Measure It, See It, Manage It:
Using Real Time Data to Benchmark, Optimize, and Sustain System Energy Efficiency

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ABSTRACT

Even after years of training and awareness building at the state and national level, industrial cross-cutting systems (motor-driven, steam, process heating) continue to offer significant opportunities for energy savings. The US Department of Energy estimates these remaining savings at more than 7% of all industrial energy use. This paper presents a different approach to promoting industrial system energy efficiency - providing plant personnel with ready access to data upon which to base energy management decisions.

In 2005, a Del Monte Foods fruit processing plant in Modesto, California worked with Lawrence Berkeley National Laboratory (LBNL) to specify and purchase permanent instrumentation for monitoring their compressed air system. This work, completed as part of a demonstration project under a State Technologies Advancement Collaborative (STAC) grant, was designed to demonstrate the effectiveness of enterprise energy management (EEM), which is predicated on the assumption that the energy efficiency of existing, cross-cutting industrial systems (motor-driven, steam) can be improved by providing management and operating personnel with real-time data on energy use. The initial STAC grant provided for the installation and some initial analyses, but did not address the larger issue of integrating these new data into an ongoing energy management program for the compressed air system.

The California Energy Commission (CEC) decided to support further analysis to identify potential for air system optimization. Through the CEC's Energy in Agriculture Program, a compressed air system audit was performed by Tom Taranto to:

- Measure and document the system's baseline and CASE Index of present operation;
- Establish methods to sustain an ongoing CASE Index measure of performance;
- Use AIRMaster+ to analyze supply side performance as compared to the CASE Index;
- Identify demand side opportunities for efficiency and performance improvement;
- Assess supply / demand balance and energy reduction opportunities;
- Evaluate the present air compressor control strategy and potential improvement, and
- Collect data to benchmark parameters for compressed air systems at similar facilities.

This paper addresses the benefits and limitations of both continuous and targeted measurement in benchmarking, optimizing, and sustaining an efficient compressed air system. Included are methods used in applying both of these measurements to a complex industrial system. Further, this paper will describe the results of these additional analyses and the plant response to them.

Introduction

The optimization of industrial systems offers a large potential for both energy efficiency and corresponding reductions in carbon emissions. The US Department of Energy estimates the unrealized energy savings potential from steam, process heating, compressed air, pumping, and fan systems at more than 7% of all industrial energy use. System optimization projects often pay for themselves in energy savings in two years or less with a positive effect on system reliability and maintenance. Significant opportunities exist in most US plants, regardless of age, size, or industrial sector. Despite this potential, many industrial managers operate under the assumption that their plants are “energy efficient.” The major barrier to better results is lack of awareness of the opportunity—managers simply do not realize that their plants are not cost-optimized for energy efficiency. While traditional operational practices can contribute to this lack of efficiency, in many companies adherence to traditional practices in other areas, such as materials management, have been overcome through collecting and managing the data. Unfortunately, for many industrial systems, the data required to manage and to improve energy use are neither collected nor analyzed. The results are under-performing, inefficient industrial systems.

Enterprise Energy Management (EEM) is a combination of software, data acquisition hardware, and communication systems designed to collect, analyze and display information on energy use in a building or an industrial plant. EEM is an emerging market in the U.S. industrial sector which uses off-the-shelf information technology previously developed for other applications, including metering and the commercial building sector, transfers those technologies and adapts those application skills to the industrial sector.

When applied to industry, EEM describes a method of real-time monitoring of the energy performance of industrial systems to produce information that can assist an industrial facility to improve the energy efficiency of these motor-driven, steam, and process heating systems. The annual energy savings potential from the application of EEM in these systems in California industries is more than 4 TWh of electricity[1] and 42 TBtu of natural gas[2].

EEM provides validation of energy usage and costs that contribute to measurement and verification (M&V) requirements, and which allow the industrial facility to quantify the energy savings achievement of these improved systems. This M&V capability also provides a foundation for plants to make better informed and more effective demand response decisions, resulting in greater demand reduction at a lower perceived risk.

In 2005, as part of a demonstration project under a STAC grant to promote energy efficiency in the food processing industry, a Del Monte Foods fruit processing plant in Modesto, California worked with LBNL to specify and purchase permanent instrumentation for monitoring their compressed air system. The initial STAC grant provided for the installation and some initial analyses, but did not address the larger issue of integrating these new data into an ongoing energy management program for the compressed air system. The CEC decided to support further analysis to identify compressed air system optimization potential. The plant’s permanently installed compressed air system instrumentation provides continuous measurement. Portable equipment was used during the audit for targeted measurement of dynamic performance and to identify supply demand interactions.

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[1] From analyses conducted by Lawrence Berkeley National Laboratory – electricity projection is based on a CA industrial electricity consumption of 20.8 TWh for driven systems and an estimated 20% improvement opportunity.

[2] Natural gas projection is based on a CA industrial process heating and boiler consumption of 282 TBtu and an estimated 15% improvement opportunity.

The balance of this paper describes how continuous measurement from the EEM instrumentation was supplemented with intensive short-term measurement to analyze the operation of the compressed air system and make recommendations for improvement. Two assessment tools are also used to evaluate the system performance, the AIRMaster+ software[3] and the CASE Index.[4] The focus of this discussion is the value of accurate data and analysis in developing a system optimization plan.

Compressed Air System Measurement – Why, What, Where, How?

An automobile has a range of data monitoring systems including engine temperature, oil pressure, speed, and fuel level. In recent years the driver has been given more detailed information such as average fuel economy (mpg), oil change and service intervals along with travel distance calculated for remaining fuel. When service technicians investigate performance issues, they have access to diagnostic tools including historical operating data and fault indicators. These data are used to aid in safe, efficient, reliable, and sustainable operation of the automobile. The data gathered falls into three categories:

- Real time operating data used when operating the automobile;
- Diagnostic data used to optimize performance and identify operational issues, and
- Historical data to aid in long term operation and maintenance.

Imagine operating an automobile without a speedometer, no fuel gauge, or engine condition indicators. How much time would a service technician need to diagnose and repair the complex systems in today’s automobile without any diagnostic data?

Industrial compressed air systems frequently operate in an information vacuum. Real time operating data is often limited to an indication of air pressure, usually located somewhere in the compressor room. When problems occur, diagnostic measures are often subjective and based on casual observation. Historical records are generally limited to scheduled equipment maintenance records and sometimes maintenance cost. As a result compressed air system operation is typically inefficient, wasting compressed air and energy. Furthermore, production operations are often compromised by poor compressed air quality and inconsistent performance.

Why Measure

Industrial compressed air systems represent a significant capital investment and large operating expense. The obvious operating costs are energy and maintenance cost. Somewhat less obvious is the air system’s performance impact the production process and plant productivity. There are four components which contribute to the total cost of ownership of a compressed air system.

- Capital investment
- Maintenance cost
- Energy cost
- Air system performance and lost plant productivity

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[3] AIRMaster+ software is available through the US Department of Energy and the Compressed Air Challenge www.compressedairchallenge.org .

[4] For Compressed Air System Efficiency (CASE) Index, developed by Southern California Edison with support from the CEC http://www.energy.ca.gov/pier/final_project_reports/500-04-037.html

Of these four cost components, the majority of management effort is focused on the capital investment and maintenance cost. However, over the lifetime operation of a compressed air system, the largest cost is a result of the energy consumed and air system's impact on production operations.

To optimize compressed air system performance and sustain efficient operation requires management information. Excessive measurement is not cost effective. Therefore, measurement priorities should be limited to performance parameters which directly contribute to established informational objectives.

What to Measure

Airflow measurement. One of the most expensive compressed air system performance parameters to measure is airflow. System generation efficiency is determined by measuring the total amount of energy used for generation (kWh) and the airflow (scfm) delivered. The Compressed Air Supply Efficiency (CASE) Index expresses total supply side generation efficiency as scf/kWh. Airflow must be measured. If airflow is calculated from power using theoretical compressor performance no meaningful index of performance can be created[5].

Dew Point measurement. A survey of industrial compressed air systems determined that 50% of systems are plagued by the presence of liquid water which has condensed in the system[6]. Two common reasons for lost production due to excessive water contamination are product contamination and unscheduled downtime of production equipment.

Differential pressure measurement. When measuring the pressure drop through individual components like a filter or air dryer, differential pressure transducers work well. However, when measuring pressure gradient over several hundred feet of distribution piping, it is not practical to connect piping to a differential pressure transducer. An alternative method to measure differential pressure involves using two pressure transducers to make independent pressure measurements and compare their values. When using two pressure transducers to measure small pressure differentials, high accuracy (and more costly) pressure transducers must be used.

Power measurement using amperage transducers. Amperage measurement is the simplest and least expensive means of measuring power. However, since voltage and power factor also affect electrical power, some error is introduced when only amperage is measured.

Power measurement using kW transducers. Power transducers directly measure kW. For 3-phase 3-wire systems, kW measurement requires two current transformers and three voltage connections. Since voltage and power factor are measured, kW transducers provide a more accurate power measurement than when only amperage transducers are used.

Pressure measurement. Pressure transducers measure a key indicator of compressed air system performance. Pressure may be measured at many locations in a compressed air system for several different reasons.

Other measurements. Consider temperature, sound, vibration, rotational speed, and cooling air or water flow.

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[5] It is possible to calculate airflow based on the power consumption of an air compressor provided its performance rating and part load performance characteristics are known. However, many site specific factors can cause a compressor's actual on-site performance to deviate greatly from its design and laboratory test performance. Because the CASE Index is represented by power divided by flow, estimating flow from power will not produce a meaningful result.

[6] DOE Market Assessment for Compressed Air Efficiency Services US Department of Energy *Assessment of the Market for Compressed Air Efficiency Services,* 2001

Where to Measure

Thorough performance measurement of compressed air system will address performance of the compressed air supply, demand side distribution piping, and point of use application of compressed air energy.

Supply side measurement often includes power at each compressor and perhaps at each air dryer as well. Airflow supplied to the system is important and might be measured for each air compressor. Pressure at the compressor discharge, upstream and downstream of dryers and filters, along with the main header pressure leaving the supply side are all potential measurement points.

Demand side distribution piping measurement could include airflow and pressure measurement to various production areas, and processes. Pressure measurements at the far ends of distribution piping as well as known or suspected low pressure problem areas may be useful.

Demand side point of use measurement may include flow and pressure to specific machines or individual actuators. Pressure might be measured at the supply header, piping drop to the machine connection, and at a specific air cylinder or tool.

How to Measure

Performance measurements are recorded using a data acquisition system. Measurements may be continuous, or targeted for some specific period of hours, days, or weeks. How data is measured; including the sample rate and data interval, affects the information that can be gained when analyzing the data. *Sample rate* is the frequency at which data input channels are scanned to evaluate the measured performance parameter. *Data interval* is the frequency at which measured performance data are recorded in the data acquisition system's non-volatile memory.

Decisions regarding sample rate and data interval. The sample rate and data interval used affects the integrity of recorded data.

For example, a kW transducer is used to measure compressor energy kWh. The desired data interval is one data point per hour. A sample rate of 1 sample hour could be used and if the compressor's air delivery and discharge pressure were constant for the entire hour, the data would be correct. However, air compressor power changes as the system air pressure or compressor air delivery increases or decreases. Therefore, it is more appropriate to use a higher frequency sample rate, perhaps 1 sample per second and by averaging 3600 samples the data interval is 1 data point per hour.

If power data will be used to count the frequency of compressor load / unload cycles, a data interval of 1 data point per hour is of no benefit. The required data interval would depend on the load / unload cycle frequency of the compressor. A sample rate of 1 sample per second and a data interval of 1 data point every few seconds might be required.

A high speed packaging or assembly machine operates in a repetitive cyclic manner with each cycle taking only a few seconds of time. What sample rate and data interval are necessary to measure the use point pressure? Using the measurement plan as described above with a 1 second sample rate and data interval every few seconds is too slow to gather good diagnostic data for an operation the only lasts for a few seconds. A sample rate of 25 Hz or 50 Hz and a data interval of 5 Hz. or 10 Hz might be necessary. As a general rule, the data interval should be at a high enough frequency to store 5 to 10 data points during the shortest time interval of the machine operation being evaluated. To capture performance of an air cylinder which extends in one second, a data interval of 10 Hz is required.

Signal noise[7] can also influence decisions about sample rate and data interval; “noisy signals” may be a result of instability in the measured parameter generated. Signal noise can result from a transducer being subjected to mechanical vibration, electrical disturbance, or other source of signal interference. Over-sampling[8] with signal averaging is one filtering method used to reduce signal noise in measurements.

Data acquisition hardware and sample rate limitations. The hardware and software used in various Distributed Control Systems, Building Management Systems, Data Loggers, etc. have limitations in their frequency of sample rate (scan rate). The hardware and software used must have performance capabilities that are appropriate to support the necessary measurements.

Most building management (BMS) or Distributed Control (DCS) Systems have practical limits on the frequency of channel scan rate. As a result, constraints are placed on the sample rate that can be achieved. The slower the sampling frequency, the less accurate accumulated airflow and energy totals will be. An alternative measurement plan to improve the accuracy of accumulated totals is to install totalizing digital displays or integrators that monitor the analog airflow rate or power measurement and output a scaled pulse value of scf and kWh. The scaled pulse can be connected to counter inputs on the BMS or DCS which are unaffected by limitations on channel scan rate.

If it is better, why not always use faster sample rates and more frequent data intervals? At a sample rate of 10 Hz, 24 hours of data recording gives 864,000 data points for each measured parameter. Whereas a data interval of 1 data point every 6 seconds represents 14,400 data points in a 24 hr period. As data density increases, large data files result in increased data storage, and post processing costs. It is not cost effective to record excessive amounts of data.

Summary Compressed Air Measurement

When considering why, what, where, and how to measure compressed air system performance, there are virtually an unlimited number of choices. To control cost and produce the best results requires clearly defined informational objectives supported by a well designed measurement plan. All measured parameters should be reviewed as to their direct input to informational objectives. Performance parameters that do not directly contribute to informational objectives should not be measured.

Conducting a Compressed Air Study at Del Monte Foods

Study results show that the plant spends $ 237,761 annually for compressed air energy. The conversion efficiency of energy to compressed air as measured by the CASE (Compressed Air Supply Efficiency) Index is 257.4 scf/kWh. The system should be able to achieve a CASE Index of approximately 300 scf/kWh. Decreased generation efficiency is due to multiple compressors operating at part load capacity. There is a mismatch where-by the total full load

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[7] Signal Noise is a result of random fluctuations in the current or voltage of an electrical signal resulting variations of the signal’s value. Signal noise can result instantaneous measured values that deviate significantly from the average value of the measured parameter.

[8] Over-sampling to reduce signal noise is a measurement technique whereby the noisy signal is measured at a high sample rate and averaged to a somewhat lower data interval.

rated airflow capacity of the operating compressors significantly exceeds the plant's compressed air demand.

Informational Objectives and Measurement Plans

Del Monte Foods – Informational Objectives

Informational objectives for the study were as follows:

- Baseline the present operating cost of the compressed air system during two typical operating periods during the year. Seasonal Peak operation typically lasts for 13 weeks beginning sometime in early to mid-June and ending mid-September to early October. Winter Production operates under a significantly different profile for the remaining 39 weeks of the year;
- Assess the performance of generation equipment including compressor control response to system dynamics and dew point performance of treatment equipment;
- Identify the compressed air demand and pressure gradients in four key sectors of the system; Continuous Production, Continuous Packaging, Seasonal Production, and Seasonal Packaging;
- Assess operation of high volume intermittent demand associated with the retort process in the continuous production area, and
- Evaluate the pneumatic performance of the ARPAC Wrapper in the seasonal packaging area. This compressed air use point has a history of intermittently unreliable operation. Assess the potential that variations compressed air system performance is a root cause issue contributing to the operational concerns.

The measurement plan at Del Monte Foods' fruit packaging plant was three fold. To benchmark performance, identify opportunities to optimize air system operation and energy efficiency, and to provide manage information to achieve sustainable reliability and energy efficiency. Measurement objectives for this study were identified as follows:

1. Provide a platform and methods for historical data to benchmark performance and trend operational efficiency.

2. Install permanent transducers for continuous measurement to provide real time operating information to the compressed air system operators.

3. Gather diagnostic data with portable equipment performing targeted measurement of system dynamics and identify cost savings opportunities.

Continuous monitoring provides real time operating data to guide operating strategy.

A measurement plan to support real time operating data requires a continuous monitoring plan. Whether compressors are operated manually or use various automation technologies, measured data must support operating decisions and provide oversight of operation. Real time operating information includes the availability and operating status of all air compressors, whether compressors are: available or unavailable; running or stopped; and if running, loaded or unloaded (for variable delivery machines, what portion of its full capacity is being utilized). The air flow of individual compressors is particularly desirable in the case of centrifugal compressors[9], which may blow-off or by-pass large amounts of airflow with no change in power consumed.

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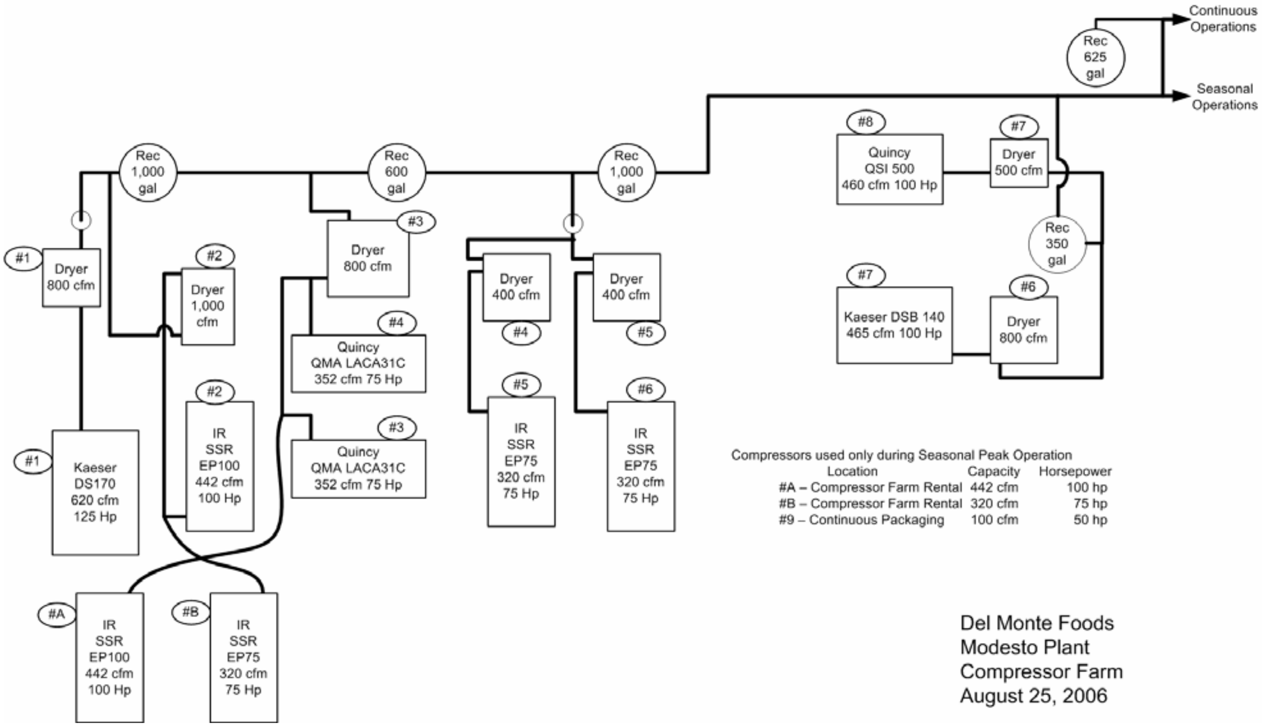
[9] Note, airflow is the most expensive performance parameter to measure. Alternatively an indication of inlet and blow-off valve positions can be used to assess the actual air delivery of individual centrifugal compressors.

The Del Monte Foods compressed air system is currently operated as two separate but not independent air demand sectors; Seasonal Operations (production & packaging) and Continuous Operations (production & packaging). The Supply Side block diagram shown in Figure 1 is operated as a single system with 11 compressors and 7 air dryers (referred to as the compressor farm). Individual pipelines leave the compressor farm to each area.

Figure 1. Supply Side Block Diagram, Del Monte Foods Compressor Farm



Presently, operators start and stop air compressors manually. Permanently installed instrumentation connects to the Rockwell Automation RSView32 Data Collection System (DCS). The DCS provides operators with real time information through a computer running HMI (Human Machine Interface) software. This information includes: power input to each compressor, total airflow, and pressure delivered to the system. With power and airflow data updated several times per minute, operators can continually assess the system's supply / demand balance. Informed decisions are made regarding when to start and stop the compressors.

System operation is made more complex because even though the DCS collects real time data for the supply side, compressor *operation* is based on local control settings at each compressor. These independent compressor controls require a manual operating strategy, which may result in periods of time when multiple compressors are operating at part load capacity. Currently, the operators can assess the relative contribution each air compressor to the total system flow only by monitoring the power of individual compressors. Future improvements are planned to include a system master style multiple compressor control to automate operation. When automation is complete the RSView32 HMI will give the operators oversight necessary to ensure efficient operation.

Continuous monitoring applied to benchmark and trend operational efficiency

Performance accountability is crucial to achieving sustainable energy efficiency in an industrial compressed air system. Continuous monitoring of real time data along with, daily, weekly, and monthly reporting allow informed management of the system. A summary performance report is shown in Table 1. Key elements are air demand, generation efficiency, and production output. Key questions include how much air is consumed, what is the energy cost, and what is the plant's production output? Air quality, i.e. dew point may be critical at certain production areas or processes.

Benchmarks provide performance data for comparison to other plants with similar production processes, or can compare a single plant's operations during different time periods. The total weight or mass of air is typically measured in MMscf (million standard cubic feet). Energy use is the total energy input, kWh or MWh (kilo-watt hours or mega-watt hours), to the supply side of the compressed air system. Production output should use the normal measure of the plant's output; tons, cases, dollars or other measure of production output.

Operational Efficiency at Del Monte Foods

Del Monte Foods' production and compressed air demand has two typical operating profiles; Seasonal Peak and Winter Production. Baseline performance for one representative week from each season was used to establish annual operating cost.

Measuring winter production baseline (39 weeks). To establish the system's winter baseline performance, a typical winter production operating week from 2/12 through 2/18/2006 was used. Compressed airflow from the compressor farm and the power inputs for compressors #1 through #8 were monitored with permanently installed transducers. The Rockwell RSView32 DCS collects data using a 1 minute sample rate with averaging to a 15 minute data interval.

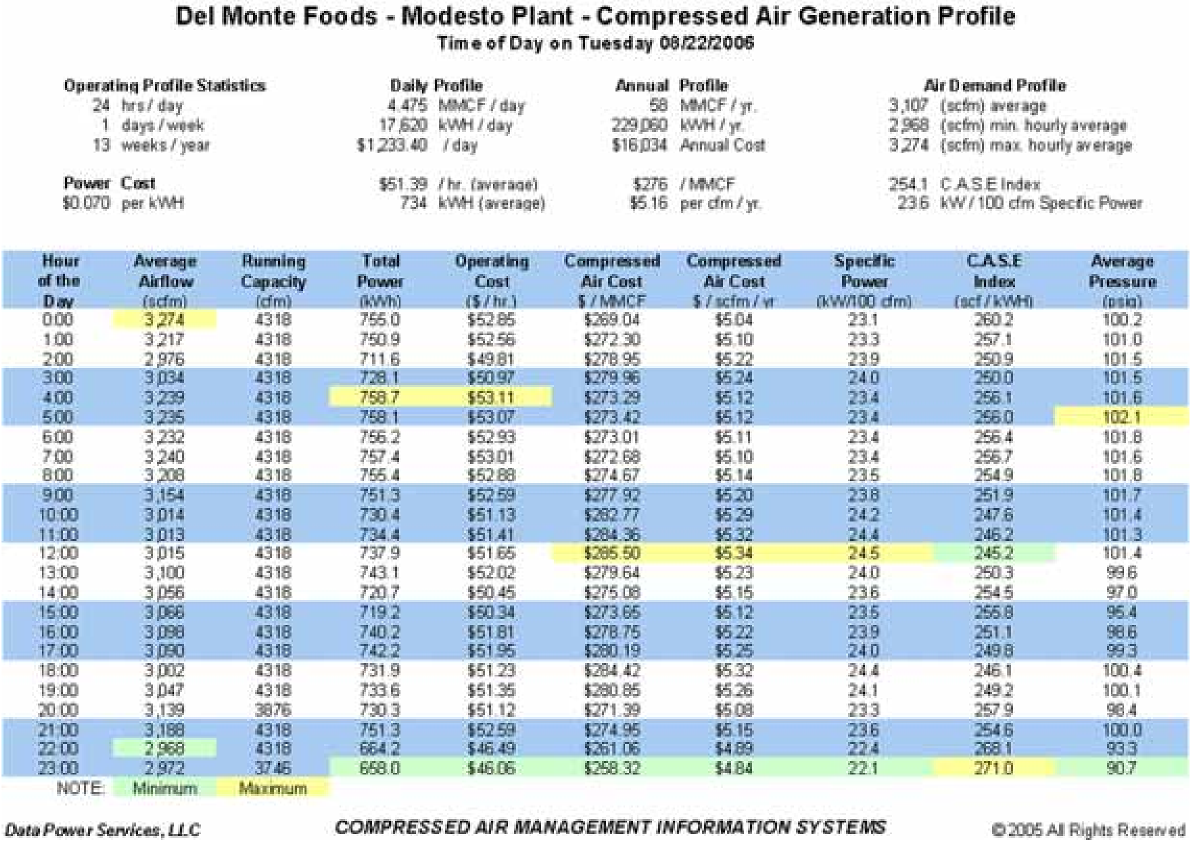
Seasonal peak baseline measurement (13 weeks). To establish the system's Seasonal Peak Baseline, performance was measured for one operating week 8/20 – 8/26/2006.

Airflow was measured at the compressor farm with the permanently installed thermal mass flow transducer, and at compressor #9 with a portable thermal mass flow transducer. For compressors #1-8, the power input of each compressor was measured with a permanently installed kW monitoring transducer. For compressor #9 and the two temporary rental compressors, portable amperage or kW transducers were used. Where amperage was measured, spot check measurements of voltage and power factor were used to calculate power.

Data collected with the portable data acquisition equipment were intended for use in both baseline and dynamic measurement. Therefore, high frequency sample rates and data intervals were used – a 10 ms sample rate, and a 6 second data interval.

Measured system performance information for one baseline day is shown in Table 1. The seven baseline Seasonal Peak days were averaged together and annualized for 13 weeks of operation. Similar data for the Winter Production baseline week was annualized for 39 weeks. The total annual electrical energy cost is $ 237,761 to supply 874 MMCF of compressed air to the facility. The average cost for each MMSCF of compressed air is $ 272. The conversion efficiency of energy to compressed air as measured by the CASE Index 257.4 scf/kWh (Compressed Air Supply Efficiency) is less efficient than would be found in facilities with very efficient air supply where the CASE Index would be approaching 300 scf/kWh.

Table 1. Seasonal Peak Baseline Profile for Tuesday 22 Aug 2007



Del Monte Foods - Modesto Plant - Compressed Air Generation Profile

Time of Day on Tuesday 08/22/2006

Operating Profile Statistics		Daily Profile		Annual Profile		Air Demand Profile	
24	hrs / day	4.475	MMCF / day	58	MMCF / yr.	3,107	(scfm) average
1	days / week	17,620	kWH / day	229,060	kWH / yr.	2,968	(scfm) min. hourly average
13	weeks / year	$1,233.40	/ day	$16,034	Annual Cost	3,274	(scfm) max. hourly average
Power	**Cost**	$51.39	/ hr. (average)	$276	/ MMCF	254.1	C.A.S.E Index
$0.070	per kWH	734	kWH (average)	$5.16	per cfm / yr.	23.6	kW / 100 cfm Specific Power

Hour of the Day	Average Airflow (scfm)	Running Capacity (cfm)	Total Power (kWh)	Operating Cost ($ / hr.)	Compressed Air Cost $ / MMCF	Compressed Air Cost $ / scfm / yr	Specific Power (kW/100 cfm)	C.A.S.E Index (scf / kWH)	Average Pressure (psig)
0:00	3,274	4318	755.0	$52.85	$269.04	$5.04	23.1	260.2	100.2
1:00	3,217	4318	750.9	$52.56	$272.30	$5.10	23.3	257.1	101.0
2:00	2,976	4318	711.6	$49.81	$278.95	$5.22	23.9	250.9	101.5
3:00	3,034	4318	728.1	$50.97	$279.96	$5.24	24.0	250.0	101.5
4:00	3,239	4318	758.7	$53.11	$273.29	$5.12	23.4	256.1	101.6
5:00	3,235	4318	758.1	$53.07	$273.42	$5.12	23.4	256.0	102.1
6:00	3,232	4318	756.2	$52.93	$273.01	$5.11	23.4	256.4	101.8
7:00	3,240	4318	757.4	$53.01	$272.68	$5.10	23.4	256.7	101.6
8:00	3,208	4318	755.4	$52.88	$274.67	$5.14	23.5	254.9	101.8
9:00	3,154	4318	751.3	$52.59	$277.92	$5.20	23.8	251.9	101.7
10:00	3,014	4318	730.4	$51.13	$282.77	$5.29	24.2	247.6	101.4
11:00	3,013	4318	734.4	$51.41	$284.36	$5.32	24.4	246.2	101.3
12:00	3,015	4318	737.9	$51.65	$285.50	$5.34	24.5	245.2	101.4
13:00	3,100	4318	743.1	$52.02	$279.64	$5.23	24.0	250.3	99.6
14:00	3,056	4318	720.7	$50.45	$275.08	$5.15	23.6	254.5	97.0
15:00	3,066	4318	719.2	$50.34	$273.65	$5.12	23.5	255.8	95.4
16:00	3,098	4318	740.2	$51.81	$278.75	$5.22	23.9	251.1	98.6
17:00	3,090	4318	742.2	$51.95	$280.19	$5.25	24.0	249.8	99.3
18:00	3,002	4318	731.9	$51.23	$284.42	$5.32	24.4	246.1	100.4
19:00	3,047	4318	733.6	$51.35	$280.85	$5.26	24.1	249.2	100.1
20:00	3,139	3876	730.3	$51.12	$271.39	$5.08	23.3	257.9	98.4
21:00	3,188	4318	751.3	$52.59	$274.95	$5.15	23.6	254.6	100.0
22:00	2,968	4318	664.2	$46.49	$261.06	$4.89	22.4	268.1	93.3
23:00	2,972	3746	658.0	$46.06	$258.32	$4.84	22.1	271.0	90.7

NOTE: Minimum Maximum

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When viewing hourly performance data in Table 1, it is observed that the CASE Index varies from a more efficient 271.0 scf/kWh to a lowest efficiency of 245.2 scf/kWh. Data shows that there is a significant supply / demand mismatch. The “Running Capacity” (rated air flow for the running compressors) significantly exceeds “Average Airflow” (compressed air demand) to the plant. The result is decreased generation efficiency. During the most efficient operation 2,972 scfm air demand was being served with 3,746 scfm of running compressor capacity. The least efficient operation was the result of 4,318 scfm of compressor capacity supplying only 3,015 scfm of air demand.

During the 7 day Seasonal Peak baseline period; depending on the plant’s demand profile, and supply / demand mismatch; the overall generation cost of compressed air ranges from $ 231 to $ 370 / MMCF. The CASE Index, mass / energy balance for the facility ranges from 302.1 scf/kWh during the most efficient operation to 189.4 scf/kWh at the lowest efficiency. System operation and supply / demand imbalance are shown in the Table 2.

Table 2. Compressed Air System Mass / Energy Balance

Date and Time	Air Demand	Running Capacity	Specific Power	CASE Index
08/26/2006 4:00 am	3,503 scfm	3,746 scfm	19.9 kW/100 scfm	302.1 scf/kWh
08/21/2006 4:00 am	1,894 scfm	4,096 scfm	31.7 kW/100 scfm	189.4 scf/kWh

The mass / energy balance and generation efficiency data in Tables 1 & 2 identifies an opportunity to improve supply efficiency. Permanently installed compressed air instrumentation should produce daily performance reports. Proper management information is essential to achieve efficient operation and sustainable energy efficiency.

Targeted measurement gathers diagnostic data to optimize performance.

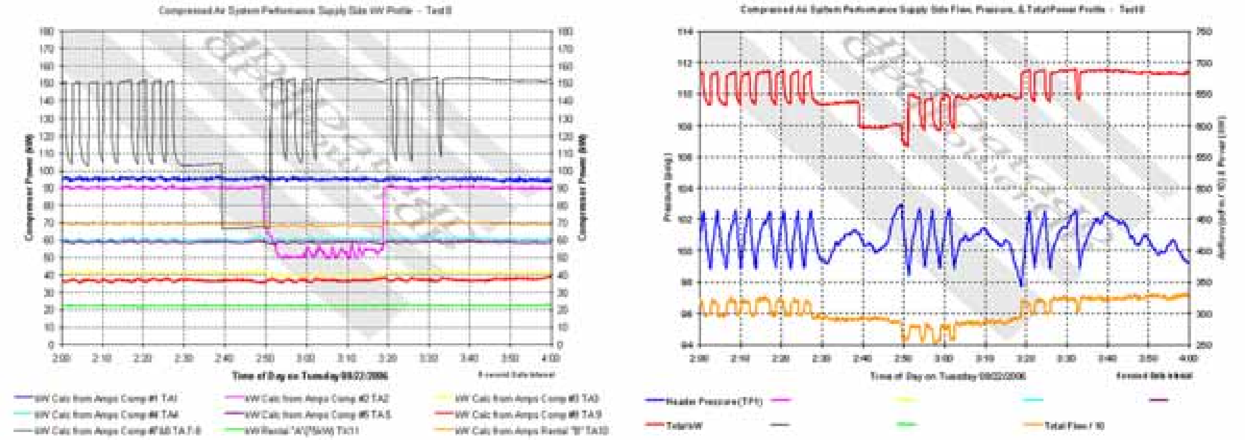
Diagnostic measurement is a discovery process targeted to understand current operating methods and evaluate the air system's ability (or inability) to reliably and efficiently support the production process. The optimization process begins with a baseline measure and identifies opportunities for improvement and energy reduction. Different performance characteristics for supply, demand, distribution, and points of use results in widely varied diagnostic informational objectives. Diagnostic information often requires targeted measurement at high frequency data intervals using portable data acquisition equipment.

These targeted measurements address specific aspects of system operation and efficiency; compressor control, distribution pressure gradients, air demand of the facility and / or individual demand sectors, departments, processes, or specific pieces of equipment. Measurement may identify characteristic signatures of pressure and / or flow profiles at high volume intermittent demands, perceived high pressure uses, or end uses which have a history of unreliable operation.

System supply side targeted measurement objectives. Supply side optimization's goal is to maximize generation efficiency i.e., generate compressed air at the lowest cost per MMCF. Generation efficiency is a function of how air compressor controls react to dynamic pressure changes of the system. Average demand is most efficiently supplied using the air compressor's rotating energy, while peak air demand is best supplied with compressed air energy storage.

Measurements are taken to understand the control action of existing compressors. Since air compressors react to pressure sensed by their controls, pressure and power data are recorded. To capture dynamic performance, a high sample rate (10 ms) and frequent data interval (6 sec.) are used. The same interval is used on multiple data loggers which are time synchronized and used to measure airflow rate and pipeline pressure gradients throughout the system.

Figure 2. Dynamic Control Response



The resulting valuable diagnostic information about system dynamics is shown in Figure 2. A comparison of rated performance to measured kW data in Table 3 reveals that the

"Rental A" compressor is continuously unloaded, while compressors #3, #4, #8, and #9 are all running in modulation. At the same time compressors #2 and #7 load and unload without a clearly defined control strategy.

Diagnostic data identifies opportunities to optimize system performance. When running all compressors at full load rated performance as shown in Table 3; airflow of 4,318 cfm can be generated with approximately 772 kW at a theoretical CASE Index of 335. However, due to poor control response identified in Figure 2; from 2:00 to 3:00 am serving 2,976 scfm average demand results in a CASE Index of 250.9; and from 3:00 to 4:00 am serving 3,034 scfm average demand has a CASE Index of 256.1

Table 3. Compressor Rated Performance and Measured Power

Compressor ID – Rated Capacity – Rated / Max Pres	Hp / kW – kW +SF	Measured kW
#1 – 620 cfm – 125psig / 128 psig	125 Hp / 90 kW – 103.5	95.7
#2 – 442 cfm – 125psig / 128 psig	100 Hp / 75 kW – 86.3	90.0
#3 – 352 cfm – 125psig / 128 psig	75 Hp / 55 kW – 63.3	40.9
#4 – 352 cfm – 125psig / 128 psig	75 Hp / 55 kW – 63.3	61.0
#5 – 320 cfm – 125psig / 132 psig	75 Hp / 55 kW – 63.3	58.8
#6 – 320 cfm – 125psig / 132 psig	75 Hp / 55 kW – 63.3	59.0
#7 – 465 cfm – 125psig / 128 psig	100 Hp / 75 kW – 86.3	85.8
#8 – 460 cfm – 100 psig / 110 psig	100 Hp / 75 kW – 86.3	66.5
#9 – 220 cfm – 125psig / 128 psig	50 Hp / 37 kW – 42.6	37.9
"A" – 447 cfm – 125psig / 132 psig	100 Hp / 75 kW – 86.3	22.3
"B" – 320 cfm – 125psig / 132 psig	75 Hp / 55 kW – 63.3	69.6
TOTAL – 4,318 cfm – 100 psig / 1110 psig	**950 Hp / 702 kW – 807.3**	**687.5**

Measuring sector air demand and pressure gradient. Targeted measurement of airflow and pressure at key locations were identified in the piping distribution system. Measurements were made with multiple data loggers which were time synchronized and measured at a sample rate of 10 ms with averaging to a 6 second data interval. The airflow transducers used were thermal mass style with ±2% sensor accuracy.[10] Pressure transducers are 0 to 200 psig range with ±0.15% FS accuracy.

The production sectors are shown in Figure 3, Site Plan: Continuous Production, Continuous Packaging, Seasonal Production and Seasonal Packaging. Test points described below were selected to quantify air demand in each sector and pressure gradients to, and within each sector.

Test flow points (TF1 – TF5) measured airflow in main headers supplying various production sectors. At each test flow point there was a corresponding test pressure point (TP1 – TP5). Additional test pressure points TP9 – TP14 were located at the far ends of distribution piping.

Total airflow (supply) is the sum of TF1, airflow from the compressor farm; and TF6, airflow of compressor # 9. Airflow at TF2 was the total airflow to both seasonal production and

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[10] When using insertion style meters, many factors affect measurement accuracy; most notably the actual versus assumed cross-sectional area of the pipeline affects the mass velocity calculation used to arrive at mass airflow rate.

seasonal packaging while TF3 was airflow to seasonal packaging. The difference of TF2 minus TF3 represents the airflow to seasonal production.

The airflow measured at TF4 was used by continuous production. Air compressor #9 is located in the continuous packaging area. Therefore, the total air demand in continuous packaging was the airflow from compressor #9 plus the airflow measured at TF5.

A sample of diagnostic data shown in Figure 4 allows the dynamic flow / pressure gradient profile to Continuous Production (Bldg 6) to be evaluated. It was observed that a main line filter installed in the Bldg 6 supply was creating unnecessary pressure drop. The filter remained from the original system which was supplied using lubricated reciprocating compressors and is no longer needed. At 14:03 hrs the filter was bypassed. As a result, the pressure in Continuous Production is increased by 3 psig. More importantly however, the supply flow of air was much more responsive to demand events as evidenced by the increased flow spikes to the area after the filter is bypassed.

Figure 3. Site Plan Test Points

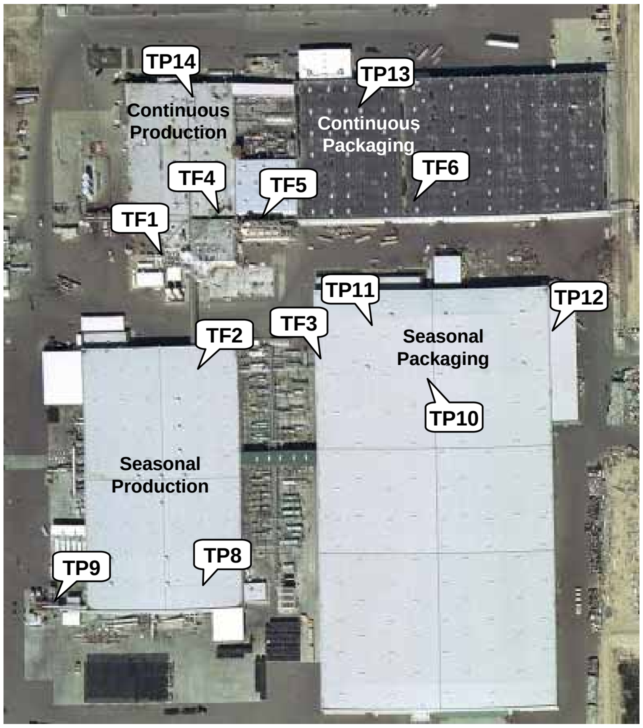
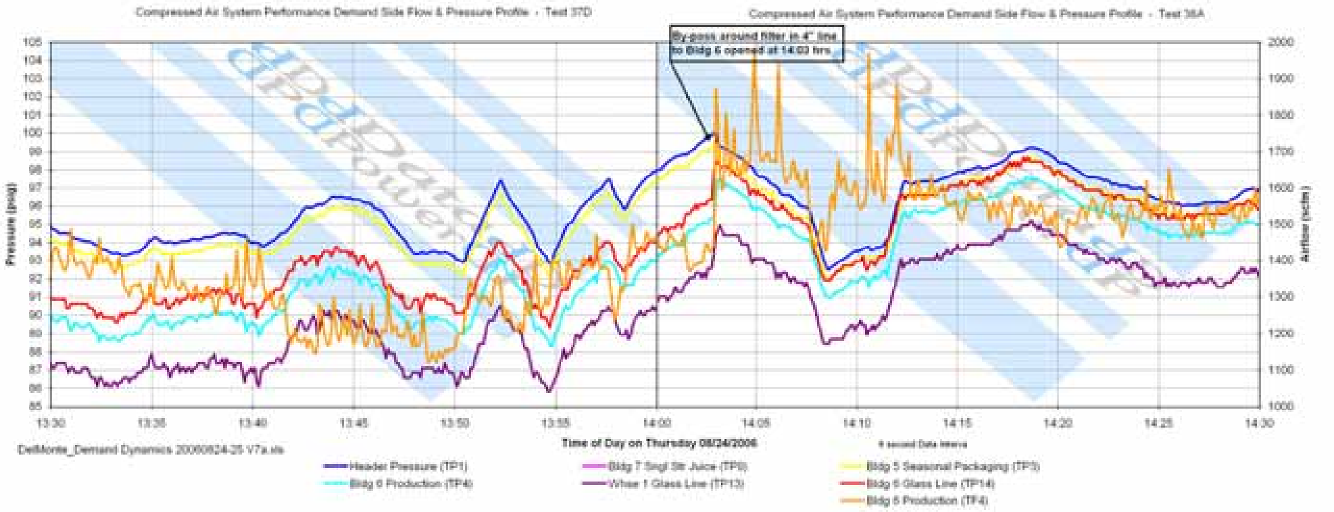


Figure 4. Continuous Production Dynamic Flow / Pressure Gradient



Historically, equipment in the Continuous Packaging area has its operation interrupted from time to time as a result of inadequate air supply. Diagnostic data was used to identify the unnecessary flow restriction caused by unneeded filtration. The increased dynamic flow supply to event demands in continuous production should reduce pressure excursions in continuous packaging, thus increasing system reliability.

Study the demand side to understand the needs of productive compressed air use. What is required to reliably support production? Key measurements include air demand scfm, (or perhaps scf/second), dynamic pressure profiles, and transient distribution pressure gradient. Point of use piping and dynamic pressure losses should be measured to identify characteristic signatures[11] at select compressed air use points.

Critical air use points affect product quality, production throughput, product rejects, rework, and scrap rate. Targeted measurements must evaluate compressed air performance as a process variable. The true pressure requirement (as opposed to the perceived requirement) for air demands that require high supply pressure need to be validated. Large demand events which intermittently consume high volumes of compressed air must be measured and profiled. Potentially inappropriate uses[12] of compressed air need to be reviewed.

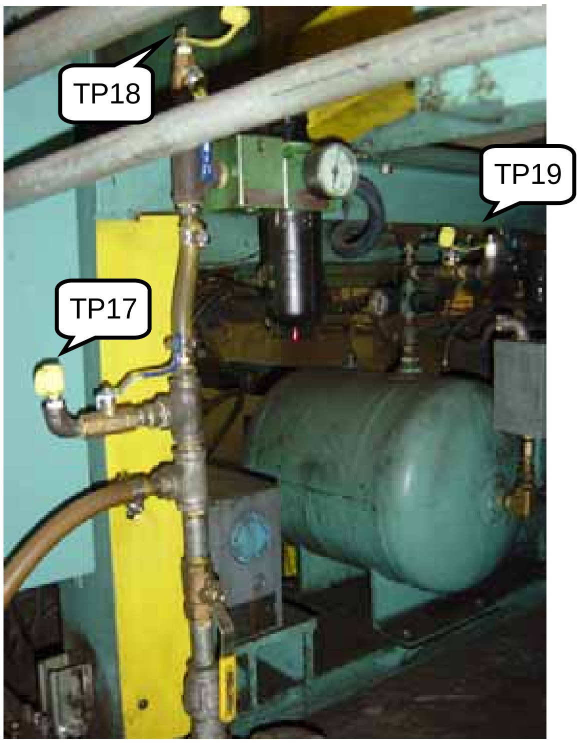
Identifying characteristic signatures at critical use points requires an aggressive measurement plan: for example, to document the point of use pressure profile for the ARPAC Wrapper at Del Monte, air pressure is measured at several locations, the air header, the connection to the machine, and at the actuator in the machine which performs the work. Each cycle of the ARPAC Wrapper is 2 seconds duration. Therefore the measurement plan included a 1 ms sample rate and 25 Hz data interval.

ARPAC Wrapper Dynamic Pressure Profile Signature. The ARPAC Wrapper intermittently malfunctions. Measurement was used to assess the comparison of pressure signatures during normal operation and cycles when there is a malfunction. Pressure measurement at three points in the supply piping to the ARPAC Wrapper provided dynamic characteristic signatures. Compressed air is used for 2.6 seconds during each 4 second cycle of the wrapper. Data acquisition used 0-200 psig pressure transducers with ±0.15% FS accuracy and response time (10 to 90%) of < 1.0 ms. Data logging used over-sampling at a sample rate of 1 kHz with data averaging to 25 Hz data interval.

Test pressure points shown in Figure 5 to the right included TP17 at the termination of hard pipe to the machine, TP18 after the short hose connection, and TP19 at the outlet of a small surge tank and pressure regulator supplying the end use application.

The similarity of pressure profile signatures shown in Figure 6 suggested that the malfunction observed was not related to compressed air performance.

Figure 5. Test Points



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[11] Characteristic signatures are repetitive dynamic airflow and/or pressure changes associated with specific cyclic compressed air demand events.

[12] Potentially inappropriate use; air demands that may be reliably and more efficiently performed with an alternative energy technology.

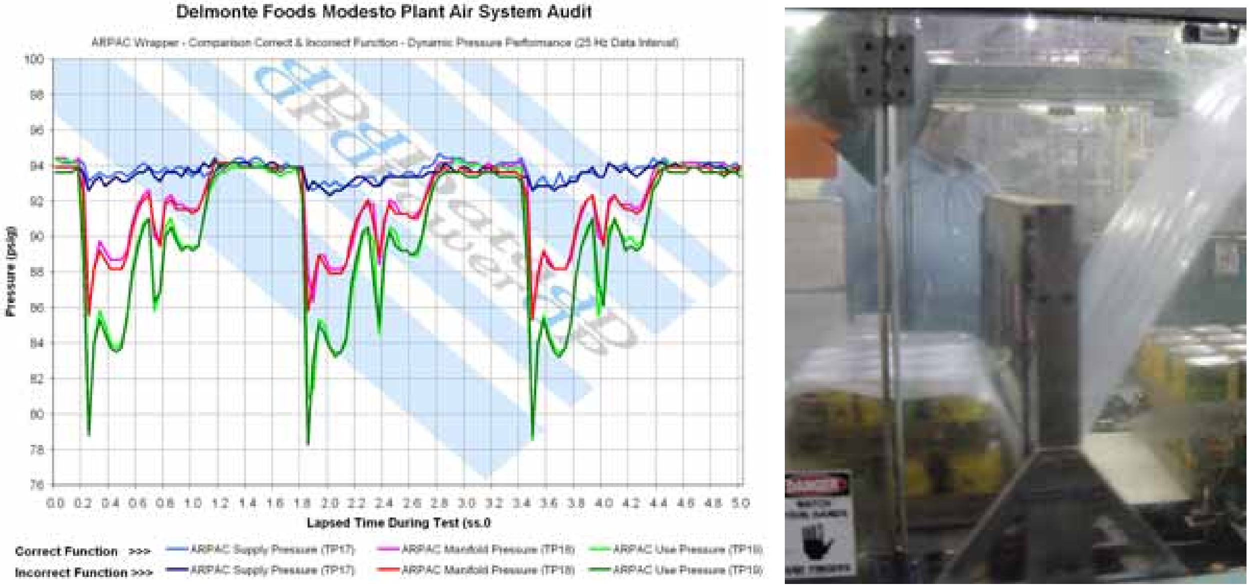

Figure 6. ARPAC Wrapper Dynamic Pressure Profile Characteristic Signature

Study Recommendations

The study identified many projects to reduce the plant's overall energy use and cost. Implementation of Phase 1 described below will reduce overall energy cost by 24 percent, an estimated $57,000 per year. Phase 2 would reduce energy use by another $18,000. Phase 3 includes: re-baseline system performance measurement, and investigate incremental savings.

Phase 1 includes installation of air dryers, piping, receivers, and a centralized sequencer control to optimize supply side operation. A central master compressor sequencer capable of interfacing all of the existing compressors was recommended. Modification to the existing treatment equipment will improve air quality, allowing the filter to Buildings 5 & 6 to be removed and eliminating the associated pressure loss. Finally Phase 1 includes minor updates to the RSView32 DCS necessary to track and trend compressed air cost and management reports on system performance.

Phase 2 implementation targets compressed air demand management. This includes final piping modifications to eliminate unnecessary pressure drop and allow the system to operate as two independent sectors. The key is to shut down or supply minimum pressure to the Seasonal Production and Packaging areas during Winter Production. Operating the demand side of the system at the final recommended target pressure of 86 psig will also eliminate artificial demand[13]. Compressed air blowing applications should be replaced with a low pressure blower source, and leak management should result in a new reduced plant air demand profile.

Phase 3 includes a new baseline assessment of the present compressors in the context of the newly created demand and pressure profiles. Replacement and or upgrade of the air compressors should be considered, including evaluating the potential benefit of a variable speed compressor to operate as a dedicated trim compressor.

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[13] Artificial demand is the incremental amount of flow in a compressed air system that services the system rather than the actual compressed air end use. It typically is a function of excess pressure, waste, and leakage.

Conclusion

Training and awareness in the “Systems Approach” for industrial cross - cutting energy systems (motor - driven, steam, process heating) has increased implementation of energy saving measures. These measures target the objective to reduce energy cost and improve performance. However, the majority of system improvement projects do not provide plant personnel with ready access to data upon which to base ongoing energy management decisions.

Enterprise Energy Management (EEM) tools provide essential information necessary to identify opportunities for continuous improvement and system optimization necessary to achieve sustainable energy savings. A combination of data acquisition hardware and software are needed to measure and collect, analyze, and report information on system efficiency and energy use.

When properly installed EEM tools provide:

- Real time performance data on which to base informed operating decisions
- Diagnostic data to optimize performance for continuous improvement
- Historical data to manage sustainable energy reduction and cost savings

Informational objectives and measurement plans should be designed to collect data that assists in the diagnosis and correction of the root causes of system problems while also supporting long term system management, thus sustaining optimum performance and energy efficiency. Measurement plans should also evaluate the whole system. Attempting to address individual parts of the system, such as compressor controls; without also evaluating issues of air storage, distribution, and point of use operation, inevitably produces results that fall well short of optimized system performance.

Excessive measurement does not produce better results, it just costs more. Care must be taken to establish a measurement plan that is appropriate to the informational objectives of a compressed air study. Targeted measurements using portable data acquisition can supplement EEM data to gather diagnostic information. Proper diagnostic data ensures that the root cause factors affecting performance are addressed. Dynamic performance and critical end uses affecting compressor control response and distribution piping performance must be defined before remedial measures can be implemented.

Management reports should be generated on a regular basis; i.e. daily, weekly, etc., and must be reviewed and used to manage the system**.** Timely information is essential for operation and management of industrial energy systems. Enterprise Energy Management tools, if properly implemented, can provide data for real time operation, diagnostics for optimization, and historical management reporting.

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