. Power for air use above the unloading point will remain the same. Power will decrease for air use below the unload point. Proposed power (%P) is calculated for each plant operating period based on system airflows using formulas in Chapter 2 for the compressor. Proposed system operating conditions are summarized in the Proposed Conditions table.

Formulas for calculating savings are given in the Electrical Calculations and Economic Calculations sections of the body of this manual. Demand and energy savings are summarized in the Savings Summary table. Total demand savings are the demand savings from the peak production period.

Existing Conditions					
Operating Conditions	Air Use (%C)	Power (%P)	Power (kW)	Operation (hours)	Energy (kWh)
no load	0 %	64.9 %	56.0	0	0
unload point	N/A	N/A	N/A	N/A	N/A
plant loads (1)	90 %	96.5 %	83.4	5,475	456,615
(2)	80 %	93.0 %	80.4	1,460	117,384
(3)	50 %	82.5 %	71.3	1,460	104,098
full load	100 %	100.0 %	86.4	0	0
Total			83.4	8,395	689,047

Proposed Conditions					
Operating Conditions	Air Use (%C)	Power (%P)	Power (kW)	Operation (hours)	Energy (kWh)
no load	0 %	17.0 %	14.7	0	0
unload point	95 %	98.2 %	84.8	0	0
plant loads (1)	90 %	93.9 %	81.1	5,475	444,023
(2)	80 %	85.4 %	73.8	1,460	107,748
(3)	50 %	59.7 %	51.6	1,460	75,336
full load	100 %	100.0 %	86.4	0	0
Total			81.1	8,395	627,107

Savings Summary						
Demand Charge: $4.00 /kW-mo.				**Energy Charge:** $0.025 /kWh		
	Demand (kW)	Demand ($)	Operation (hours)	Energy (kWh)	Energy ($)	Cost Savings
plant loads (1)	2.3	$110	5,475	12,592	$315	$425
(2)	6.6	$0	1,460	9,636	$241	$241
(3)	19.7	$0	1,460	28,762	$719	$719
Total	0.0	$0	8,395	50,990	$1,275	$1,385

Table 15: Use Unloading Controls Operating Conditions

Implementation Cost

Implementation cost (IC) of low-unload controls for this compressor is approximately $1,200, including all necessary hardware and installation.

IC = $1,200

The cost savings will pay for the implementation cost in 0.9 year (IC/EC).

Reduce System Air Pressure

Recommended Action

Reduce average system pressure from 100 psig to 90 psig. This reduction will reduce power and save energy.

Summary			
Energy Savings (kWh)	Cost Savings	Implementation Cost	Payback (years)
52,961	$1,613	$0	0

Table 16: Reduce System Air Pressure Summary

Background

Reducing system pressure will reduce full load power by approximately one half percent per psi reduction. In addition, end uses and leaks will receive less air as a result of reducing average system pressure, thereby reducing system air use.

Compressor power at no load, full load, and unload point (if applicable) is measured. By monitoring compressor power at up to three plant operating loads, an average for each load is obtained. Plant operating loads may include various production and maintenance loads. These values are then converted to percentage of full load power of the compressor (%P). Airflow (%C) at these points is calculated using the appropriate formula. Refer to Chapter 2 for required information, explanation of compressor control strategy, part load characteristics, and formulas for calculating airflow. See the Compressor Summary table for required information.

Equipment and Operating Conditions

Compressed air is supplied by the compressor listed in the Compressor Summary table. Power measurements (see Electrical Calculations section in the body of this manual for power calculation if amperage and voltage are measured) are taken during various plant operating loads, and are recorded in the Compressor Summary table. From this, system airflow requirements are determined for each load. Average system gauge pressure and absolute barometric pressure are also recorded.

Existing system operating conditions and schedules for the air compressor are tabulated in the Existing Conditions table. Total operating hours and energy are the sums of the individual operating periods. Total power is the peak demand of all operating periods.

Compressor Summary			
Manufacturer	Quincy Northwest	**Capacity (ACFM)**	435 ACFM
Model	QNW410	**System pressure (psig)**	100 psig
Type	rotary screw	**Control strategy**	throttle
Hp	100 hp	**Unload capacity (%C)**	N/A
		Barometric Pressure	14.4 psia

	voltage			amperage			power	operation
	A-B	B-C	A-C	A	B	C	(kW)	(hours)
no load power							56.0	0
unload power							N/A	N/A
plant loads (1)							83.4	5,475
(2)							80.4	1,460
(3)							78.8	1,460
full load power							86.4	8,395

Table 17: Reduce System Air Pressure Compressor Summary

Anticipated Savings

Reducing system pressure will reduce demand and save energy. Full load power will be reduced approximately one half percent per psi pressure drop. Proposed full load power (P_{pfl}) for a 10 psi reduction is:

$$\begin{aligned} P_{pfl} &= P_{fl} \text{ x } (100\% - 0.5\% \text{ x pressure drop in psi}) \\ &= 86.4 \text{ kW x } (100\% - 0.5\%/\text{psi x } 10 \text{ psi}) \\ &= 82.1 \text{ kW} \end{aligned}$$

End uses and leaks will require less air once pressure has been reduced. Proposed system airflow ($\%C_{ps}$) for all operating periods is calculated as existing system airflow ($\%C_{es}$) multiplied by proposed average system absolute pressure (proposed average system gauge pressure, p_p + atmospheric pressure, p_a) divided by existing average system absolute pressure (existing average system gauge pressure, $p_e + p_a$). All pressures are in pounds per square inch.

$$\begin{aligned} \%C_{ps} &= \%C_{es} \times \frac{(p_p + p_a)}{(p_e + p_a)} \\ &= 90\%C_s \times \frac{(90 \text{ psig} + 14.4 \text{ psia})}{(100 \text{ psig} + 14.4 \text{ psia})} \\ &= 82.1\ \%C_s \end{aligned}$$

Proposed power (%P) is calculated for each plant operating period based on proposed airflows using formulas in Chapter 2 for the compressor. Proposed system operating conditions are summarized in the Proposed Conditions table.

Formulas for calculating savings are given in the Electrical Calculations and Economic Calculations sections of the body of this manual. Demand and energy savings are summarized in the Savings Summary table. Total demand savings are the demand savings from the peak production period.

Existing Conditions					
Operating Conditions	Air Use (%C)	Power (%P)	Power (kW)	Operation (hours)	Energy (kWh)
no load	0 %	64.9 %	56.0	0	0
unload point	N/A	N/A	N/A	N/A	N/A
plant loads (1)	90 %	96.5 %	83.4	5,475	456,615
(2)	80 %	93.0 %	80.4	1,460	117,384
(3)	75 %	91.2 %	78.8	1,460	115,048
full load	100 %	100.0 %	86.4	0	0
Total			83.4	8,395	689,047

Proposed Conditions					
Operating Conditions	Air Use (%C)	Power (%P)	Power (kW)	Operation (hours)	Energy (kWh)
no load	0 %	64.9 %	53.3	0	0
unload point	N/A	N/A	N/A	N/A	N/A
plant loads (1)	82 %	93.7 %	76.9	5,475	421,028
(2)	73 %	90.5 %	74.3	1,460	108,478
(3)	68 %	88.9 %	73.0	1,460	106,580
full load	100 %	100.0 %	82.1	0	0
Total			76.9	8,395	636,086

Savings Summary						
Demand Charge: $4.00 /kW-mo.				**Energy Charge:** $0.025 /kWh		
	Demand (kW)	Demand ($)	Operation (hours)	Energy (kWh)	Energy ($)	Cost Savings
plant loads (1)	6.5	$288	5,475	35,587	$890	$1,178
(2)	6.1	$0	1,460	8,906	$223	$223
(3)	5.8	$0	1,460	8,468	$212	$212
Total	6.5	$288	8,395	52,961	$1,325	$1,613

Table 18: Reduce System Air Pressure Operating Conditions

Implementation Cost

No implementation cost is associated with reducing system pressure. Consult the compressor operators' manual for instruction on how to adjust the pressure settings.

Reduce Run Time

Recommended Action

Install a timer to turn off the air compressor when it is not needed to reduce energy use.

Summary			
Energy Savings (kWh)	Cost Savings	Implementation Cost	Payback (years)
18,574	$464	$200	0.4

Table 19: Reduce Run Time Summary

Background

Compressors operating at part load use between 16% and 100% of full load power depending on load, compressor type, model, and control. Shutting off the compressor when no air is required will result in energy savings. See the Compressor Summary table for required information.

Equipment and Operating Conditions

Compressed air is supplied by the compressor listed in the Compressor Summary table. Power measurement is taken during a period where the compressor is not needed (see the Electrical Calculations section in the body of this manual for power calculation if amperage and voltage are measured) and is recorded in the Compressor Summary table. Energy is saved when the compressor is shut off.

<table>
<tr><th colspan="9">Compressor Summary</th></tr>
<tr><td>Manufacturer</td><td colspan="3">Quincy Northwest</td><td colspan="4">Capacity (ACFM)</td><td>435 ACFM</td></tr>
<tr><td>Model</td><td colspan="3">QNW410</td><td colspan="4">System pressure (psig)</td><td>100 psig</td></tr>
<tr><td>Type</td><td colspan="3">rotary screw</td><td colspan="4">Control strategy</td><td>throttle</td></tr>
<tr><td>Hp</td><td colspan="3">100 hp</td><td colspan="4">Unload capacity (%C)</td><td>N/A</td></tr>
<tr><td colspan="9"></td></tr>
<tr><td rowspan="2"></td><td colspan="3">voltage</td><td colspan="3">amperage</td><td>power</td><td>operation</td></tr>
<tr><td>A-B</td><td>B-C</td><td>A-C</td><td>A</td><td>B</td><td>C</td><td>(kW)</td><td>(hours)</td></tr>
<tr><td>shut off time</td><td></td><td></td><td></td><td></td><td></td><td></td><td>61.1</td><td>304</td></tr>
</table>

Table 20: Reduce Run Time Compressor Summary

Anticipated Savings

Compressor energy is saved by shutting off the air compressor during times when compressed air is not needed (such as lunch time or weekends). A timer could be installed to shut off and restart the compressor automatically. The timer should be programmed to restart the compressor approximately five minutes before production restarts to restore system pressure. The compressor could be shut off for the following time.

$$H = 304 \text{ hours}$$

Formulas for calculating savings are given in the Electrical Calculations and Economic Calculations sections of the body of this manual. Energy savings are summarized in Table 19. No demand cost savings are realized as peak demand occurs during plant production periods.

Implementation Cost

The implementation cost (IC) for a dial-type timer and installation is approximately

$$IC = \$200$$

The cost savings will pay for the implementation cost in 0.4 years (IC/EC).

Appendix E: Glossary of Terms

acfm: Actual cubic feet per minute, free air delivery. This is the amount of air at atmospheric conditions that actually leaves the compressor discharge.

airflow: Air delivered by compressors or used by devices.

airflow control strategy: How airflow delivered by a compressor is controlled or modulated. Strategies include: modulation, flow/no flow, and low-unload.

airflow profile: Airflow distribution over a specified period of time.

annual operating schedule: A set of daytypes with each daytype having a number of annual operating days assigned to it.

automatic shutdown timer: A device that turns off a compressor after it has operated at no load for a specified length of time. This is different than on-off control which turns off an air compressor when the full load discharge pressure is reached.

automatic sequencer: A device used to sequence compressors according to a programmed schedule. An automatic shutdown timer is used to turn off compressors that operate at no load for a specified length of time.

capacity: Maximum airflow delivered by a compressor in acfm.

cycle: The following sequence of steps at which a compressor with unloading controls operates: 1) fully loaded, 2) modulating, 3) unloading, 4) unloaded idle, 5) reloading. Eliminate step 2 for compressors that do not modulate before unloading.

cycle losses: The energy lost during each compressor cycle due to air lost during sump and oil separator blow down and recovery; only applies to compressors with unloading or on-off controls.

cycle time: The time it takes for a compressor to complete one cycle.

daytype: A 24 hour period representing a typical operating day, such as a peak-season weekday or an off-season weekend day.

daytype operating schedule: A 24 hour profile indicating which compressors are on and how they are staged or sequenced.

demand savings: Difference between existing and proposed peak power requirements.

EEM: Energy Efficiency Measure. An opportunity to alter a system to improve efficiency and save energy.

flow/no flow: A method of controlling airflow delivery by causing the compressor to operate at full load or no load, which includes load-unload and on-off. Also included is multi-step control, which isn't actually a flow/no flow control strategy, but can be modeled as such. With multi-step, the compressor operates at full load, no load, and one or more intermediate points. Multi-step is found only on reciprocating compressors.

full load discharge pressure: Maximum discharge pressure ever experienced at full air delivery for a specified compressor. This pressure will occur just before a compressor modulates or unloads.

full load power: Power required when a compressor is at capacity (maximum airflow) and full load pressure; it is the maximum power experienced by the compressor. Full load discharge pressure must be achieved before full load power can be measured.

leak airflow: Airflow, expressed as percentage of system capacity, to support plant air leaks.

leak airflow as a percentage of peak plant airflow: Leak airflow divided by peak plant airflow, expressed as a percentage of system capacity.

load-unload: A flow/no flow control strategy found on rotary screw and reciprocating compressors. The compressor operates at two conditions: full load and no load.

low-unload: A method of controlling airflow delivery by combining modulation and flow/no flow strategies. Applies to rotary screw type compressors.

key compressor: The compressor AIRMaster uses to calculate the load contributions of other compressors based on pressure settings and control strategies. A key compressor is identified by the user in the appropriate load wizard for the specified hour. The key compressor must have a contributing airflow greater than 0 and less than 100 percent for AIRMaster to determine other compressor loads.

maximum discharge pressure: Equal to no load discharge pressure for modulating-only compressors, or equal to pressure at which compressor unloads or turns off if equipped with unloading or on-off control.

minimum discharge pressure: Equal to full load discharge pressure for modulating-only compressors, or equal to pressure at which compressor reloads or turns on if equipped with unloading or on-off control.

modulation: A method of reducing airflow delivery by causing the compressor to operate at part load. Common methods of modulation include: throttle, turn or spiral valve, or poppet valves.

modulation-only: Refers to a compressor with modulation control, and no unloading controls.

multi-step: A flow/no flow control strategy found on reciprocating compressors. The compressor operates at full load, no load, and one or more intermediate points.

no load discharge pressure: Minimum discharge pressure when compressor is on but delivering no air. This is equal to Pmax for modulating-only compressors.

no load power (modulated): Power measured when compressor is fully modulated and delivering no air.

no load power (unloaded): Power measured when compressor is unloaded and completely blown down. For compressors with on-off control, this value is zero.

on-off: A flow/no flow control strategy found on rotary screw and reciprocating compressors. The compressor operates at two conditions: full load and off. This is not the same as a compressor with an automatic shutdown timer, which allows the user to program how long a compressor operates unloaded before it turns off.

operating point: A load that an compressor operates at to meet a requirement. An operating point has power and an associated airflow.

peak plant airflow: Peak system airflow minus leak airflow, expressed as a percentage of system capacity.

peak system airflow: The peak system airflow, expressed as a percentage of system capacity.

percentage of compressor capacity: Airflow for a single compressor expressed as a percentage of that compressor's capacity.

percentage of full load power: Power for a single compressor expressed as a percentage of that compressor's full load power.

percentage of system capacity: Airflow of the compressed air system expressed as a percentage of system airflow capacity.

percentage of system full load power: Airflow of the compressed air system expressed as a percentage of system airflow capacity.

performance point: One of the following compressor operating conditions (airflow and power): no load (modulated), no load (unloaded), unload point, and full load. Depending on compressor control, some or all of these points are necessary to construct the compressor's performance profile.

performance profile: A graph illustrating how power is related to airflow. This is created using necessary performance points and control strategy.

poppet valves: A form of variable displacement which includes a collection of valves used to modulate airflow of a rotary screw compressor. As air requirements decrease, the poppet valves open, allowing intake air to escape to atmospheric pressure through ports in the compression chamber walls, shortening the effective rotor length. The volumetric compression ratio and airflow are reduced.

power: Electrical power, either measured directly or calculated from current, voltage, phase factor, and power factor.

power profile: Power distribution over a specified period of time.

pressure range: Difference between Pmin and Pmax of a given air compressor.

proportional modulation pressure range: For compressors with modulation controls, it is the difference between full load no load discharge pressures. This value is equal to the pressure range for modulating-only compressors.

proposed leak airflow: Proposed percentage of peak plant airflow expressed as a percentage of system capacity.

rated pressure: Discharge pressure to which manufacturer's specifications, such as full load power and capacity. This value may be different from actual operating full load discharge pressure.

scfm: Standard cubic feet per minute. This is airflow rated at standard conditions. Standard conditions are typically 14.696 psia, 60°F, and 0% humidity.

sequence: The order which compressors are brought "on line" (either compressor turns on or reloads to deliver air) according to a programmed automatic sequencer or pressure ranges for compressors with modulating, unloading, or on-off controls. See staging definition for compressed air systems with modulating-only compressors which are not controlled by an automatic sequencer.

spiral valve: A form of variable displacement control used to modulate airflow of a rotary screw compressor. As air requirements decrease the turn valve rotates, allowing intake air to escape to atmospheric pressure through ports in the compression chamber walls, shortening the effective rotor length. The volumetric compression ratio and airflow are reduced. This is the same as a turn valve.

staging: How compressors deliver air according to fixed Pmax and Pmin settings. Staging applies to compressed air systems with compressors not controlled by an automatic sequencer.

system capacity: Maximum airflow available to the entire compressed air system--the sum of all available compressors.

throttle: A device used to modulate airflow of a rotary screw or reciprocating compressor. Airflow is reduced by creating a partial vacuum at the compressor inlet by closing a butterfly or slide valve.

turn valve: See spiral valve.

unload point: Airflow at which compressor unloads.

unload power: Compressor power at the unload point.

unloading controls: Controls that allow a compressor to operate at no load with a substantially lower discharge pressure. Unloading controls are found on load-unload, on-off, low-unload, and multi-step airflow control strategies.

variable displacement: A device used to modulate airflow of a rotary screw compressor. The controls allows progressive reduction of compressor displacement without reducing inlet pressure. As air requirements decrease, a portion of intake air is allowed to escape to atmospheric pressure through ports in the compression chamber walls, shortening the effective rotor length. The volumetric compression ratio and airflow are reduced. See turn valve, spiral valve, or poppet valves for specific examples of variable displacement control.