COMPRESSED AIR SYSTEM AUDIT SOFTWARE

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INTRODUCTION

Air compressors are a significant industrial energy user. Based on a survey of energy audit reports from 125 northwest plants, air compressors account for roughly 10% of total plant energy use. Air compression is inherently inefficient with up to 95% of 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 inappropriate uses of air can also produce energy and cost savings.

Since air compressors often are encountered in industrial energy audits, one goal of this project is to develop a software analysis tool. A spreadsheet-based program was developed to model compressed air system operation and estimate energy savings for six typical Energy Efficiency Measures (EEMs). The program can model part load system operation with up to three compressors operating simultaneously and independent operating schedules.

The model was developed in conjunction with an audit methodology and is intended to enable energy auditors to simulate both existing and modified system operation and evaluate the EEMs. Thus, the program title is: Justify Air Operation and Maintenance (JAirOAM, also known as "Jerome"). Ten audits are currently being conducted to develop and validate the model.

COMPRESSOR CHARACTERISTICS

Compressed air systems often have multiple compressors with different operating schedules and control strategies. There are three common types of compressors: rotary screw, reciprocating, and centrifugal. Since centrifugal compressors are used primarily in large plants with high air use, they were not specifically included in this project. To assist industrial energy auditors, Jerome should be able to model each type of system that might be encountered.

There are three 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 air flow profiles.

Modulation Control

There are two types of modulation: throttle and turn or poppet valves. Air flow is controlled by the position of the throttle or turn valve, or the number of poppet valves open, which proportional to discharge pressure within the Proportional Modulation Pressure Range (PR). The PR is the difference between the Full Load Discharge Pressure (PMIN) and the No Load Discharge Pressure (PMAX) and is generally fixed for a given compressor. In general, when discharge pressure is low, the throttle is wide open, or the turn or poppet valves are closed, resulting in full air delivery. If air flow requirements are 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 turn or poppet valves will begin to open, reducing air flow from the compressor. Modulation continues until compressor air flow matches plant air requirements and discharge pressure stabilizes. If no air is required from the compressor (for example, another compressor can meet air flow requirements), discharge pressure will continue to increase and modulation will continue until no air flows from the compressor. PMAX is defined as the discharge pressure at which the throttle finally closes completely, the turn valve opens completely, or all poppet valves are open. If pressure drops below PMAX, the throttle will open, or the turn or poppet valves will close.

Throttling is a form of inlet modulation accomplished by a butterfly or slide valve, and is typically found on rotary screw compressors. Air flow 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 air flow. Part load performance will fall on a straight line drawn between the full load and no load operating points, as illustrated in Figure 1.

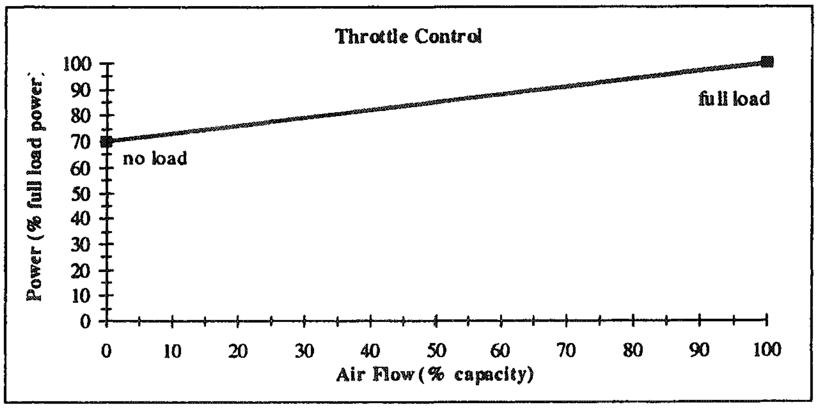

Figure 1. Performance Profile for Throttle Control

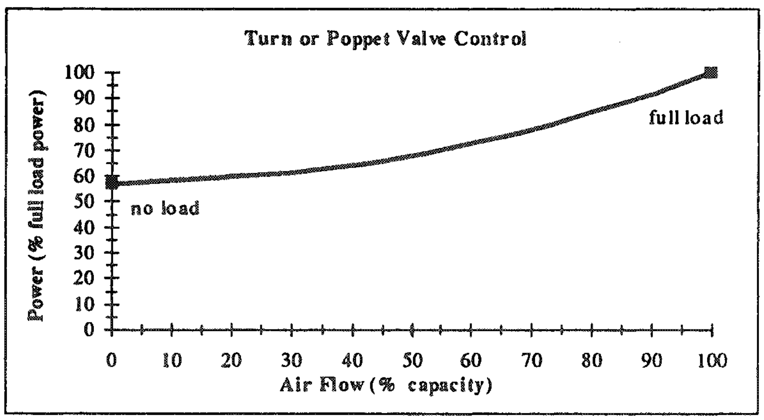

Figure 2. Performance Profile for Turn or Poppet Valve Control

Turn and Poppet Valves are the other forms of modulation used on rotary screw compressors. 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 air flow are reduced, resulting in a quadratic reduction of power with air flow (Figure 2). Similarly, poppet valves open to allow intake air to escape, reducing air flow.

Flow / No Flow Control

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

Load-Unload controls on rotary screw and reciprocating compressors allow the compressor to operate at two points: fully loaded and unloaded. The compressor operates at full load until the system reaches the maximum set pressure (PMAX) at which time the compressor unloads. An unloading valve at the compressor discharge vents the oil separator and sump to a lower pressure. No modulation occurs with this strategy. The compressor reloads when system pressure drops to the minimum set pressure (PMIN). No load power is reduced because the

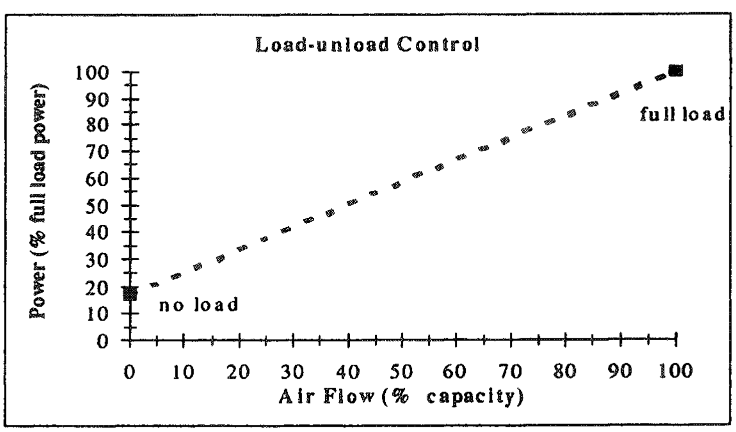

Figure 3. Performance Profile for load-unload Control

compressor discharge pressure is less than system pressure. Average power is linear with average air flow between full and no-load (Figure 3). The dashed lines indicate the compressor never actually operates between full load and no load.

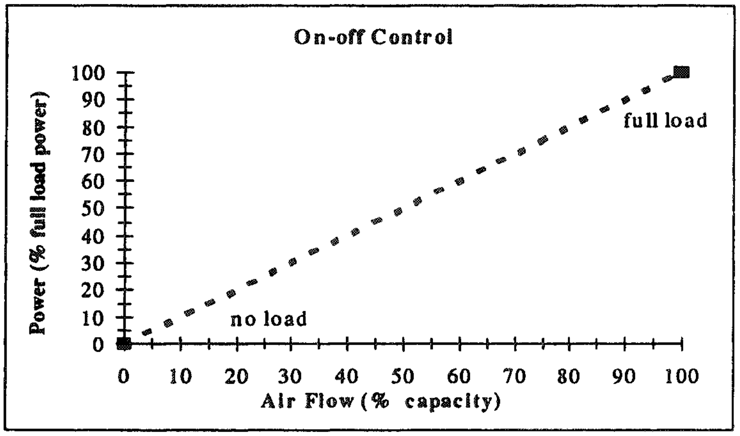

Figure 4. Performance Profile for On-off Control

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. The motor then turns off until system pressure drops to PMIN, at which time the compressor turns back on. This strategy is also modeled as a linear reduction in average power with average air flow (Figure 4).

Multi-step control is found only on reciprocating compressors. Reciprocating compressors with multiple pistons reduce capacity by opening intake valves or chambers. This type of 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 with a linear reduction in power with flow. The compressor operates at full load, no load, and one or more intermediate loads (Figure 5).

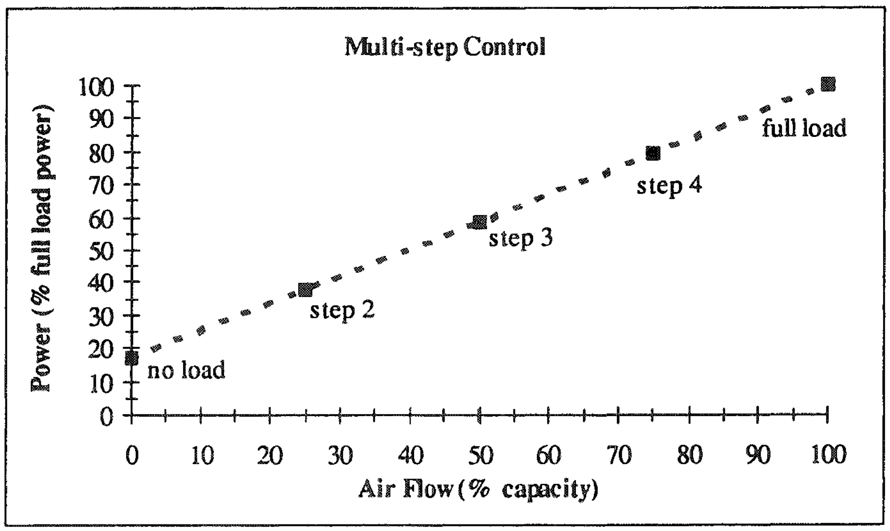

Figure 5. Performance Profile for Multi-step Control

Low-Unload Control

This control strategy is a combination of inlet modulation and load-unload controls and is found only on rotary screw type compressors. Modulation may be either throttle, turn or poppet valves. Compressors operate at full load until PMAX is reached, then begin to modulate to match system air requirements. If air requirements are below the unload point, the compressor will unload (Figures 6 and 7). 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.

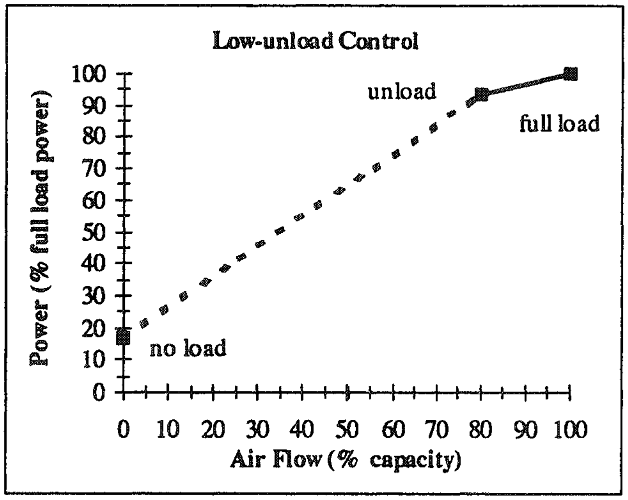

Figure 6. Performance Profile for Throttle Modulation and Low-unload Control

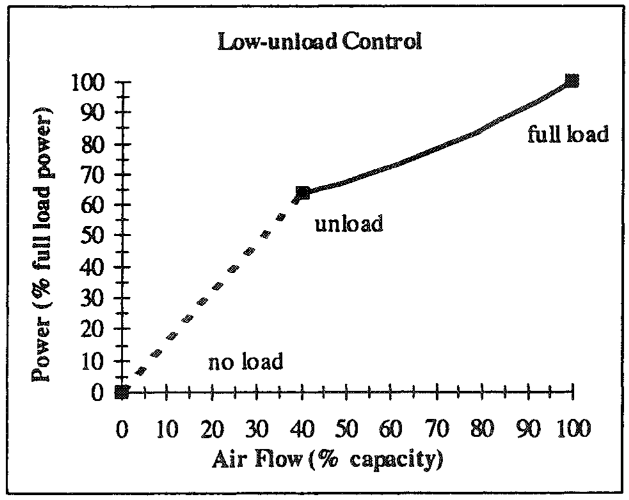

Figure 7. Performance Profile for Turn or Poppet Valve Modulation and Low-unload Control

Compressors that unload often have a timer that turns off a compressor after being unloaded for a specified amount of time, such as 15 minutes. This minimizes the number of motor starts.

Operating Pressure Ranges

The pressure range is important when staging multiple compressors. The PR dictates which compressors will be in lead, second, and third positions. Following are examples of three compressors with different PR configurations. The compressors in Figure 8 have nonoverlapping PRs, resulting in nonoverlapping, staged operation; the compressors in Figure 9 have overlapping but different PRs, resulting in overlapping, staged operation; the compressors Figure 10 have identical PRs, resulting in simultaneous modulation or cycling.

For modulating compressors, system pressure remains constant for an air flow requirement. An air flow requirement can be met by finding a pressure where the sum of each compressor's contributions matches the system air requirement. Compressors with multi-step or low-unload control are modeled the same way.

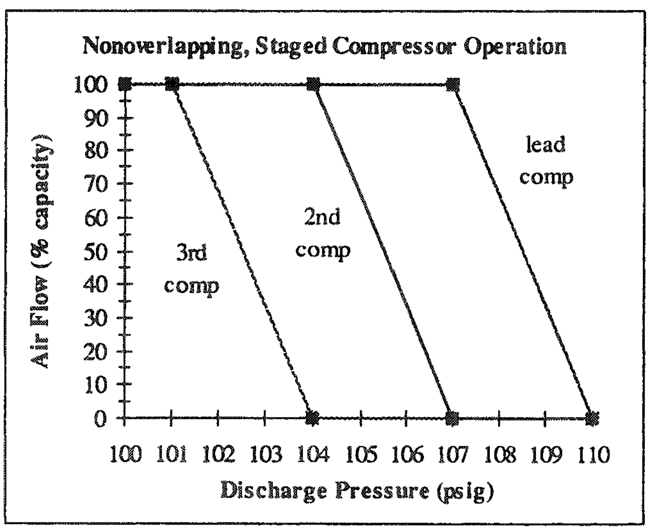

Figure 8. Compressors with Staged PRs

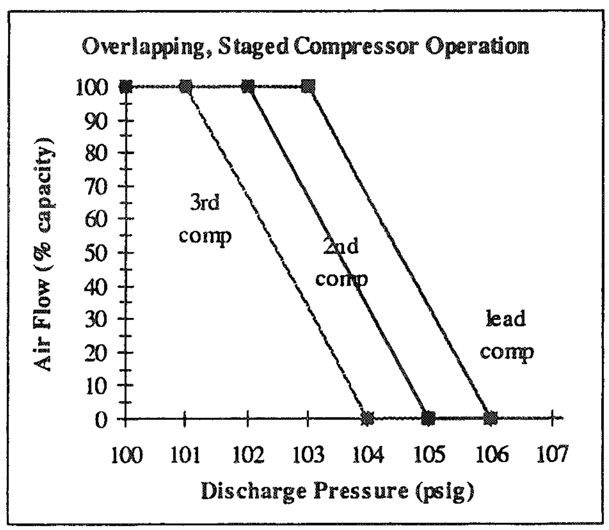

Figure 9. Compressors with Overlapping, Staged PRs

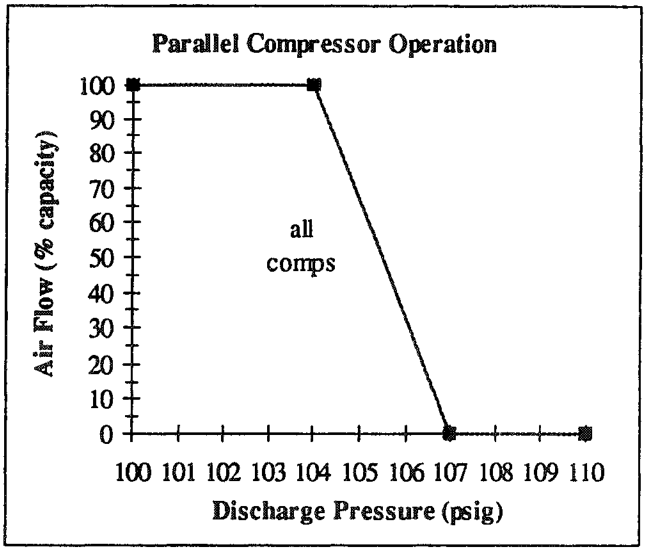

Figure 10. Compressors with Identical PRs

Compressors with load-unload or on-off control stage similar to modulating compressors, but system pressure changes as compressors cycle. Air flow requirements that can be met by the lead compressor alone will leave the second and third compressors unloaded. The lead compressor will cycle. This is because system pressure will never drop to the other compressors' minimum pressure. If air flow requirements increase, system pressure will drop to the second compressor's minimum pressure, and it will reload. The second compressor will cycle and the lead will remain at full load.

The compressors in Figure 10 have identical PRs, resulting in simultaneous modulation. All compressors will cycle simultaneously.

As an example of how staging affects compressor operation, consider an air flow requirement of 150 acfm. The available compressed air system includes three compressors of 100 acfm capacity each. Table 1 shows how the required air flow is distributed among the compressor based on their control strategies and PRs. Refer to Figures 8, 9, and 10 for pressure range configurations.

Air Flow Distribution				
Pressure Range Configuration	**System Pressure (psig)**	**Lead Compressor (acfm)**	**2nd Compressor (acfm)**	**3rd Compressor (acfm)**
modulation, nonoverlapping staged	105.5	100	50	0
modulation, overlapping staged	103.5	83.3	50	16.7
modulation, parallel	10.5	50	50	50

Table 1. Distribution of an Air Flow Requirement of 150 acfm for Different Control Strategies and Pressure Range Configurations

Control strategies that turn off unneeded compressors are most efficient.

Model Operation

Inputs

Data collection methods range from simple to complex, depending on equipment available and desired accuracy. For example, compressor operation can be estimated, developed from an observed capacity gauge or amperage readings at selected operating conditions, or taken from weeks or months of data logger recordings of air flow, power, and pressure.

Manufacturers' data is entered. Jerome needs to know numbers and types of compressors and controls that comprise the compressed air system. Jerome accepts up to three compressors of either rotary screw or reciprocating type. Manufacturer's data entered into Jerome include:

- manufacturer and model
- compressor type
- motor horsepower, rpm, voltage, and full load amps
- override motor efficiency and power factor
- air flow capacity
- rated full load discharge pressure
- full load compressor brake horsepower at rated full load pressure
- control strategy
- no load power expressed as a percentage of full load power

A database of several manufacturers' compressors is included. Given the manufacturer and model of a compressor, Jerome looks up the remaining data and enters it automatically in the appropriate cells.

Actual compressor operating conditions are entered. Jerome accepts compressor inlet conditions and corrects power and capacities for actual inlet conditions. Measured power can be entered for each operating point necessary to define the performance profile (such as full load and no load power). PMIN and the PR are entered for each compressor. If a compressor is equipped with low-unload controls, the unload point is entered. Jerome constructs performance profiles for each compressor. Calculated power may be compared to measured power.

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. Jerome accepts up to four daytypes and an annual schedule of occurrences for each daytype. Hourly averages of air flow or power are entered for each compressor and daytype. Jerome uses compressor performance profiles to calculate hourly air flow averages if power was entered or hourly power averages if air flow was entered. System air flow and power profiles are created for each daytype. To create system air flow profiles, each compressor's air flow is weighted by its capacity compared to system capacity for each hour of each 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 air flow 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 air flow and power profiles for a daytype are shown in Figures 11 and 12 respectively.

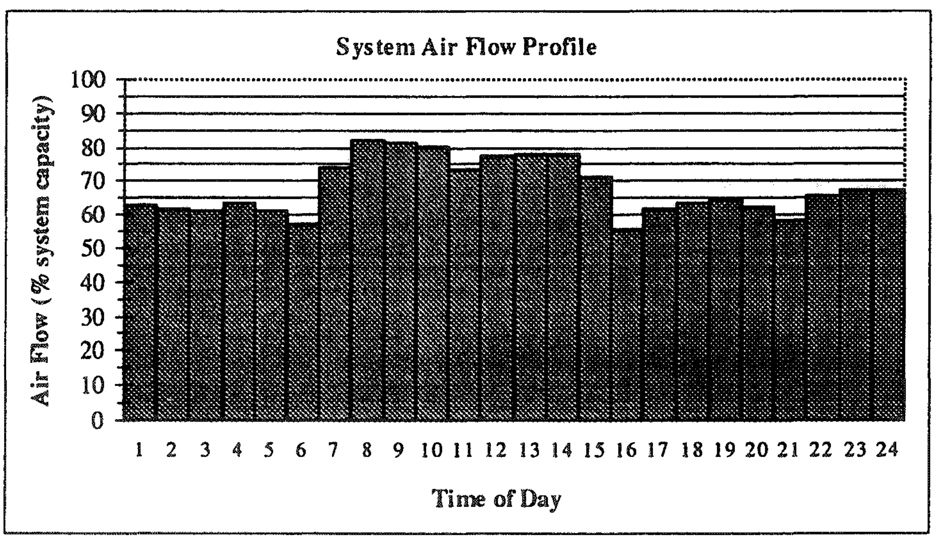

Figure 11. System Air Flow Profile for a Weekday

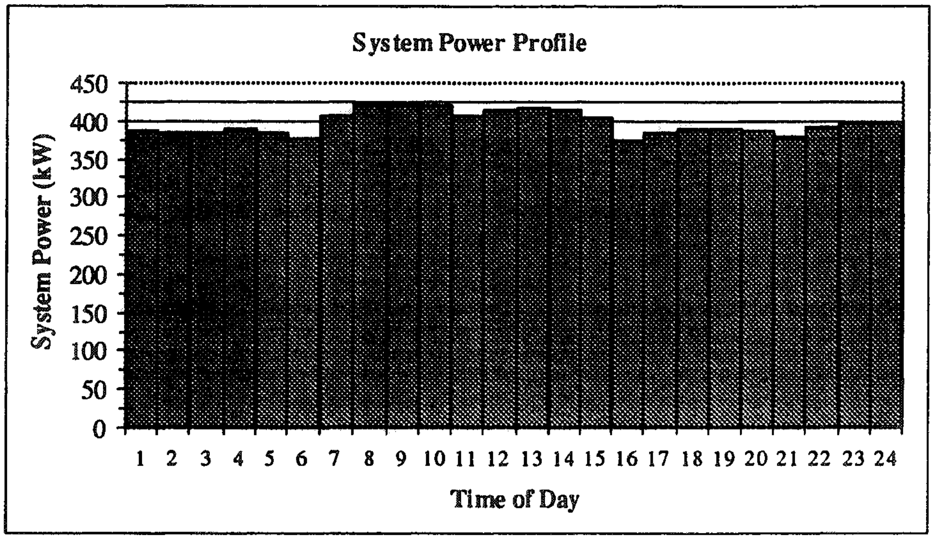

Figure 12. System Power Profile for a Weekday

Jerome constructs compressor operating schedules for each daytype. If no air flow (0% of capacity) is entered, Jerome assumes the compressor is turned off that hour unless this is overridden by the operating scheduled. If the compressors are controlled by an automatic sequencer, the sequence schedule is entered for each daytype.

Annual Air Flow and Power Profiles

Each daytype is multiplied by the annual days of occurrence to create annual system air flow and power duration profiles (Figure 13). Finally, to simplify calculations and results presentation, air flows are put into 10% capacity bins. Jerome then calculates average power for each bin and annual energy use by multiplying each power bin by its corresponding number of annual operating hours.

Energy Efficiency Measures

Jerome implements each EEM interactively in the following order. The biggest savings are usually found by reducing leaks, installing an automatic sequencer, and reducing run time.

1. **Reduce Air Leaks** is implemented first. The user enters a fixed flow reduction, representing a reduction in leaks. A typical leak load target is 10%-30%, depending on plant conditions. Jerome subtracts this amount from each air flow bin in the annual air flow profile, and a new annual air flow profile is created. Figure 13 illustrates a proposed annual system air flow profile and air flow reduction.

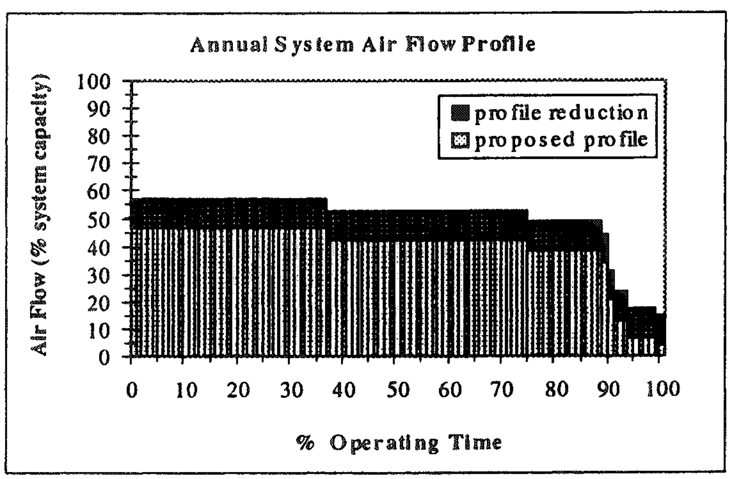

Figure 13. Proposed and Reduction of Annual Air Flow

2. **Manual Staging** allows pressure ranges to be altered. The user enters proposed PMINs for modulating, low-unload, and multi-step controls, or proposed minimum and maximum pressures for load-unload and on-off controls. This allows compressor with the poorest part load efficiency to operate at full load and the compressor with the best part load efficiency to pick up the slack.

3. **Unloading Controls** are added to selected compressors. No load power is significantly reduced, thereby improving part load performance. Figure 14 compares modulation to load-unload control for different operating points. Power savings is the difference between modulating power and average load-unload power. An automatic shutdown time can be included in unloading control packages that will turn off compressors that have been unloaded for a specified length of time. This EEM is implemented after compressors have been staged.

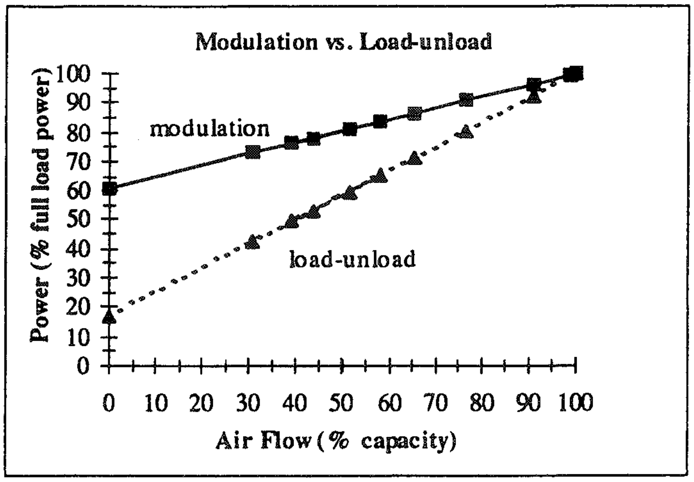

Figure 14. Modulation vs. Load-Unload Performance Profile

4. **Automatic Sequencing** allows the user to specify a compressor sequence (specify lead, second, and third compressors) for each daytype and hour. Unloading controls are automatically added to compressors that don't have them. Individual compressor pressure ranges are no longer relevant since compressor sequence is specified by the user.

5. **Reduce System Pressure** allows the user to reduce system pressure by a specified amount. Full load power for each compressor is reduced by one half of a percent per psi of pressure reduction.

6. **Reduce Run Time** allows the user to turn off unneeded compressors by changing compressor operating schedules. Power reduction is based on compressor power at the particular unneeded times after implementing previous EEMs. Most savings are for compressors operating at no load, which is significant (approximately 65%) for modulated compressors

Calculations
Next, compressor power to meet the proposed air flow profile must be calculated. Air flow must be apportioned to the compressors based on control strategies and/or sequencing. Once an air flow is determined for a compressor, power is easily calculated based on its proposed performance profile.

For load-unload, on-off, and automatic sequencing controls, air flow is supplied by each compressor, depending on pressure ranges or sequence. For example, an air flow requirement of 350 acfm supplied by a system of a 100 acfm compressor and a 300 acfm compressor. 300 acfm would go to the 300 acfm compressor and the remaining 50 acfm would go to the 100 acfm compressor, if pressures are set properly or compressor sequence is specified.

Systems with modulating, low-unload compressors (unload point set less than 100% capacity), and multi-step controls present a greater challenge. Pressure range and discharge pressure dictate how much air each compressor will deliver. Jerome uses a numerical solution routine built into the spreadsheet program to determine how much air each compressor must supply to meet a required air flow. Jerome guesses a discharge pressure and calculates air flow for each operating compressor. Jerome compares the sum with the required air flow. Discharge pressure is corrected and a new air flow is calculated and checked. Corrections are made until air flow matches required air flow within 0.5%. This is done for each required air flow in the proposed air flow profile.

Savings
Power reduction is calculated as existing minus proposed power for each EEM. Demand charge savings is based on power reduction during the peak demand period. Energy savings are calculated for each EEM by multiplying power reduction by operating time for each bin. A summary table presents all power, energy, and cost savings. Cost savings include demand charge and energy cost savings.

RESULTS

Jerome produces results in graphical and tabular form for each compressed air system audit. The three outputs from Jerome are:

- Graphs of individual compressor and system performance profiles, and daytype power and air flow profiles
- Existing and proposed operating conditions tables for each EEM
- Savings summary table of all EEMs

Graphs. The figures shown in the Energy Efficiency Measures section are examples of performance, power, and air flow profiles from an audit of a plant with two twin screw compressors. Both compressors had inlet butterfly valve modulation controls. Jerome creates performance profiles for each compressor, using relationships defined in the compressor characteristics section. Graphs of hourly power and air flow profiles are created for each daytype from measured audit data. Proposed compressor performance profiles are created for any modifications to compressor performance, such as adding unloading controls.

Operating Conditions Table. For each EEM recommended, Jerome creates a three part table that shows: existing conditions, proposed conditions, and demand, energy and cost savings for proposed conditions (Table 2). The first section of Table 2 shows existing system operation, while the second section shows proposed operating conditions after implementation. The third section shows demand, energy, and cost savings. The tables were taken from the Reduce Air Leaks EEM recommended for the same plant.

Several modifications to system operation can be seen in Table 2. Proposed system leak load was reduced from 40.5 percent of the existing system capacity (2,500 acfm), to 30.4 percent of the proposed system capacity (1,000 acfm). System capacity was reduced because it was recommended that one compressor be turned off. A second reduction in air use from eliminating inappropriate uses (330 acfm) can be seen during production periods 3 through 8.

System power and energy use were also significantly reduced. Because one compressor was turned off, full load power was reduced from 421.5 kW to 175.5 kW. A majority of the savings resulted from shutting off the compressor. Power reduction is calculated as existing minus proposed power for each EEM. Energy savings are calculated for each EEM by multiplying power reduction by operating time for each production level (bin).

Summary Table. Jerome produces a Savings Summary table that presents power, energy and cost savings for all recommendations. Cost savings include demand and energy costs savings. Table 3 shows the energy and cost savings estimated by Jerome for implementation of the three EEMs recommended during the audit used for the graphics and operating conditions examples. Note that operation and maintenance measures in compressed air systems represent a significant opportunity for savings with attractive economic returns.

Savings Summary Table							
Demand Charge: $4.35 / kW-mo				Energy Charge: $0.03327 / kWh			
EEM #	EEM Description	Demand (kW)	Energy (kWh)	Percent Savings *	Cost Savings	Implementation Cost	Payback Years
1	Reduce Leaks	246.0	1,600,438	59.3%	$63,461	$24,655	0.4
2	Unloading Controls	0.9	250,449	9.3%	$8,369	$1,200	0.1
3	Reduce Run Time	0.0	70,516	2.6%	$2,346	$200	0.1
	Maximum Savings	246.9	1,921,403	71.2%	$74,157	$6,323	0.2

* *Percent of total compressed air system annual energy use*

Table 3. Savings Summary Table

Existing Conditions						
Operating Conditions		Air Flow ($\%C_s$)	Power ($\%P_s$)	Power (kW)	Operation (hours)	Energy (kWh)
no load		0%	60.3%	274.6	0	0
leak load		40.5%	53.4%	243.0	0	0
compressors off		0%	0%	0.0	395	0
non-production		40.7%	53.4%	243.3	1,500	364,999
production	(1)	45.8%	55.5%	252.9	237	59,901
	(2)	51.6%	80.8%	367.8	395	145,226
	(3)	57.2%	83.0%	377.9	711	268,573
	(4)	62.2%	85.0%	386.9	1,895	733,188
	(5)	67.9%	87.2%	397.2	869	344,989
	(6)	72.3%	89.0%	405.3	790	320,007
	(7)	78.0%	91.3%	415.5	553	229,679
	(8)	81.3%	92.6%	421.5	553	232,956
full load		100%	100%	455.3	0	0
Total			92.6%	421.5	7,896	2,699,518

Proposed Conditions						
Operating Conditions		Air Flow (%C)	Power (%P)	Power (kW)	Operation (hours)	Energy (kWh)
no load		0%	60.9%	107.3	0	0
leak load		30.4%	72.8%	128.3	0	0
compressor off		0%	0%	0.0	395	0
non-production		30.8%	72.9%	128.6	1,500	192,885
production	(1)	43.5%	77.9%	137.3	237	32,534
	(2)	58.0%	83.6%	147.3	395	58,163
	(3)	39.0%	76.1%	134.2	711	95,368
	(4)	51.3%	81.0%	142.7	1,895	270,419
	(5)	65.5%	86.5%	152.5	869	132,420
	(6)	76.6%	90.9%	160.1	790	126,429
	(7)	90.7%	96.4%	169.8	553	93,878
	(8)	98.9%	99.6%	175.5	553	96,984
full load		100%	100%	176.2	0	0
Total			99.6%	175.5	7,896	1,099,079

Savings Summary								
Demand Charge:		$3.46 /kW-mo.			Energy Charge:		$0.03327 /kWh	
		Air Use (acfm)	Demand (kW)	Demand ($)	Operation (hours)	Energy (kWh)	Energy ($)	Cost Savings
compressors off		0	0.0		395	0	$0	$0
non-production		704	114.7		1,500	172,114	$5,726	$5,726
production	(1)	704	115.5		237	27,367	$911	$911
	(2)	704	220.5		395	87,063	$2,897	$2,897
	(3)	1,034	243.7		711	173,205	$5,763	$5,763
	(4)	1,034	244.2		1,895	462,768	$15,396	$15,396
	(5)	1,034	244.7		869	212,569	$7,072	$7,072
	(6)	1,034	245.2		790	193,578	$6,440	$6,440
	(7)	1,034	245.7		553	135,801	$4,518	$4,518
	(8)	1,034	246.0	$10,214	553	135,972	$4,524	$14,738
Total		1,034	246.0	$10,214	7,896	1,600,438	$53,247	$63,461

Table 2. Existing Conditions, Proposed Conditions, and Energy and Cost Savings

Conclusions

An automated spreadsheet-based program, Jerome, was developed that can model existing and proposed operation of industrial compressed air systems. Some of the modeling capabilities of Jerome include:

- multiple compressor systems (up to three compressors operating simultaneously)
- common control strategies
- rotary screw and reciprocating compressor types
- staging and sequencing of multiple compressor systems
- variable operating schedules (up to four distinct daytypes)
- ability to predict annual compressed air system energy use and costs

The model was developed in conjunction with a compressed air system audit methodology. Jerome is designed to allow energy auditors to evaluate energy and cost savings for six Energy Efficiency Measures (EEMs). The six EEMs were selected because they were often recommended in previous industrial audits, and have yielded significant energy and cost savings. The EEMs evaluated by Jerome are:

1. Reduce Air Leaks.
2. Manual Staging: compressor minimum and maximum pressures are manually adjusted to minimize or avoid overlap.
3. Unloading Controls: this includes low-unload and load-unload type controls.
4. Automatic Sequencing: an automatic sequencer is added to the system; compressor sequence is defined by the user, unneeded compressors are turned off.
5. Reduce System Pressure: average system pressure, and therefore compressor power, are reduced.
6. Reduce Run Time: compressors are turned off when not needed.

Ten compressed air system audits are currently being conducted to validate and further develop the model. Jerome's baseline accuracy has been verified for each audit by comparing modeled baseline power and energy use with recorded use. For these audits baseline energy use has been within 1% of measured use. Future work will include post implementation power monitoring at some of the audited industrial facilities to verify predicted energy and cost savings, and to improve estimates of implementation costs.