Compressed Air Load Reduction Approaches and Innovations

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ABSTRACT

The use of compressed air is widespread throughout every sector of industry and acts as a primary energy source for many industrial applications. Compressed air systems are as essential a utility as electricity, gas, or oil, and can account for a significant percent of a manufacturing facility's electricity bill. Although the development of compressed air is very expensive, this energy cost is rarely evaluated within the plant operation and is commonly overlooked when energy reduction opportunities are assessed. It is a common practice in facilities to simply add compressor capacity when faced with supply pressure or volume deficiencies, increasing the energy consumption associated with compressed air systems in industry. Additionally, in recent years, compressor plant installations and enhancements have trended toward minimizing the first cost of installation at the expense of increased operating costs. This can be seen in the rise of packaged rotary screw system purchases that require no foundations in lieu of the larger, more efficient reciprocating compressors that require more involved site work. With such a trend in the supply side of compressed air systems, it becomes increasingly important to improve the efficiency of the demand side, or end-use side, of compressed air systems. This paper will focus on addressing compressed air end-use inefficiencies and alternatives for inappropriate uses with the goal of reducing the demand placed on the compressor plant.

Compressed Air Systems

Compressed air systems are best discussed by differentiating the supply side of the system from the demand side. In brief, the supply side generates and stores the compressed air, and the demand side distributes and consumes the air. The supply side of a compressed air system is comprised of the components that generate, condition, store, and centrally regulate the compressed air. Components associated with these operations are the compressors, air dryers, filters, receivers, and central flow/pressure controls prior to the plant distribution network. The compressed air system demand side includes all components downstream of the central storage and pressure/flow controls. These components include the distribution network throughout the facility; point-of-use accessories such as filters, regulators, and lubricators; and any number and type of air consuming end-use equipment.

There are two fundamental compressor types available—positive displacement and dynamic. Of these two types, it is far more common to find positive displacement units used in industry, particularly when small to medium air volumes are required and loads vary. These compressors include single and double acting reciprocating units and oil-flooded or oil-less rotary screw machines. Dynamic compressors are used when large volume base loads are present that do not require much capacity modulation. These compressors include centrifugal and axial type units.

The efficiency of an air compressor under full load conditions is a measure of the power consumed to generate a unit volume of compressed air. Units of efficiency are often presented as bhp/100 CFM or kW/CFM at inlet conditions when compressing to 100 psig. According to the Department of Energy's Compressed Air Challenge program, full load values range from approximately 0.15 kW/CFM to 0.24 kW/CFM, with double acting, water-cooled reciprocating machines being the most efficient.

Compressed air loads are typically highly variable, and compressors do not operate at full load most of the time, since they are normally sized to handle peak requirements. Part load operations are achieved by various control strategies and technologies that may incorporate unload, modulation at part-load conditions, variable speed operation, or complete shut down for periods. Each of these strategies has inherent advantages and disadvantages that impact efficiency. The user should obtain current data on several compressor models from various manufacturers to make valid comparisons, but it can broadly be said that operating at other than full load often considerably lowers overall compressor system efficiency. Thus, it is important to pay close attention to the demand side use of compressed air in order to minimize consumption and reduce energy costs.

Energy Consumption

Over the lifetime of compressed air systems, operating energy is the single greatest cost, in many cases exceeding five times the initial equipment cost (Laurel and Associates et al. 1999). Overall system efficiencies can be as low as ten to fifteen percent (Laurel and Associates et al. 1999). Consequently, anywhere compressed air can be conserved is a potential opportunity to reduce operating expenses associated with the system. Establishing these opportunities for reducing air consumption in the demand side of the system is a major step toward identifying ways to reduce overall energy consumption. For example, it is not uncommon to find that a compressed air system has an artificial demand created by air leaks that is as high as 20% to 30% of overall compressor output (Laurel and Associates et al. 1999). This loss can be minimized by performing periodic leak detection surveys and correcting the leaks, thereby saving thousands of dollars annually.

Demand Side End-Uses

The demand side air consumption is made of various components, some of which are appropriate and provide functional value to the facility and some of which are inappropriate and represent considerable inefficiencies. System demand can be segmented into four categories listed below.

- ❑ Normal Appropriate Usage
- ❑ Leaks
- ❑ Artificial Demand due to Excessive Pressure
- ❑ Inappropriate Usage

Pneumatic equipment is ubiquitous in industry and performs an expansive array of manufacturing processes that are integral to production and must be considered not only valuable and appropriate, but also vital. In contrast, demands composed of inefficient air applications, distribution and point-of-use air leaks, unregulated demands at excessive pressures, or applications that can utilize low pressure air (less than 15 psig) do not provide efficient resource usage and should be targeted for improvements.

It is important to consider which choice of power is best for a given application. Typical options include compressed air, hydraulics, and electric motors. The best option will vary from one piece of equipment to another; however, the energy consumed for an application should be an important consideration in the selection process.

Stopping excess energy waste and reducing the compressed air demand can significantly reduce the volume of air required in a facility. In many instances, this reduction may mean that a reduced number of compressors are required to operate in order to meet the plant's air requirements in a given facility.

Analytical Evaluation

For all proposed energy efficiency measures, it is important to perform an energy and cost analysis to provide economic justification for the project. This process involves a comparison of the existing-case energy consumption to that of the proposed-case consumption. Specific parameters associated with the individual process under review should be established through field observation, performance specifications, and monitoring. Demand and energy components should be considered, and costs should then be calculated using the utility tariffs for the facility.

For compressed air systems, the calculations must establish the volumetric rate reduction in CFM of the efficiency measure and evaluate how that reduction impacts the energy consumption of the compressor plant based on the system performance curve. This process entails quantifying the CFM reduction for each end-use considered, totaling the overall impacts on the output requirements of the compressor, and calculating the associated energy savings for compressor operations. Examples of this process are presented below in the section on air leaks and in the case study.

Air Leaks

As mentioned above, leaks in the compressed air system provide no benefit and can commonly account for 20-30% of a facility's compressed air demand (Laurel and Associates et al. 1999). For example, in a facility with 500 horsepower (HP) of compressor capacity, the leaks could typically be consuming 150 HP, equating to substantial wasted energy at significant expense. It is typical for a large facility to have hundreds of concurrent leaks, some of which are audible and others that are not. It is highly effective to implement leak abatement programs that minimize air loss in a system and should be included as part of a regular preventative maintenance program that ideally should be performed quarterly.

Leak detection. Leak detection should be conducted regularly and performed in a methodical manner. The use of proper equipment can make the process considerably more effective than simple audible surveys using the human ear as a detection mechanism. The ambient noise level in an industrial facility is typically too loud to hear even those leaks that would otherwise be readily audible. Thus, leaks often persist for extended periods. Ultrasonic leak detection equipment is an essential component to successful leak abatement programs. This equipment facilitates identification of even the smallest leak regardless of the baseline ambient noise level in an industrial plant.

When a pressurized gas passes through a restrictive orifice, such as a leak in an air line fitting, the flow pattern changes from laminar to turbulent. This turbulent flow generates a broad spectrum of sound that includes an ultrasonic component. The ultrasonic component will have the highest magnitude at the leak site and is easily detected by ultrasonic equipment. With this method of leak detection, it is possible to detect leaks that are difficult to hear or even feel. Upon determining a leak location, the leak should be tagged with a numbered identification tag and referenced on an inventory sheet for later repair. The inventory should describe the location of the leak along with the pressure and estimated air volume (CFM) associated with the leak.

Typical leaks range from large leaks that are audible to the unaided ear at full system pressure, to smaller, inaudible diffuse leaks at lower regulated pressures. Common leak sizes range from less than 1 CFM to greater than 10 CFM. Many leaks occur at threaded connections on point-of-use equipment and are the result of decayed or absent pipe thread sealant at fitting junctions. Other typical leaks are found in rubber hoses, at connections to fittings, filter/lubricator/regulator gaskets or drains, cracked filter bowls, and at quick-couplers. An example of a typical inventory sheet for a section of an industrial facility is presented below in Table 1.

Table 1. Compressed Air Leak Survey Tally Sheet

Tag #	Room	Leak Location	Pipe Dia.	Pipe Type	Pressur (psi)	Estim. CFM	Leak Description/Comments
00-834	Machine	Air drop 2" nipple	3/8	Iron	105	2.5	Reducer to iron nipple
00-835	Tool	Sharp milling machine	3/8	Plastic	105	3.8	Quick connect at air gun
00-836	Tool	Sharp milling machine	3/8	Rubber	105	1.3	Brass coupling-outlet of regulator
00-837	Wax Dept	Assembly line- hose to	1/4	Plastic	65	1.6	Leak in air hose (taped up at
00-838	Wax Dept	Assembly line	1/2	Copper	45	1.1	Regulator at 10' height
00-839	Wax Dept	Solubles area air gun	1/2	Rubber	45	1.6	Brass coupling into air gun 45
00-840	Wax Dept	Wax press #009	3/8	Plastic	87	2.1	Brass nipple to hose connector at
00-862	Wax Dept	Wax press #010	1/4	Plastic	95	2.3	T connectors underneath unit
00-863	Wax Dept	Wax press #006	1/4	Plastic	105	5.0	Back of press-brass nipple into
00-864	Wax Dept	208 Tank #3	1/4	Rubber	35	1.3	Oil lubricator at regulator
00-865	Wax Dept	Wax Press #004	1/4	Plastic	105	2.5	Brall L into solenoid underneath
00-866	Wax Dept	Wax Press #003	1/4	Plastic	105	3.8	Brass coupling into solenoid
00-867	Wax Dept	Wax Press #003	1/4	Plastic	105	2.5	Brass connector to wax injector
00-873	Wax Dept	Wax Press #002	-	-	105	3.2	Ejector air cylinder seal
00-868	Autoclave	Wax Press #017 - rear	1/2	Plastic	95	4.6	Hose coupling at hose clamp
00-869	Autoclave	Wax Press #017	3/4	Rubber	105	5.0	Hose connection to T inlet at
00-870	Autoclave	Wax Press #015	3/4	Rubber	35	0.8	Hose connection out of solenoid
00-871	Foundry	Burn out oven	1/2	Rubber	110	2.6	Hose clamp connection to quck
00-872	Foundry	Permanent mold	1/2	Rubber	105	6.3	Air gun above mold leaks
00-874	Shell Dept	Air gun at sand tank	1/2	Rubber	105	1.3	Quick connect at air gun
00-875	Shell Dept	Air gun at Sand Tank	1/4	Rubber	80	3.8	Coupling from quick connect to
00-876	Cutoff	Air gun at #101 band	1/2	Rubber	105	3.2	Hose coupling to quick connect
00-877	Cutoff	Wall behind #101 band	1/2	Rubber	105	4.4	Hose coupling at hose end
00-878	Waterblast	Unit #095 regulator at	1/4	Plastic	50	1.5	Hose fitting to solenoid
00-879	Finish	Finishing bench	3/8	Rubber	80	2.9	Hose leak & leak at fitting to
00-880	Finish	Finishing bench	3/8	Rubber	80	2.9	Coupling between quick connect
00-881	Finish	Delta table drill	1/2	Rubber	105	2.5	Middle quick connect coupling-
00-882	Finish	Unit #119 sand blaster	1	Iron	105	3.8	Nipple between regulator and
00-883	Finish	Sand Blaster #114	3/8	Rubber	85	3.1	Connection between quick
00-884	Finish	Sand Blaster #117	3/8	Rubber	85	0.5	
					Total	83.6	

Leak repair procedures. Leaks at threaded connections can be repaired by simply backing off the fitting, applying thread sealant, and reassembling. Where parts have failed, such as hoses and filter bowls, regulators or control blocks, new replacement parts should be installed. Distribution leaks may involve more costly piping repair. We believe it is imperative to check repairs with ultrasonic equipment. Alternatively, the use of soapy water can be used to verify the quality of a particular leak repair.

Cost and savings assessment. The costs associated with compressed air leaks are often estimated as a simple percentage of average compressed air system operating costs. This method does not accurately represent air leak costs since the compressor operates at different efficiencies at different loads, while the volume of air lost remains constant with the pressure.

A better method uses the diversity of compressor loading along with performance curves for the size and type of compressors involved, thereby predicting energy losses associated with the detected air leaks. This method more accurately estimates energy losses by considering normal fluctuations and differences in weekday production shifts and weekend work. Table 2 illustrates the average hourly compressor load in CFM (determined from monitored data) and associated air leak losses for a typical three-shift weekday operation. The energy savings can then be equated with dollar savings by applying the specific utility tariff associated with the facility. It should be noted that since each bin represents one hour, kW=kWh for each line item. These bins are then totaled at the bottom to obtain overall energy associated with the Existing and Post Repair scenarios. Savings is determined by calculating difference between the two cases.

Table 2. Compressed Air Loss CFM and Energy Impacts

Compressed Air System Leak Analysis							Rate	Rate	
		Existing	Existing	Post Repair	Post Repair	Exist-Prp	$0.07074	$0.06584	
Day	Hour	Total CFM	Total kW=kWh	Total CFM	Total kW=kWh	Savings kW=kWh	Savings Onpeak	Savings Offpeak	Savings Total
Weekday	1	1,770	528.6	1,320	423.5	105.1		$6.92	$6.92
	2	1,770	528.6	1,320	423.5	105.1		$6.92	$6.92
	3	1,770	528.6	1,320	423.5	105.1		$6.92	$6.92
	4	1,770	528.6	1,320	423.5	105.1		$6.92	$6.92
	5	1,770	528.6	1,320	423.5	105.1		$6.92	$6.92
	6	1,770	528.6	1,320	423.5	105.1		$6.92	$6.92
	7	1,770	528.6	1,320	423.5	105.1		$6.92	$6.92
	8	1,770	528.6	1,320	423.5	105.1		$6.92	$6.92
	9	1,858	538.9	1,407	422.5	116.3	$8.23		$8.23
	10	1,858	538.9	1,407	422.5	116.3	$8.23		$8.23
	11	1,858	538.9	1,407	422.5	116.3	$8.23		$8.23
	12	1,858	538.9	1,407	422.5	116.3	$8.23		$8.23
	13	1,858	538.9	1,407	422.5	116.3	$8.23		$8.23
	14	1,858	538.9	1,407	422.5	116.3	$8.23		$8.23
	15	1,858	538.9	1,407	422.5	116.3	$8.23		$8.23
	16	1,858	538.9	1,407	422.5	116.3	$8.23		$8.23
	17	1,770	528.6	1,320	423.5	105.1		$6.92	$6.92
	18	1,662	449.0	1,212	343.9	105.1		$6.92	$6.92
	19	1,662	449.0	1,212	343.9	105.1		$6.92	$6.92
	20	1,662	449.0	1,212	343.9	105.1		$6.92	$6.92
	21	1,662	449.0	1,212	343.9	105.1		$6.92	$6.92
	22	1,662	449.0	1,212	343.9	105.1		$6.92	$6.92
	23	1,662	449.0	1,212	343.9	105.1		$6.92	$6.92
	24	1,662	449.0	1,212	343.9	105.1		$6.92	$6.92
		Total	**61,057**		**47,997**	**13,060**	**$329.16**	**$553.49**	**$882.66**
		Max	**538.9**		**423.5**	**116.3**			
					Note:	Savings are Existing less Proposed.			

Costs to implement leak abatement programs will vary based on the size of a facility and the density of air connections. Simple paybacks are very favorable and can range from just a few months to slightly over a year.

Improving Efficiency of Appropriate End Uses

Compressed air is clean, readily available, and simple to use. Consequently, there are many appropriate uses for compressed air including powering pneumatic tools, operation of air-actuated process equipment, dust filtration shake down, and numerous other applications. Although certain operations are appropriate, there are often opportunities for reducing compressed air consumption and optimizing the efficiency of an air powered process. This section describes opportunities for reducing compressed air usage at the end-use level.

Pressure Reduction

It is prudent to operate compressed air systems at the lowest functional pressure that meets production requirements. When pressure supply is higher than required, greater volumes of air are expelled for any given end use, which equates to wasted energy. The standard rule of thumb is that reducing pressure settings by 2 psi will reduce energy consumption by 1 percent (Lawrence Berkeley National Laboratory et al. 1998).

It is very common to walk through an industrial facility and observe end use operations with air supply pressures in excess of 100 psig. In certain cases, this pressure setting is warranted, but in many cases it is due to the absent or improperly adjusted point-of-use regulation. Most operations can be conducted with 85 psi or less. Each end-use should be regulated separately and be supplied with compressed air pressures specifically set to meet the needs of that process. In contrast, if pressures are set to meet the needs of the highest pressure end use load, the impact on consumption can be considerable. Quality regulators should be selected that have low pressure drops, minimize pressure swings, and provide consistent supply pressure.

Volumetric Flow Control

Compressed air flow in open end-use applications such as blow-off, part clearing, and moisture removal is often uncontrolled and/or manually controlled by equipment operators via in-line valves. Open or crimped tubing is often used as a delivery nozzle and pressures are often unregulated. More efficient use of compressed air can be achieved by regulating pressures and using flow control devices for delivery, such as entraining nozzles, air amplifiers, or air knives. These devices use flow dynamics and geometric design to entrain ambient air into the compressed air stream. By doing so, a greater volume of air is delivered at the point-of-use, thereby limited the quantity of air that must be supplied directly by the compressed air system.

Demand Flow Control

There are many applications that require only intermittent bursts of air to perform a process, yet the supply of air remains constant. For example, an air stream can be used to index a small part in an assembly machine. Once indexed and in position, the operator pushes a button and the machine automatically clamps and bonds two components together for a brief period. During this portion of the cycle, air is not actually required. If the compressed air stream is left on continuously after the indexing function, significant energy is wasted. In such a situation, a solenoid valve can be interlocked with machine operation to supply a burst of air only when required for part indexing. During the clamping phase, air is shut-off and valuable energy is saved.

A similar approach can be taken for machines that operate intermittently throughout the day or sit idle during break and lunch periods. During periods of machine inactivity, air supply is often left on. Solenoid valves can be used to automatically shut off the air supply when the machine is idle and not producing product.

Alternative Solutions for Inappropriate End-Uses

Compressed air is frequently used for applications in a facility that may be more economically served by another power source. While air is likely the most expensive form of energy in a typical facility, it may be too readily viewed as the easy and clean solution for all potential applications. As a result, there are many typical uses of compressed air that are considered "inappropriate," since other energy sources could serve equally well with more favorable operating costs. For example, an air motor rated at 1 HP output requires 7-8 HP of electrical energy input into the compressor to develop the required CFM to drive the motor. Using an electric motor for the same task will require considerably less energy. More cost-effective forms of power should be considered before selecting compressed air. Inappropriate applications of compressed air and appropriate alternatives are presented in Table 3 below.

Prototypical Case Study

System Details

The compressed air systems observed at this facility supply typical end-uses ranging from air-activated machinery to hand blow-guns and air tools. At the time of our site visit, the plant had six 150 HP rotary screw compressors sharing the same dryer and distribution network. Additionally, the installation of a 200 HP rotary screw compressor was in the planning phase to replace two of the older 150 HP machines. Table 4 details the compressor information at the time of our site visits.

The Sullair and two Worthington compressors are single-stage, lubricant injected, air-cooled units. The three Gardner-Denver compressors are single-stage, lubricant injected water-cooled machines. All of the compressors use inlet modulation to vary the output based on system demands. The dryer used in the compressed air system is a Hankison H-33 refrigerant charged dryer and has a capacity rating of 3,340 CFM at 125 psig and 100°F. The dryer inlet air temperature was observed at 84°F; the air exiting the dryer was 68°F. No central receiver is present at the facility and each compressor is operated under local, inlet modulation control based on pressure set points. No automated control was present to optimize the number of compressors operated at any given time. The network of compressed air distribution lines throughout the facility was orderly and follows a consistent grid pattern with minimal dead end drops.

Table 3. Alternative Solutions for Inappropriate Compressed Air Uses

Open Blowing: Compressed air is applied with an open, unregulated tube, hose, or pipe. Typical applications for open blow-off are part and debris clearing, machine tool cooling, drying, and clean up. **Alternative:** Replace with blower systems or nozzles, air amplifiers, air knives, or other flow distributing devices.
Sparging/Agitation: The process of aerating, agitating, oxygenating, or percolating a liquid with compressed air. **Alternative:** High volume, low-pressure blower systems driven with electric motors can be used in place of compressed air for many sparging or agitating applications.
Aspirating: Using compressed air to induce the flow of another gas with compressed air. **Alternative:** As with sparging above, the use of blowers can be used to induce the flow of another gas instead of compressed air.
Personnel Cooling: Operators direct compressed air on themselves to provide personnel cooling ventilation. **Alternative:** This is a gross waste of energy. A ¼" tube blowing air on an operator can consume 100 CFM of compressed air. Space and occupant cooling should be adequately supplied by HVAC systems.
Air Powered Diaphragm Pumps: Air-powered pumps are a convenient way to transfer chemicals or treated water, since their plastic components are corrosion free. **Alternative:** Specially designed electrically driven pumps with plastic bodies are available for the pumping of chemicals and treated water.
Induced Vacuum Systems: Compressed air is often employed to develop a vacuum for process systems in place of a separate vacuum system. **Alternative:** Independent vacuum systems should be used that do not use compressed air as the power source. Electric vacuum pumping systems are far more efficient.
Cabinet Cooling/Pressurization: Compressed air is commonly used to provide cooling or positive pressurization for electronic cabinets that are located in warm or dirty environments. Cooling is typically provided by air powered vortex tubes that provide a cold air stream output from a compressed air input. **Alternative:** Cabinet cooling can be provided by blower or heat-pipe systems depending on the environment. For dirty environments, heat-pipe units can be installed that maintain the internal cabinet temperatures without interchange of external air.

Table 4. Existing Baseline Compressor Information

				Average Percent Loading			Average CFM			
Manufacturer	Type	Size (HP)	Full Load CFM	1st Shift	2nd Shift	3rd Shift	1st Shift	2nd Shift	3rd Shift	Line Pressure (psi)
Sullair	Rotary Screw, Single-Stage, Modulating	150	616	90%	90%	90%	554.4	554.4	554.4	105
Worthington	Rotary Screw, Single-Stage, Modulating	150	600	44%	44%	44%	271.0	271.0	271.0	105
Worthington	Rotary Screw, Single-Stage, Modulating	150	600	18%	18%	18%	110.9	110.9	110.9	105
Gardner Denver	Rotary Screw, Single-Stage, Modulating	150	625	92%	78%	78%	566.7	480.5	480.5	105
Gardner Denver	Rotary Screw, Single-Stage, Modulating	150	625	57%	57%	57%	351.1	351.1	351.1	105
							1,854	1,768	1,768	
		kW	kWh							
	Facility Compressed Air Usage:	538.9	3,052,863							

Pressure readings observed at the major supply side components, the compressors and dryer, were all between the range of 110-120 psi. Normal pressure drop ranges indicate that there are no blockages or restrictions in the main compressor plant. Line pressures observed at point of use equipment were between 105 –110 psi. For analytical purposes, line pressure is assumed to be 105 psi.

Compressor Performance Curve

All types of compressors operate at different efficiencies at different loads. This efficiency-load relationship is usually termed the performance curve. This curve serves as the basis for all energy usage calculations. Table 5 illustrates typical performance characteristics in charted form for a 150 HP single-stage inlet modulating, oil-lubricated rotary screw compressor.

Table 5. Performance Curve

Rotary Screw - single stage, inlet modulation, air-cooled, premium efficiency motor										
150 HP	110 PSI capacity	CFM	% HP	BHP	motor eff.	cooling fan BHP	cooling fan eff.	cooling pump kW	KW	KW/CFM
	100%	616	110%	165	0.945	0.00	85%	0.0	130.25	0.211
	90%	554	100%	150	0.942	0.00	85%	0.0	119.19	0.215
	80%	493	91%	136	0.938	0.00	85%	0.0	108.04	0.219
	70%	431	81%	121	0.935	0.00	85%	0.0	96.82	0.225
	60%	370	71%	107	0.932	0.00	85%	0.0	85.52	0.231
	50%	308	62%	92	0.928	0.00	85%	0.0	74.13	0.241
	40%	246	52%	78	0.925	0.00	85%	0.0	62.66	0.254
	30%	185	42%	63	0.922	0.00	85%	0.0	51.11	0.277
	20%	123	32%	49	0.918	0.00	85%	0.0	39.48	0.320
	10%	62	23%	34	0.915	0.00	85%	0.0	27.76	0.451
	0%	0	13%	0	0.000	0.00	0%	0.0	0.00	0.000

Summary of Recommended Energy Efficiency Measures (EEMs)

Six Energy Efficiency Measures (EEMs) were recommended for implementation at this prototypical facility. The savings and costs associated with each measure are listed in Table 7 below. It should be noted that this table presents the measures independently from one another and do not reflect interactive results. Installation costs are vendor supplied for each measure. Facility specific energy rates were supplied by the utility company for demand, peak, and off-peak charges. Brief descriptions of each of the measures are contained in the paragraphs that follow Table 6.

Table 6. Summary of Recommended Energy Efficiency Measures

Energy Efficiency Measure	Annual Energy Savings (kWh)	Demand Reduction (kW)	Installed Cost	Annual Cost Savings	Simple Payback (Years)
EEM-1 Repair Tagged Leaks					
Savings Summary	652,989	115.4	$14,960	$53,429	0.3
EEM-2 Install Efficient Nozzles on Designated Equipment					
Savings Summary	79,698	10.27	$5,180	$5,482	0.9
EEM-3 Install Air Solenoid Valves on Designated Equipment					
Savings Summary	121,499	0.0	$3,650	$8,357	0.4
EEM-4 Install Flow Controller and Reduce Demand Side Pressure					
Savings Summary	72,724	60.6	$40,600	$9,850	4.1
EEM-5 Install Sequencing Controls for the Compressor Plant					
Savings Summary	657,842	-	$43,405	$45,246	1.0
EEM-6 Install Blower Systems for Extrusion Line Blow Off Operations					
Savings Summary	683,940	220.9	$79,278	$64,846	1.2

EEM-1: repair tagged leaks at building 1. *ERS* tagged one hundred seventy six (176) compressed air leaks throughout the facility. The majority of these leaks were located at connection points of fittings, filters, lubricators, regulators, control valves, and hand blowguns. All are easily correctable.

EEM-2: install efficient nozzles on designated equipment. Blow-off and part positioning on selected equipment is achieved with a steady stream of high velocity compressed air. The compressed air is currently delivered through copper tubing focused at the desired locations. The installation of efficient air nozzles would meet the process requirements but with significantly reduced compressed air consumption.

EEM-3: install air solenoid valves on designated equipment. Selected machines consume compressed air even during idle periods. Compressed air supply should be controlled by installing solenoid valves in the air supply lines and electrically interlocking with machine operation. With this installation, compressed air would only be supplied to the machine when it was required for operation, eliminating waste during non-producing periods.

EEM-4: install flow controller and reduce demand side pressure. A flow controller isolates the supply and demand sides of the compressed air systems to provide even pressure and flow delivery to the end-uses. Systems incorporating a flow controller and adequate receiver capacity can deliver compressed air to equipment within a much tighter pressure band (+/- 1-2 psi versus +/- 5 psi for typical systems) and subsequently facilitate reduced demand-side pressure set points. Operating at lower pressures will consume less volume and require less compressor runtime to meet the facility's demand.

EEM-5: install sequencing controls for the compressor plant. Six compressors were present at the facility at the time of our site visit. Each of these compressors was independently controlled. Installation of a master sequencing control system would network the compressors together and allow for dynamic optimization of the system as a function of demand. This control type minimizes the compressor horsepower operated to meet the requirements of the demand side and allows all but the trim machine to run at optimum efficiency.

EEM-6: install blower systems for extrusion line blow-off operations. Six extrusion lines consume large volumes of compressed air for flock and coolant blow-off operations. Installation of centrifugal blowers to eliminate compressed air usage will support the requirements of the process and use considerably less energy. This system consists of blower installations ducted to supply air knives and nozzles at the point of use.

Conclusion

As has been described throughout this paper, compressed air systems are widely utilized in the industrial sector and act as a primary energy source for innumerable industrial applications. However, it is not common knowledge that the overall energy efficiency of compressors are quite low and that optimization of the way compressed air is used in a facility can have substantial impacts on consumption and system operating costs. Paying careful attention to the demand, or end-use, side of the system can reveal significant opportunities for reduced compressed air use and energy savings.

Optimizing end-use operations by reducing and regulating the incoming pressure, minimizing pressure drops, controlling the volume of flow, and supplying flow only when needed can all reduce consumption while still meeting production requirements. Additionally, numerous inappropriate compressed air uses have proliferated throughout industry that are inefficient and wasteful. Alternatives using equipment such as high volume blowers, vacuum systems, electric driven pumps, and heat-pipes should be evaluated and implemented to reduce air consumption associated with blow-off, sparging, induced vacuum, air pumps, and cabinet cooling operations.

Additionally, in recent years, compressor plant installations and enhancements have trended toward minimizing the first cost of installation at the expense of increased operating costs. This approach can be seen in the rise of packaged rotary screw system purchases that require no foundations over the larger, yet more efficient, reciprocating compressors that require more involved site work. With such a trend in the supply side of compressed air systems and with the escalation of energy costs, it becomes increasingly important to improve the efficiency of the demand side uses in compressed air systems.

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