Compressed-Air Evaluation Protocol
Nate Benton, Nexant, Inc.

1 Measure Description

Compressed-air systems are widely used throughout the industry for a multitude of operations including pneumatic tools, packaging and automation equipment, conveyors, and other industrial process operations. Compressed-air systems are a group of subsystems composed of air compressors, air treatment equipment, controls, piping, pneumatic tools, pneumatically powered machinery, and process applications using compressed air. A compressed-air system has three primary functional subsystems: supply, transmission, and demand. Brief descriptions of each follow:

1. **Supply**: conversion of primary energy resource to compressed-air energy. The supply subsystem includes generation, treatment, primary storage, piping, controls, performance measurement equipment, and reporting systems.

2. **Transmission**: movement of compressed-air energy from point of generation to end use. The transmission subsystem includes distribution piping mainline and branch headers, piping drops, secondary storage, and transmission controls.

3. **Demand**: the total of all compressed-air consumers, including productive end-use applications and various forms of compressed-air waste. The demand subsystems include all end uses, point-of-use piping, secondary storage, and point-of-use controls.

Air compressors are the primary energy consumer in a compressed-air system and are the primary focus of this protocol. Brief summaries for other common compressed-air energy-efficiency measures affiliated with components of the transmission and demand subsystems are provided in Section 2.1.

The four compressed-air energy-efficiency measures addressed in this protocol are as follows:

1. Variable speed drive (VSD) compressor replacing constant-speed compressor
2. Compressor control system upgrades and optimization sequencing in multi-compressor plants
3. Optimization of system air pressure setpoint
4. Compressed-air leak survey and repairs

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1 As discussed in *Considering Resource Constraints* in the Introduction of this UMP report, small utilities (as defined under the Small Business Administration regulations) may face additional constraints in undertaking this protocol. Therefore, alternative methodologies should be considered for such utilities.
1.1 **High-Efficiency (VSD) Compressor Replacing Modulating Compressor**

This measure relates to the installation of a rotary screw compressor with VSD or variable displacement capacity control. Most incentive programs and technical reference manuals use a baseline system definition of a standard modulating compressor with blow-down valve. The energy-efficient compressor is typically defined as an oil-flooded, rotary-screw compressor with variable-speed control.

It is common for demand-side-management (DSM) programs to require appropriately sized air receivers and/or pressure/flow controllers to be installed in conjunction with high-efficiency compressor units in order to improve energy performance. This measure is frequently offered for the replacement of an existing unit at the end of its useful life or for the installation of a new system in a new building (at the time of sale).

Several control methods are available for air compressors, and control methods greatly affect the overall operating efficiency of a compressor. In order to accurately estimate energy savings resulting from an air compressor replacement project, it is important to know the method of control used by the baseline and energy-efficient equipment. A brief description of common control methods is provided below. Whether it is for a compressor replacement project or a controls upgrade/installation project, the method of system control will have a significant impact on savings.

### 1.1.1 Inlet Valve Modulation / Inlet Throttling

Inlet valve modulation throttles off the air inlet to a compressor as the discharge pressure rises above the setpoint pressure. This causes the compressor to draw in less air, matching compressor capacity with air usage for relatively steady pressure control. The part-load performance of modulating compressors is relatively poor. Some modulation-controlled machines may be adjusted to fully unload or “blow down” if capacity reduces to a certain level, such as 40%. This reduces energy consumption, but requires the use of air storage receivers to meet demand when in the fully unloaded state. This type of system is most often used as the baseline system definition. This method is used in oil-flooded, rotary-screw compressors; oil-flooded, rotary-vane compressors; and centrifugal compressors.

### 1.1.2 Load/No-Load (Dual) Control

Load/no-load or dual controls, also known as constant-speed controls, require storage receiver volume and operate a compressor at full capacity until the unload pressure (cut-out) setpoint is reached. At the unload pressure, the compressor switches to “no load” and plant demand is met by the stored air in the receiver(s) and piping. Once a lower load (cut-in) pressure is reached, the compressor returns to full capacity, and the cycle repeats. This control method is applicable to virtually any compressor system type.

### 1.1.3 Variable-Displacement Control

Variable-displacement controls change compressor capacity by opening compressor ports that limit the amount of the cylinder or air-end used for compression. This is often accomplished in discrete steps (e.g., 50%, 75%, and 100%), but may also be accomplished by a sliding or turning mechanism that opens the port such that continuous variation of capacity is possible. Efficiencies are typically good within the variable displacement range, but typically have a limited turndown range.
1.1.4 Variable-Speed Control

VSD and variable-frequency drive compressor controls use an integrated variable frequency AC or switched-reluctance DC drive to control the frequency of the electrical signal to the motor and, in turn, vary the speed of the motor and compressor. Compressors equipped with VSD controls continuously adjust the drive motor speed to match variable demand requirements. Variable speed compressors typically have an excellent turndown range.

1.2 Compressor Control System Upgrades and Optimization Sequencing in Multi-Compressor Plants

Two other common compressed-air energy-saving measures offered by utility incentive and rebate programs (usually on a custom track as opposed to prescriptive) are compressor control system upgrades or installations and optimization sequencing for plants with multiple compressors. These measures are typically implemented in concert.

Multiple Compressor Controls

Systems with multiple compressors generally use more sophisticated controls to orchestrate compressor operation and air delivery to the system.

*Local/Network Controls* use the on-board compressor controls’ microprocessors, which are linked together to form a chain of communication that makes decisions to stop/start, load/unload, modulate, vary displacement, and vary speed. Usually, one compressor assumes the lead and the others are subordinate.

Local/network controls use a cascade setpoint scheme to operate a compressed-air system as a whole. These systems are capable of avoiding part-load compressor operation when properly designed and set, but can present problems with maintaining minimum pressure setpoints for production when more and more compressors are added and the range of compressor load and unload setpoints increases. In addition, due to control drift, this type of control is prone to operating in a less-efficient state. If there are any significant pressure drops between the compressors in the system, or if the compressors are located in different areas of the plant, it is not uncommon for each compressor to be operating in a part-load state. More sophisticated network control systems use single setpoint logic to start or stop compressors.

The three major disadvantages of local/network system controls are:

1. They are only capable of controlling air compressors.
2. They cannot be networked with remote compressor rooms without a master control.
3. They have microprocessor compatibility issues and typically only work with compressors of the same brand and configuration.

*System Master Controls* coordinate all of the functions necessary to optimize compressed air as a utility. System master controls have many functional capabilities, including the ability to monitor and control all components in the system, as well as verify trending data to enhance maintenance functions and minimize costs of operation. Other system controllers, such as pressure/flow controllers, can also substantially improve the performance of some systems. The objective of an effective automatic system-control strategy is to match system demand with compressors operated at or near their maximum efficiency levels. This can be accomplished in a number of
ways, depending on fluctuations in demand, available storage, and the characteristics of the equipment supplying and treating the compressed air.

System master controls interface with all brands and types of air compressors, and can be used to coordinate the operation of satellite compressor rooms.

The most sophisticated, state-of-the-art system master controls use single-point control logic with rate-of-change dynamic analysis to determine how the compressed-air system responds to fluctuations in compressed-air demand. System master controls sometimes require short-duration support, such as additional storage, in order to maximize operating efficiency. A properly configured system master control can determine the best and most energy-efficient response to events that occur in a system. The number of functions a system master control can interface with is governed by practicality and cost limitations. The core functions of a system master control layout are:

- Send and receive communications.
- Communicate with a plant information system.
- Start/stop and load/unload compressors.
- Change base/trim duties.
- Select appropriate mix of compressors to optimize efficiency.
- Select which compressor should be started/stopped relative to change in system demand.

Energy savings resulting from control system upgrades and multiple compressor sequencing can be significant, but can also be challenging to quantify and evaluate due to the interactive effects caused by concurrent modifications to system supply and demand. The general approach, key parameters, and algorithms used to calculate energy savings for these measures are similar to those used for compressor replacement. The preferred approach to estimating project savings is through pre- and post-retrofit metering.

### 1.3 Optimization of System Air Pressure Setpoint

One of the most common compressed air energy conservation measures (ECMs) is reducing system operating pressure to reduce compressor energy consumption. In addition, system artificial demand can be reduced by decreasing system pressure, which can significantly impact some systems.

It is common for compressed-air systems to be operated based on a perceived pressure requirement with a safety factor built in to account for transmission losses. Line pressure is often also elevated to account for variability in demand caused by components in the distribution system and to compensate for pressure/friction losses through piping, dryers, filters, and valves.

Pressure at the discharge of the compressor can be reduced by minimizing pressure losses across the piping and air treatment equipment in the distribution system. In this situation, it is important to accurately measure pressure across components at various supply loads.

Two simple tools used to analyze compressed-air systems are block diagrams and pressure profiles. Block diagrams identify all of the components in a compressed-air system; a sample is shown in Figure 1.
The second tool used to analyze a compressed-air system is a pressure profile. A pressure profile involves determining the pressure drops through a system. These pressure measurements give feedback for control adjustments, outline pressure drops across components, and reveal system operating pressures. Calibrated pressure gauges or differential pressure gauges are required to measure pressure drop through individual components. The following pressure measurements should generally be taken when analyzing pressure drop through a compressed-air system:

- Inlet to compressor (to monitor inlet air filter) versus atmospheric pressure
- Differential across air/lubricant separator (if applicable)
- Inter-stage on multistage compressors
- Various points of the distribution system
- At various end-use stations (to help determine if pressure drop at one station is causing the entire system to run at a higher pressure)

Consider pressure differentials, including:

- Inlet air filter
- Intercooler
- Aftercooler

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• Treatment equipment (dryers, filters, etc.)
• Check pressure differentials against manufacturer’s specifications, if available (high-pressure drops indicate that service is required).

Figure 2 shows an example of a pressure profile in a system with excessive pressure drop.

The use of data loggers is also important for determining how a system operates over time. Data logging system pressures and flow can indicate intermittent loads, system disruptions, and general system conditions, and is important for determining system efficiency (CFM/kW), which can be benchmarked against industry standards. It can also indicate system changes (e.g., production process changes or intermittent demand) that can affect the compressed-air system operation and efficiency. These variations in pressure and flow can be managed through system control strategies and storage to minimize their impact on production. See Section 4 of this protocol for guidance on instrumentation requirements and measurement and verification (M&V) best practices.

1.4 Compressed-Air Leak Survey and Repairs

Leaks are a significant source of wasted energy in a compressed-air system, and can contribute system operation problems, including too low of system pressure, excessive size of supply equipment, and additional wear and reduced service life of supply equipment.

Although leaks can occur in any part of the system, the most common problem areas are couplings, hoses, tubes, fittings, pipe joints, quick disconnects, FRLs (filter, regulator, and lubricator), condensate traps, valves, flanges, packings, thread sealants, and other point-of-use devices. Most typical distribution piping has a more rugged construction and is not located where it is prone to damage, and therefore leaks in the distribution system are not typical. Leakage rates are a function of the supply pressure. They are identified in cubic feet per minute (CFM) and are proportional to the square of the orifice diameter (hole or crack size; see Table 1).

Table 1: Leakage Rates (CFM) for Different Supply Pressures and Approximately Equivalent Orifice Sizes

<table>
<thead>
<tr>
<th>Pressure (psig)</th>
<th>Orifice Diameter (inches)</th>
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<tr>
<td>70</td>
<td>0.3</td>
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<tr>
<td>80</td>
<td>0.3</td>
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<td>0.40</td>
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<tr>
<td>125</td>
<td>0.5</td>
</tr>
</tbody>
</table>

For well-rounded orifices, values should be multiplied by 0.97. For sharp orifices, values should be multiplied by 0.61.

There are three common methods to detect compressed-air leaks: 1) auditory and sensory observations, 2) using soapy water, and 3) ultrasonic leak detection. The industry standard and best practice is ultrasonic leak detection, which relies on specialized directional microphones and amplifiers to detect high-frequency noises generated by the turbulent flow of compressed air escaping. The high-frequency sound produced by a compressed-air leak is both directional and localized to the source.

Best practice for conducting a compressed-air leak survey is to use an ultrasonic leak detector capable of estimating the volume of leakage (in CFM) based on a recorded decibel level. Leak volumes and flow can be approximated from decibel readings using conversion tables provided by the equipment manufacturer. An example conversion table for the UE Systems Ultraprobe Model 3000 is provided in Table 5 in Section 3.2.

The basic procedures for conducting a compressed-air leak survey are as follows:

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1. Perform system leak-down test to determine combined rate of compressed-air loss prior to conducting leak survey or performing any repairs. If this is not possible, determine supply flow during a non-production period.

2. Interview facility operator to determine extent of current leak repair program, if any.

3. Conduct leak survey using ultrasonic leak detector capable of reporting decibel levels.

4. Use markers or tags to identify the location of leaks discovered. It is often beneficial to map out the identified leaks on a detailed floor plan of the facility being surveyed. Do not remove markers until verification is complete.

5. Record the observed or estimated gauge pressure in the system nearest to any discovered leaks.

6. Record the observed/estimated leak area (i.e., tube/pipe internal open area or crack area).

7. Record the decibel level (dBA) of each leak as measured on the ultrasonic leak detector for later correlation to CFM leakage rate.

8. Record annual compressed-air system operating hours for each leak identified (not always equivalent to compressed-air system operating hours due to isolation valves, controls, etc.).

9. Calibrate the total identified leak volume to the leak-down test to ensure leak volume is reasonable.

2 Application Conditions of Protocol

The measures covered by this protocol involve improvements to the operating efficiency of a compressed-air system or reductions to the overall system energy consumption. Efficiency improvements are predominantly achieved through air compressor replacements. Reductions in system demand are accomplished through upgrading the control system, implementing sequencing strategies in multi-compressor plants, reducing system pressure setpoints, reducing pressure drops due to inadequate pipe size or faulty components, eliminating inappropriate uses of compressed air, and identifying and repairing compressed-air leaks.

**High-Efficiency/VSD Compressor Replacement Measures**

Rebate and incentive programs typically offer a prescriptive compressor replacement measure, often titled “Efficient or High Efficiency Air Compressors” or “VSD Compressors.” Many incentive programs and technical reference manuals assume that the baseline compressor system is a modulating or constant-speed compressor. New energy-efficient compressors are generally assumed to be oil-flooded, rotary screw with variable displacement capacity, load/no load, or VSD controls.

Projects involving other types of air compressor systems (positive displacement, reciprocating, or centrifugal) or other types of control methods are typically channeled through a custom track. This protocol provides guidance on how to estimate the energy savings resulting from air compressor replacements for a multitude of system types and pre- and post-control methods.
Rebates or incentives for air compressor replacements are typically paid on a dollar-per-compressor-horsepower basis or are a fixed percentage of the project cost. Common eligibility requirements for compressor replacement measures are these:

- Air compressors purchased or installed for back-up or redundant systems do not qualify.
- Replaced equipment must be removed or customer must attest that the baseline system, if remaining connected, will be used only for emergency back-up purposes and will rarely (if ever) operate.
- Only one VFD compressor per system is eligible for an incentive.

This measure is commonly offered for both retrofit (replacement) projects and new construction (time-of-sale) projects. When the measure is for a new construction project or when the baseline unit has failed or is near the end of its useful life, the baseline efficiency standard must meet local energy codes, federal manufacturing standards, ASHRAE 90.1, or International Energy Conservation Code (IECC).

**Compressed-Air Leak Surveys and Repairs**

_Compressed-Air Leak Surveys and Repairs_ are another common compressed-air measure offered in rebate and incentive programs. Leak surveys are typically performed by a program-approved third-party or a trade ally. It is common for program administrators to establish specific guidelines on how to conduct the survey and report findings.

Energy savings resulting from compressed-air repairs are calculated as the estimated reduction in compressed-air loss in standard cubic feet per minute (SCFM) multiplied by the rated power input per CFM (also known as efficacy) of the air compressor serving the system.

Common eligibility requirements include:

- Customer must repair at least one leak for every five connected compressor horsepower. If less than one leak per every five horsepower is identified, then all leaks must be repaired (some programs require that a customer repair 50% of identified leaks).
- Customers must leave leak tags in place for at least 30 and up to 120 days after the incentive application is submitted to allow program administrators to verify leak repairs, if needed.
- Incentive is available only once per 12 month period, per customer site.
- The third party, trade ally, or program administrator must keep a leak log, identifying the leak location, tag number, description, severity (decibel reading from ultrasonic leak detector), estimated cost of leak using program-provided rates, and whether the leak was repaired.

Incentives are typically paid as the least of:

- A fixed dollar amount per rated compressor horsepower,
- Full reimbursement for the cost of the leak survey, or
- A program-defined, maximum dollar amount.
2.1 Programs with Enhanced Measures

Many DSM programs offer additional compressed-air measures. These measures include no-air-loss condensate drains, pressure/flow controllers, cycling thermal mass refrigerated air dryers, compressed-air heat recovery, and high-efficiency air-entraining nozzles. This protocol does not address the evaluation methods or savings calculations for these additional measures, but brief summaries are provided herein.

2.1.1 No-Air-Loss Condensate Drains

Compressed-air systems require condensate drain valves to remove condensate in the piping. No-air-loss drain valves expel condensate with no loss of compressed air, eliminating purging loads on the system and reducing air compressor energy consumption. These valves have controls that continuously measure and only purge moisture when necessary.

No-air-loss condensate drains are installed at the compressor, air dryer, filter, system storage, or any point in the transmission system where moisture may accumulate. The baseline condition for this measure is typically deemed to be a standard timer-based drain valve that is set to open on a predefined interval, resulting in the release of compressed air along with condensate.

2.1.2 Pressure/Flow Controllers

Unregulated air use creates an artificial demand on a compressed-air system. A pressure flow controller allows the system pressure to be reduced to the maximum pressure suggested for end-use equipment. This reduces the CFM demand of end-use equipment, and thus reduces the demand on the air compressor. Unregulated end-use equipment can account for up to 40% to 60% of total system demand in a production facility.

Pressure flow controllers are frequently installed in conjunction with suitable compressed-air storage; this allows compressed air to be stored at a higher pressure than the balance of the system while delivering consistent, low-pressure air to the balance of the system. Best practice is to reduce the compressed-air system pressure setpoint (psig) in gradual decrements followed by an in-depth assessment of facility operations and processes to determine whether the reduction in pressure is having a negative impact on production.

2.1.3 Cycling Thermal Mass Refrigerated Air Dryers

Air dryers remove the moisture from a compressed-air system to enhance overall system performance. There are several types of air dryers, including refrigerated, regenerative-desiccant, deliquescent, heat-of-compression, and membrane. The most common is a refrigerated dryer. Energy-efficient refrigerated air dryers are capable of either cycling on and off with thermal mass storage or of matching capacity to air flow using a variable speed or digital scroll compressor. In comparison, a typical non-cycling dryer uses the same amount of power continuously regardless of demand and varies capacity using hot-gas bypass. The energy savings from a refrigerated dryer result from the decrease in operating hours between a cycling versus non-cycling dryer. Additional energy savings can result from replacing a desiccant-type dryer with a refrigerated dryer or installing demand controls on a desiccant dryer.
2.1.4 Compressed-Air Heat Recovery

Air-cooled, packaged, rotary-screw compressors are very amenable to heat recovery for space heating, industrial drying, preheating aspirated air for oil burners, or any other application requiring warm air. Ambient atmospheric air is heated by passing it across an air compressor’s aftercooler and lubricant cooler, where it extracts heat from both the compressed air and the lubricant that cools the compressor. Because packaged compressors are typically enclosed in cabinets and already include heat exchangers and fans, the only system modification needed is the addition of ducting, as well as possibly installing an additional fan to handle the duct loading and eliminate any back pressure on the compressor cooling fan.

Using a heat exchanger, it is also possible to extract waste heat from the lubricant coolers found in packaged water-cooled, reciprocating, or rotary-screw compressors and produce hot water. Hot water can be used in central heating or boiler systems, industrial cleaning processes, food preparation, heat pumps, laundries, or any other application where hot water is required.

When calculating the energy savings and payback periods for heat recovery units, it is important to compare heat recovery with the current source of energy for generating thermal energy, which may be a low-price fossil fuel, such as natural gas. Applications where the existing heater is less efficient or uses a more costly fuel will yield proportionally higher savings.

2.1.5 High-Efficiency Air Entraining Nozzles

Engineered nozzles use compressed air to entrain and amplify atmospheric air into a stream, thus increasing flow with minimal compressed-air use. They are able to induce a large air flow entrainment while using a smaller volume of air than open jets. The velocity of the resulting air flow is reduced, but the mass flow of the air is increased, thus increasing the cooling and drying effect. Energy savings result from the decrease in energy required to provide the nozzles with compressed air.

3 Savings Calculations

Calculating compressed-air system energy use is the product of the following variables:

- Demand (CFM)
- Efficiency (CFM/kW)

While annual CFM can be estimated as the product of a production variable and a characterization of the compressed air demand (CFM/production), it can also be expensive and intrusive to meter. Therefore, it is acceptable to obtain CFM by applying Compressed Air and Gas Institute (CAGI) curves to the metered amps or kW. The basic approach is as follows:

1. After installation, meter the input power to the compressors.
2. Use CAGI curves to estimate the CFM at each metered interval.
3. Calculate the CFM/kW_post as a line or curve, not as a single value.
4. Obtain production records for the post-installation metering period.
5. Characterize the CFM/production, as a line or curve when possible (if there is sufficient resolution to the production data).
If pre-installation metering is available, the above calculation steps should also be taken for the pre-installation conditions. Otherwise, follow these steps:

1. Use CAGI curves to estimate the kW at each metered CFM interval determined above.
2. Calculate the CFM/kW\textsubscript{pre} as a line or curve, not as a single value.

In all cases, it is important to:

1. Obtain production records for a typical year.
2. Apply the CFM/production curves or values to the production to obtain the annual CFM.

### 3.1 Common Savings Calculation Approach for Air Compressor Replacement, Control Upgrades, and Pressure Setpoint Modifications

A uniform method is used to calculate the gross annual savings from installing a high-efficiency air compressor, implementing control upgrades or optimization sequencing, or implementing optimization of system air pressure setpoints.

A key parameter in determining the energy savings from compressed-air measures is the compressor package input power (kW). It is common for the manufacturer to indicate the package input power for new compressors using CAGI standard data sheets. This is the preferred method for obtaining packaged input power, and each system compressors’ performance should be based on an applicable CAGI data sheet when possible.

If CAGI data sheets are unavailable, the compressor package input power can either be calculated from the compressor shaft brake horsepower (if known) or derived as the product of the compressor-rated horsepower and the load factor. The package input power for the baseline system (in a compressor replacement scenario) will usually need to be derived. The key parameters and savings algorithms for calculating package input power are:

**Package Input Power (kW) - Equation 1 (for a constant speed compressor):**

\[
kW = (\text{compressor shaft bhp}) \times (0.746 \text{ kW/hp}) \times (1/\eta_{\text{motor}})
\]

**Package Input Power (kW) - Equation 2 (for a VSD compressor):**

\[
kW = (\text{compressor hp}) \times (\text{motor LF}) \times (0.746 \text{ kW/hp}) \times (1/\eta_{\text{motor}}) \times (1/ \eta_{\text{VSD}})
\]

where:

- **compressor shaft bhp** = Shaft brake horsepower is the input power required at the compressor input shaft for a specific speed, capacity, and pressure condition
- **0.746** = kW to horsepower conversion factor
- **\eta_{\text{motor}}** = Motor efficiency (%)
compressor hp = Compressor horsepower is the nominal rating of the prime mover (motor)

motor LF = Motor load factor is the ratio of a motor’s actual load relative to the rated full load

$\eta_{VSD}$ = Variable-speed drive efficiency (%) is the efficiency of the drive itself

When analyzing the power consumption of a load/no-load, variable-displacement capacity, or VSD compressor, it is also necessary to consider power factor changes under various load conditions. To perform an analysis that normalizes for compressed-air demand, the theoretical compressed-air output flow must be calculated based on the measured power draw and typical fraction capacity (FC) versus fraction power (FP) curves.

A compressor’s FC versus FP curve parameters can be determined based on information detailed in CAGI performance data sheets, as well as on fully loaded and unloaded spot power measurements and system pressure readings. These sources of information are used to develop applied fit curves to model and estimate power consumption under varying loads. Figure 3 shows typical FC versus FP curves for a lubricated rotary screw air compressor.

![PART-LOAD PERFORMANCE ASSESSMENT](image-url)
Table 2 presents typical percent loads versus percent power distributions determined from operation curves for various types of air compressor systems and control methods. These distributions can be used to estimate power consumption under varying loads.

### Table 2: Average Percent Power vs. Percent Load for Various Air Compressor Control Methods and Systems

<table>
<thead>
<tr>
<th>% Load</th>
<th>On/Off Control</th>
<th>Load/Unload (1 gal/CFM)</th>
<th>Load/Unload (10 gal/CFM)</th>
<th>Inlet Valve Modulation (w/ Blow Down)</th>
<th>Variable Displacement</th>
<th>VSD</th>
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<tbody>
<tr>
<td>10%</td>
<td>10%</td>
<td>42%</td>
<td>33%</td>
<td>74%</td>
<td>34%</td>
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General Equation for Compressor Energy Savings (kWh) - Equation 3:

\[
\text{kWh Saved} = (% \text{ Power}) \times (\Delta \text{kW}) \times (1 - 0.005 \times (\text{psig}_{\text{Rated}} - \text{psig}_{\text{Actual}})) \times \text{(Hours)}
\]

where:

- \text{kWh Saved} = \text{Kilowatt-hours saved per year}
- \% \text{Power} = \text{Percent power input}

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5. Source: Product brochure for Sullair S-Energy Lubricated Rotary Screw Air Compressor  

Note: The ‘% Power’ parameter fluctuates with increases or decreases in compressed-air demand

\[ \Delta kW = \text{Packaged input power reduction} \]

\[ \text{psig}_{\text{Rated}} = \text{Pressure at rated flow} \]

\[ \text{psig}_{\text{Actual}} = \text{Actual system pressure} \]

\[ \text{Hours} = \text{Annual operating hours of compressor} \]

Measured and/or trended data should be used whenever possible to support both the pre- and post-installation energy consumption calculations. It is recommended that amperage (coupled with spot power measurements) or true power be measured for a minimum of two weeks. It is also considered standard practice to concurrently meter air flow for a minimum of two weeks. In the absence of measured or trended data, parameters such as load profile or operating hours must be developed based on interviews with on-site facility personnel, a review of historic operations/production levels, and reported operating schedules.

### 3.2 Savings Calculations for Compressed-Air Leak Surveys and Repairs

#### Quantifying Amount of Compressed-Air Leakage

Prior to conducting a leak survey, it is recommended that a system bleed-down test be performed to estimate the combined loss (CFM) of compressed-air leaks. The basic bleed-down test procedures are as follows:

- Estimate the total storage volume of the compressed-air system, receivers, main headers, etc., in cubic feet.
- During non-production hours, start the system and allow it to reach normal operating system pressure.
- Turn off all production loads.
- Shut off the compressor(s).
- Allow the system to “bleed down” to approximately half of the full load pressure (psig), and record the amount of time it takes to reach this point.
- Use the following formula – Equation 4:

\[
\text{Leak Volume CFM (Free Air)} = \left[ \frac{V \times \Delta P}{\text{Time} \times 14.7} \right] \times 1.25
\]

where:

- \( V \) = Tstorage volume of compressed-air system in cubic feet
- \( \Delta P \) = Drop in line pressure during bleed-down test in psig (\( P_1 - P_2 \))
- \( \text{Time} \) = Number of minutes it takes for line pressure to drop by 50% from normal system operating pressure
- 14.7 = Atmospheric pressure (psia)
1.25 = A multiplier that corrects the leakage to normal system pressure, allowing for reduced leakage with system pressure falling to 50% of initial reading

Best practices suggest measuring power during a bleed-down test in order to collect and calibrate the actual rated power input to CFM output for the air compressor system. It is also recommended that load/unload cycles be timed (if applicable).

Leakage is expressed as the percentage of compressor capacity lost. In a well maintained system, this percentage should be less than 10%. Poorly maintained systems can have losses as high as 20% to 30% of air capacity and power.

**Compressed-Air Leak Survey and Repairs**

Energy savings resulting from the repair of compressed-air leaks can be significant. The algorithm used to estimate the energy savings of a leak repair is as follows:

Energy Savings from Compressed-Air Leak Repair (kWh) – Equation 5:

\[
\text{kWh Saved} = \text{(## leaks)} \times \text{(leakage rate, CFM)} \times \text{(kW/CFM)} \times \text{Hours} \times \text{OPAF}
\]

where:

- kWh Saved = Kilowatt-hours saved per year
- # leaks = Quantity of leaks repaired
- leakage rate, CFM = Rate of air loss from leak
- kW/CFM = Rated power input to CFM output (efficacy)
- Hours = Annual hours of leak occurrence
- OPAF = Operating pressure adjustment factor

The OPAF varies based on the method of system control. Table 3 presents typical adjustment factors for common control strategies. It is recommended to use an adjustment factor in order to ensure that energy-saving estimates are conservative. It is common for vendors to use an average measured kW/CFM value, which frequently results in over-estimated savings.

**Table 3: Recommended Adjustment Factors for Determining Energy Savings from Compressed-Air Leak Repairs**

<table>
<thead>
<tr>
<th>Control Method</th>
<th>Operating Pressure Adjustment Factor</th>
</tr>
</thead>
</table>

---

<table>
<thead>
<tr>
<th>Method</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reciprocating - On/Off Control</td>
<td>1.00</td>
</tr>
<tr>
<td>Reciprocating - Load/Unload</td>
<td>0.74</td>
</tr>
<tr>
<td>Screw - Load/Unload</td>
<td>0.74</td>
</tr>
<tr>
<td>Screw - Inlet Modulation</td>
<td>0.30</td>
</tr>
<tr>
<td>Screw - Inlet Modulation w/ Unloading</td>
<td>0.30</td>
</tr>
<tr>
<td>Screw - Variable Displacement</td>
<td>0.83</td>
</tr>
<tr>
<td>Screw - VFD</td>
<td>0.97</td>
</tr>
</tbody>
</table>

The following basic procedures should be used to quantify energy savings resulting from leak repairs:

1. Impacts from leaks should be supported with formal documentation. The rated power input to CFM output (air compressor efficiency) should be supported by trended system data whenever possible.

2. The rate of air loss (CFM) for each repaired leak should be approximated using decibel readings taken in the field matched up to a manufacturer-supplied decibel-to-CFM conversion table associated with the instrumentation used to measure the leaks. An example decibel-to-CFM conversion table is shown in Table 4.
### Table 4: Compressed-Air Loss Estimator for Digital Ultraprobes

<table>
<thead>
<tr>
<th>dB Reading</th>
<th>150 PSI</th>
<th>125 PSI</th>
<th>100 PSI</th>
<th>75 PSI</th>
<th>50 PSI</th>
<th>25 PSI</th>
<th>10 PSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.70</td>
<td>0.60</td>
<td>0.50</td>
<td>0.30</td>
<td>0.15</td>
<td>0.10</td>
<td>0.05</td>
</tr>
<tr>
<td>20</td>
<td>1.40</td>
<td>1.20</td>
<td>0.80</td>
<td>0.90</td>
<td>0.50</td>
<td>0.30</td>
<td>0.15</td>
</tr>
<tr>
<td>30</td>
<td>1.85</td>
<td>1.65</td>
<td>1.40</td>
<td>1.10</td>
<td>0.80</td>
<td>0.50</td>
<td>0.40</td>
</tr>
<tr>
<td>40</td>
<td>2.40</td>
<td>1.90</td>
<td>1.70</td>
<td>1.40</td>
<td>1.10</td>
<td>0.80</td>
<td>0.50</td>
</tr>
<tr>
<td>50</td>
<td>3.90</td>
<td>3.40</td>
<td>2.00</td>
<td>2.80</td>
<td>2.20</td>
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<td>1.90</td>
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<tr>
<td>60</td>
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<td>3.60</td>
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<td>2.80</td>
<td>2.60</td>
<td>2.30</td>
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<tr>
<td>70</td>
<td>6.80</td>
<td>6.40</td>
<td>5.20</td>
<td>4.90</td>
<td>3.90</td>
<td>3.40</td>
<td>3.00</td>
</tr>
<tr>
<td>80</td>
<td>10.20</td>
<td>9.10</td>
<td>7.70</td>
<td>6.80</td>
<td>5.60</td>
<td>5.10</td>
<td>3.60</td>
</tr>
<tr>
<td>90</td>
<td>11.00</td>
<td>10.30</td>
<td>8.40</td>
<td>7.70</td>
<td>7.10</td>
<td>6.80</td>
<td>5.30</td>
</tr>
<tr>
<td>100</td>
<td>12.90</td>
<td>12.50</td>
<td>10.60</td>
<td>10.00</td>
<td>9.60</td>
<td>7.30</td>
<td>6.00</td>
</tr>
</tbody>
</table>

Note that the table values provided by the manufacturer are not factual CFM measurements, but are a general guideline. Factors such as turbulence, leak orifice configuration, operating pressure, moisture, and instrument sensitivity will affect the results. There is also a certain amount of error inherent in ultrasonic decibel readings.

3. The leakage rate (CFM) from a compressed-air system can be estimated based on the system line pressure and approximate orifice diameter of the crack or leak identified. Leakage rate is proportional to the square root of the measured orifice diameter. Table 4 showsthe leakage rates for various line pressures (psig) and orifice diameters (inches). Correction factors for well-rounded versus sharp orifice shapes must be applied to the leakage rates in order to ensure that the estimates are conservative.

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4 Measurement and Verification Plan

When choosing an M&V option, consider:

- The equation variables used to calculate savings.
- The uncertainty in the claimed estimates of each parameter.
- The cost, complexity, and uncertainty in measuring each of those variables.
- The interactive effects of concurrently implementing multiple compressed-air efficiency measures.

4.1 IPMVP Option

The following steps are used for the International Performance Measurement and Verification Protocol (IPMVP) Option A: Partial Retrofit Isolation/Metered Equipment:

1. Obtain CAGI standard data sheets for the air-compressor system in order to accurately estimate package input power.

2. Use one of the equations provided in Section 3.1 with manufacturer-rated values for compressor brake horsepower, motor efficiency, VFD/VSD efficiency (if applicable), the rated power input (kW) at maximum design pressure (psig) or rated CFM, and load operation curves for the air compressor motors.

3. Incorporate program-specific measured values for the operating hours, load factor(s), and load profile(s).

Option A is intended for projects that allow for performance factors or operational factors to “be measured on a spot or short-term basis during baseline establishment and post-installation periods, or for measures for which a measured proxy variable can, in combination with well-established algorithms and/or stipulated factors, provide an accurate estimate of the savings.”

According to the Metering Cross-Cutting Protocols from Chapter 9 of the Uniform Methods Project (UMP), “spot measurements” (also known as “instantaneous measurements”) are used to either quantify a parameter that is expected to remain constant or to calibrate instruments that will collect data over a period of time. The parameters to be spot-measured as part of a compressed-air evaluation project include:

- Line voltage.
- Integrated true root mean square (RMS) kilowatt three-phase power under all common compressor loading conditions

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Chapter 9 from the UMP also defines “short-term metering” as when instrumentation is “put into position for periods ranging from several hours to one month.” The metering duration for any given compressed-air project should be established to represent all operating modes of the facility. This period should span two full operating cycles from minimum to maximum energy use in order to be able to confirm the rate of re-occurrence in the metered data. This allows for evaluating the consistency of operations on a cycle-to-cycle basis, and avoids circumstances where data collected during a single cycle coincides with abnormal operations (e.g., data logging during the week of annual maintenance shutdown). Also, the appropriate monitoring period should include peak loads if demand-saving estimates are part of the M&V effort.

The energy use of a compressed-air system may be, and frequently is, governed by plant production levels, which typically vary on a weekly cycle. Two weeks of data is typically all that is needed to define system performance. This is not true in instances where production levels vary throughout the year, or where system operation is weather dependent. For most non-weather-dependent compressed-air applications, a metering period of one month or less is acceptable.

The actual recommended metering period and sampling interval depend on the load type (as defined in the UMP, Chapter 9, page 9-24, Table 1: Load Type Definitions). The three most common load types used by compressed-air systems are constant load cycling, variable load continuous, or variable load cycling. Each of these terms is defined in Table 6.

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant Load Cycling</td>
<td>The load or energy demand does not change. The energy use only depends on when the load is operated, and conditions dictate when the load cycles on or off.</td>
</tr>
<tr>
<td>Variable Load Continuous</td>
<td>The load or energy demand varies, and the equipment runs continuously during a scheduled period.</td>
</tr>
<tr>
<td>Variable Load Cycling</td>
<td>The load or energy demand varies. The load may be repetitive, turn on and off, or cycle based on conditions.</td>
</tr>
</tbody>
</table>

The actual recommended metering period and sampling interval is secondarily influenced by the level of rigor associated with the desired level of precision, with a higher level of rigor corresponding to a higher level of precision and corresponding costs. The relationship between precision and cost should be considered when selecting the preferred metering approach.

Evaluators will generally determine the required targets for confidence and precision levels, subject to specific regulatory or program administrator requirements. In most jurisdictions, the generally accepted levels of 10% precision at the 90% confidence interval are standard. Sampling intervals of 30 seconds to one minute are recommended, although sampling must occur
at a high enough frequency to avoid aliasing errors associated with rapidly fluctuating system demand.

It should be noted that metering periods and sampling intervals can also be influenced by the data storage capacity of the logging equipment being deployed. Storage capacity should be considered when selecting metering periods and sampling intervals.

Long-term measurements are conducted to record variations of a parameter that occur over a period generally ranging from one month to one year. The long-term metering instruments are typically installed at sites that are:

- Weather-dependent (such as HVAC loads)
- Seasonal (such as agricultural processing)
- Based on planned schedules (such as educational facilities)

### 4.2 Secondary Options

IPMVP Option B: Retrofit Isolation could be applicable in two scenarios. First, Option B could be used if amperage cannot be measured as a proxy variable and reliably converted to power, although there are few cases where this would apply. Second, Option B should be used if the equipment loading cannot be captured by short-term sampling.

IPMVP Option D: Calibrated Simulation is another common approach used by evaluators in circumstances where multiple ECMs are concurrently implemented.

### 4.3 Verification Process

The first step of the protocol entails verifying key data collected on typical program application or rebate forms. This typically includes:

- Number of shifts per day, shift-hours per week, weekend hours per week, and estimated total operating hours per year.
- Average air demand in SCFM for each shift
- Baseline equipment use pre- and post-retrofit (lead, trim, or back-up compressor)
- Baseline compressor system type (reciprocating, screw oil-less/oil-flooded, two-stage, centrifugal, vane, etc.)
- Baseline compressor system control type (load/no load, inlet modulating dampers, other)
- Baseline compressor system operating pressure (psig) at rated SCFM
- Manufacturer, model number, system type, control method, nominal horsepower, rated SCFM, operating pressure at rated SCFM, and installation date for the new energy-efficient air compressor.

For compressed-air leak survey and repair projects, the following information is also frequently requested:
• Whether the facility currently has a formal compressed-air leak detection program in place
• An estimate of total plant air leakage as a percentage of total use
• Type and model of leak detection instrument used by the trade ally to conduct the survey

Some of this data can be verified with a desk review of invoices, manufacturer specification sheets (which are typically required for rebate/incentive payments), and compressed-air survey reports, or by conducting an on-site audit of a sample of participants to verify the quality of self-reported information. If efficiency and unit capacity are not collected for each participant, it is recommended that program application requirements be modified to include these important data.

4.4 Data Requirements
The minimum data required to evaluate a high-efficiency, air-compressor replacement projects are:

• Equipment manufacturer, model, and serial number
• Compressor system type (positive-displacement, reciprocating, oil-flooded rotary screw, centrifugal, etc.)
• Prime mover (motor) efficiency
• Rated compressor shaft horsepower (bhp) or rated compressor horsepower (hp) and prime mover (motor) load factor
• Rated SCFM output
• Rated input power of the compressor in kilowatts divided by the output flow rate in CFM
• Annual operating hours of constant speed or modulating compressors
• Load factor of baseline constant speed or modulating compressor
• Load profile of new variable displacement capacity or VSD compressor
• Type of control system (modulation, load/no-load, VSD, variable displacement, etc.)

Note: All of the above-listed parameters should be gathered for both the baseline and energy-efficient equipment.

The parameters to be metered or trended during the evaluation include:

• Preferred Method: True Poly-Phase RMS Power (kW)
  This protocol prefers a trend log of true poly-phase RMS power for the circuit powering the VSD compressor. The selected sampling interval should be at a high enough frequency to avoid aliasing errors, and should be at least twice the frequency of events in the system. In general, a sampling interval of once per minute is preferred.
• Alternative Method of Power Measurement: Trend Amperage w/ Spot Power Measurements

In lieu of true power metering, trending of the current (amperage) combined with several one-time true power measurements can be used for base-loaded/constant speed systems; however, it is not recommended for VSD compressors. This is due to difficulties in simulating part-load conditions (varying amps/flow) for VSD compressors by sampling. Taking a few spot power factor measurements and applying those values to the entire spectrum of collected amperage measurements may not be representative of true loading conditions, since the power factor varies with system load/amps.

Additional data required to evaluate compressed-air leak survey and repair projects include:

• Compressed air system efficacy (kW/CFM) including compressors, dryers, and significant end-uses.
• Supply- and demand-side, one-line diagram showing all generation equipment and significant end-uses.
• Presence of intermediate pressure and/or flow controllers.
• System pressure profile of the supply- and demand-side, noting points of measurement referenced in the system diagram.
• Generation pressure (psig).
• System Air Flow (SCFM)
• Historical production data for systems affecting compressed-air consumption (number of products produced, active equipment, etc. as appropriate for facility). Production data should be collected for both the pre- and post-measurement periods, and appropriate production adjustments should be made to the collected data.

5 Data Collection Methods

5.1 Metering

The typical metering equipment used to measure and trend the energy consumption of a VSD compressor are:

• Handheld (or portable) power meters
• Current transducers (CTs)
• Watt-hour transducers
• Meter recorders (data loggers)
• In-line air flow meter (for use with data logger)

Handheld power meters are used to measure true RMS volts, amps, watts, and power factor. Ideally, these meters have a digital display and measure power to an accuracy of ±2.5% or better. A clamp-on current sensor can either be an integral part of the meter or a separate sensor connected to the meter with a wire cable.
CTs are typically selected based on the maximum load current that the compressor is anticipated to draw while metering and the size of the conductor being monitored. For temporary metering installations, split-core CTs are recommended to avoid turning off customer loads. CTs should have a linearity accuracy of ±1.0% of the reading or better and a phase angle shift (time difference between the voltage waveform and the resulting current waveform) of 2° or less.

Watt-hour transducers measure the true power (kW) or energy use of a system (kWh). Watt-hour transducers coupled with one, two, or three current transducers are generally capable of measuring one, two, or three phases of a system with voltages ranging from 120 to 600 VAC. Watt-hour transducers typically produce a pulse output in which each pulse represents a predetermined number of kWh, depending on the system voltage and CT ratings. Following the recording, a multiplier is applied to scale the pulse output into kWh units. The watt-hour transducer should have an accuracy of ±1.0% of the reading or better.¹⁰

A logging device is required to store the measured data from each type of transducer. The selected device should have a 12 bit or greater analog-to-digital converter to minimize resolution errors in the measurement. In addition, the model should have adequate storage to collect the required number of data points necessary to match the logging interval and measurement frequency.

The selected measurement equipment should always be installed on the line side of the VFD, not the load side. Measuring on the load side of the VFD would not capture the VFD losses or the total power consumption of the equipment.

Note that installing measurement equipment on the output of a VFD can lead to significant data errors. The VFD output is an approximated sine wave produced by rectifying the input AC power to DC power, then creating a simulated sinusoidal waveform using power electronics to rapidly switch the DC supply on and off. The resulting waveform has spikes (in amps) that occur at a rapid rate that can be beyond the measurement sampling of the meter, resulting in significant aliasing error. Also, the RMS voltage output of the VFD varies with speed, which would necessitate measuring voltage as well as current.

Metering should capture the integrated true RMS amps or kilowatt power measurements for a sufficient period of time so as to capture and characterize the system load. In general, two full system operating cycles should be recorded. For example, if a facility operates for five days of production followed by two days of weekend operation, it is recommended that two full weeks of data be collected to capture two full cycles of normal operation. If a system operates for nine days of production followed by one day of maintenance, then the data should be collected for 20 days of operation. In most instances, the measurement period should be at least two weeks.

The selected sampling interval should be at a high enough frequency to avoid aliasing errors. In general, the sampling frequency should be at least twice the frequency of events in the system. It may not be known how quickly system events occur until some logged data have been obtained.

¹⁰ Note that the CT accuracy must be added to the transducer accuracy to determine the power measurement accuracy. In the event that the two pieces of equipment are correlated, the accuracies are added together. If they are not correlated, then the combined accuracy is the square root of the sum of the squares of the individual accuracies.
In general, a sampling interval should be at least once per minute. Systems with rapidly cycling load/unload compressors may require a much higher frequency of data recording to capture system operation. Note that if the metering equipment is a kilowatt transducer that sums the operation between logging intervals, then aliasing errors are avoided and the sampling frequency is less of a concern, although fast sampling may still be required to capture how the system is operating.

In the pre- and post-measurement periods, all regularly operating compressors should be logged simultaneously regardless of the quantity of compressors. Compressors that are only used for back-up purposes do not need to be logged, although it is still recommended to log the back-up compressor since it may be used during other shifts or by a different system operator. Typical operations can be determined by reviewing the operating log of a compressor to see if the equipment is truly for back-up purposes only.

Spot measurements should also be performed at several different loadings of the equipment to correlate trend data with actual power measurements at the different loadings.

Care should be taken with the acquisition of any power measurements and should conform to UMP, Chapter 9: Metering Cross-Cutting Protocols.

5.2 Ultrasonic Leak Detectors for Compressed-Air Leak Surveys

It is recommended that an ultrasonic leak detector with a frequency response of 35-45 kHz be used to conduct compressed-air leak surveys. It is also highly recommended to use an instrument capable of measuring and recording decibel frequency readings in order to derive the approximate air loss associated with each identified leak. Best practice is to use a flexible scanning module or rubber focusing probe once a leak has been identified in order to get a more accurate decibel reading. It is also beneficial to use a set of noise attenuating headphones, which are designed to block out intense sounds often found in industrial environments, so that the user may easily hear the sounds received by the instrument.

5.3 Baseline and Post-Installation Production Data

Compressed air is critical for production at many facilities. In order to accurately estimate energy savings for a compressed-air project, appropriate production data is required for the baseline and post-trending periods. When estimating project savings, both the pre- and post-retrofit production levels should be normalized in order to ensure that typical annual operating conditions are represented in the calculation and to prevent scenarios where savings are inaccurately determined based on atypical operating conditions.

If production data is unavailable, it is recommended that system air flow (CFMs) be used to normalize savings. This is a common practice given the difficulties in gathering production data.

6 Discussion of Methodology

The primary energy-savings verification method is to monitor, by metering, energy use over a time period that reflects a full or complete range of the underlying operations within a specific industrial facility. Monitoring for a period of less than one year, as is most often the case, will require that annual energy use be approximated based on the results of short-term metering and historic production data.
A common issue encountered during compressed-air energy-efficiency project evaluations is a lack of information about the baseline energy consumption. In many instances, baseline consumption must be derived based on pre-retrofit production levels, reported equipment performance, and equipment and component specifications. Key parameters to be determined include: motor efficiencies, load factors, load profiles, operating hours, total system SCFM, and compressor efficacies (kW/CFM). Often, this information must be gathered through interviews with the program participant, implementer, or the energy advisor directly involved with the project.

Other resources frequently used to inform baseline assumptions include:

- Equipment tags.\(^\text{11}\)
- Historic trending from an Energy Management System.
- Engineering reports and calculations generated during the design and application phases of the project.
- Rebate or incentive program application forms.

When determining energy savings for VSD compressors, production data must be normalized to an independent normalizing variable. A unit indicating a relative level of production should be obtained from the site, which may be in the form of units produced, hours of machine operation, or labor hours depending on the site and the availability of information. Preferably, the independent variable would be collected with sufficient granularity to allow a correlation to be developed between the measured compressed-air energy consumption and the independent variable. The correlation should have a coefficient of determination (R\(^2\)) value of at least 0.75 in order to be valid. The pre and post periods should then be normalized to an annual variable for units of production to determine the annual effect of the system improvement. If an annual value is unavailable, it is acceptable to use an average of production between the pre and post periods.

Many sites may not be able to provide an independent variable for normalization. In these cases, normalizing to flow is an acceptable alternative. Two different methods may be used depending on the type of ECM implemented:

- **ECMs That Reduce System Flow** (leaks, air nozzles, condensate drains)
  
  For this type of upgrade, the individual installed components should be inspected and the CFM reduction confirmed. The flow reduction can then be modeled using the measured compressor data and simulating the decrease in energy consumption due to the decrease in flow.

- **ECMs That Improve System Efficacy** (new air compressors, compressor controls)
  
  For this type of upgrade, the system CFM should be determined at each measured point for both the baseline and installed system. The CFM should then be compared.

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\(^\text{11}\) Note: It is common for baseline compressor systems to be salvaged or kept in service and converted to emergency back-up. This provides an opportunity for the evaluator to observe and collect information from equipment tags.
The pre and post periods should be normalized to an annual CFM demand profile. The system should then be simulated at the normalized CFM level using the correlation between flow and power for the respective system.

In a new construction situation where past process production volume and past energy consumption data are unavailable, the “baseline” energy use per unit of production must be based on a comparable site, such as a similar process in-house or in-company at another facility. In some cases, the energy per unit of total facility production may need to be used to estimate annual energy savings. It is possible that the company applying for energy-savings credits can document different levels of energy efficiency based on different equipment used or different configurations of the system equipment.

The actual methodology used to calculate savings for a VSD compressor replacement project begins with Equations 1 and 2, provided here again.

**Equation 1** (Baseline for a Constant Speed Compressor):  
\[ kW = \text{compressor shaft bhp} \times (0.746 \text{kW/hp}) \times \left( \frac{1}{\eta_{\text{motor}}} \right) \]

where:
- \(\text{compressor shaft bhp}\) = Shaft brake horsepower
- \(\eta_{\text{motor}}\) = Motor efficiency (%)

Both motor efficiency and compressor shaft bhp are typically obtained from equipment tags or manufacturer specifications.

**Equation 2** (For a New VSD Compressor):  
\[ kW = \text{compressor hp} \times (\text{motor LF}) \times (0.746 \text{kW/hp}) \times \left( \frac{1}{\eta_{\text{motor}}} \right) \times \left( \frac{1}{\eta_{\text{VSD}}} \right) \]

where:
- \(\text{compressor hp}\) = Compressor horsepower is the nominal rating of the prime mover (motor)
- \(\eta_{\text{motor}}\) = Motor efficiency (%)
- \(\eta_{\text{VSD}}\) = Variable-speed drive efficiency (%)

Once the pre- and post-retrofit rated input power values have been determined, energy savings can be calculated using Equation 3, provided here again.

**Equation 3** (Energy Savings):  
\[ \text{kWh Saved} = \left( \% \text{ Power} \right) \times (\Delta kW) \times (1 - 0.005 \times (\text{psig}_{\text{Rated}} - \text{psig}_{\text{Actual}})) \times (\text{Hours}) \]

where:
The key parameters from Equation 3 are ‘% Power,’ ‘ΔkW,’ and ‘Hours;’ each of which fluctuate based on the operating load profile of the VSD compressor. Actual post-retrofit consumption is determined as the sum of multiple iterations of Equation 3, where a unique calculation is performed for each common loading condition. The number of iterations is dictated by the compressor load profile. This information is generally obtained through metering.

The methodology for calculating energy savings associated with compressed-air leak surveys and repairs was discussed in detail under Section 3.2 of this protocol.

7 Sample Design

Evaluators will determine the required targets for confidence and precision levels, subject to specific regulatory or program administrator requirements. In most jurisdictions, the generally accepted confidence levels should be designed to estimate operating hours and load profiles with a sampling precision of 10% at the 90% confidence interval. If attempting to organize the population into specific subgroups (such as building types or unit sizes), it may be appropriate to target 20% precision with a 90% confidence interval for individual subgroups, and 10% precision for the total population.

In addition to sampling errors, errors in measurement and modeling can also occur. In general, these errors are smaller than the sampling error; thus, sample sizes are commonly designed to meet sampling precision levels alone.

Sample sizes for achieving the desired precision level should be determined by estimating the coefficient of variation (CV), calculated as the standard deviation divided by the mean. CVs generally range from 0.5 to 1.06 for compressed-air measures, and the more homogeneous the population, the lower the CV will be. After the study is completed, the CV should be recalculated to determine the actual sampling error of the metered sample. See UMP, Chapter 11: Sample Design for further guidance.

7.1 Program Evaluation Elements

To ensure the validity of data collected, establish procedures at the beginning of the study to address the following issues:

- Quality of an acceptable regression curve fit (based on R², missing data, etc.)
- Procedures for filling in limited amounts of missing data
- Meter failure (the minimum amount of site data required for analysis)
- High and low data limits (based on meter sensitivity, malfunction, etc.)
 Units to be metered are not operational during the site visit (for example, determine whether this should be brought to the owner’s attention or whether the unit should be metered as is)

Units malfunction during the metering period (for example, determine how to handle the data or absence of data from this unit)

It is recommended to include an additional 10% in the sampled number of sites or units to account for data attrition.

At the beginning of each study, determine whether metering efforts should capture short-term measure persistence. That is, decide how the metering study should capture the impacts of non-operational rebated equipment (due to malfunction, equipment never installed, etc.). For non-operational equipment, these could be treated as equipment with zero operating hours, or a separate assessment of the in-service rate could be conducted.

7.2 Net-to-Gross
A separate cross-cutting protocol to determine applicable net-to-gross for this type of measure is currently being developed.

8 References

Product brochure for Sullair S-Energy Lubricated Rotary Screw Air Compressor


Website for UE Systems Inc. – Manufacturer of Ultrasonic Leak Detectors. Link to webpage which shows procedure for using Ultraprobe Models 3000/9000/10,000/15,000 to locate and

### 9 Resources


### Compressed Air Challenge Internet Resources

Fox, T.J. (November 2011). “Cycling Refrigerated Air Dryers – Are Savings Significant?” *Compressed Air Challenge – Air Best Practices.com*


Marshal, R. (March 2011). “VSD Compressor Control.” *Compressed Air Challenge – Air Best Practices.com*


http://www.compressedairchallenge.org/library/articles/2013-08-CABP.pdf


http://www.compressedairchallenge.org/library/articles/2010-09-CABP.pdf

http://www.compressedairchallenge.org/library/articles/2012-08-CABP.pdf

http://www.plantservices.com/articles/2010/07MonitorCompressorEfficiency.html

http://www.airbestpractices.com/system-assessments/pressure/eliminating-pressure-problems-compressed-air-systems
