# REAL WORLD ENERGY EXPERIENCES IN THE USE OF COMPRESSORS AND COMPRESSED AIR SYSTEMS

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Although compressed air systems generally represents the third highest user for energy in the average industrial plant, it does represent the number one opportunity for both energy and operating cost reduction. The rational behind a compressed air system is to convert electrical work energy to pneumatic work energy. The process involves compression to a desired pressure at which we will store air, transmission, and expansion to the pressure at which we will use the energy. All elements of this process need to be managed as efficiently as possible. The theoretical optimum of this process would produce one unit of work energy in the form of expanded mass at the use point for every 8.5 units of input energy into the prime movers or, in this case, the electric drive motors. Unfortunately, in the hundreds of thousands of industrial plant air systems which represent over 7.5% of all of the energy used in American industry, there is little understanding or effort made to achieve any level of efficiency in this process other than the occasional attempt to buy the promise of efficiency in the equipment when purchased. The compression portion of the process is normally the only area of the system where any attempt for efficiency is made. The vast majority of these systems seldom come close to a 10 to 1 conversion of theoretical work energy. In addition, the manner in which compressed air is consumed offers a major opportunity for reduced energy and operating cost. Typically, less than 60% of the total compressed air consumed directly contributes to the production of the goods and services for which the system was intended. Of the 60% of total air used in the system which contributes to productivity, more than a third of it is poorly applied and could be significantly reduced. The net result is less than 40% of the total consumption of compressed air in our industrial plants is essential to the process results. The combination of the efficiency of the systems process and the manner in which the resulting compressed air is used makes plant compressed air systems one of the most significant economic opportunities in the industrialize sector. Despite this reality, compressed air energy has been increasing while all other forms of other energy in industry are diminishing.

This paper will illustrate the findings of forty two industrial compressed air audits which were performed by Plant Air Technology between 1993 and 1994. These audits were performed on a broad cross section of SIC codes in primarily medium to larger industrial facilities. Thirty eight percent of the audited facilities were distribution electrical rate based customers, while sixty two percent were transmission rate based electrical users. The original motivation for the audits ranged from energy reduction, capital cost avoidance, operating cost management, to specific performance on the using side of the system. The majority were interested in operating cost reduction with a variety of secondary motivations. The action plans generated from the audits were acted on by thirty seven of the forty two or eighty eight percent of the total. The return on investment adjusted for tax treatment including the addition of depreciation for the capital improvements averaged less than sixteen months.

## PROFILE OF AUDITED FACILITIES

The percentage of total consumed energy used for compressed air in these plants ranged from six percent to twenty nine percent, averaging nine and one half percent. Most of the operating personnel in theses plants did not know how much compressed air volume they either used or needed. They did not know what their costs of operating the compressed air system was. Only five of the facilities had monitoring equipment for volume or power. Only two of these plants monitored both input power and compressed air consumed. There were no standards or operating procedures for the use application or supply of this utility other than maintaining a minimum acceptable result. Generally, success in systems operation was determined by the lack of complaints. The majority of operating personnel acknowledged that they were lacking in education regarding compressed air systems and its operation . Thirty six of the audited facilities did not know how their equipment was specifically adjusted and admitted that out sourced services from the compressed air industry maintained the equipment and established the equipment operating parameters. Of the balance, only two who took care of their own equipment, had records of how it was adjusted.

Thirteen of the projects were sponsored or co-funded by the local electric utility. The utilities costs ranged from a blended rate including demand charges of $.035 to $.113 per kilowatt of electricity consumed. Chemical and hydrocarbon processing as well as air separation have been deleted from this report as they are atypical of plant air systems and operated in relatively efficient approaches.

Low load or no load tests were performed at all audit locations in advance of the final audit. All operating conditions were investigated. All parts of the system including supply, storage, distribution, and demand were examined. Problems in the system were evaluated and quantified. The audited systems operating costs were determined including all ancillary equipment, maintenance, water, operators costs, and depreciation. Proposed solutions were engineered and costed. The proposed system's operating cost was determined to establish a return on investment scenario.

## CONSTITUENTS OF DEMAND

Most systems are evaluated based on perceived supply requirements. If the pressure anywhere in the system is below whatever is believed to be the minimum, the diagnosis is insufficient supply. Little more is done to determine what is going on in the system. Without demand, there is no requirement for supply. The beginning of figuring out what a reasonable needs profile is begins by analyzing demand. All of these systems used the air at the pressure it was compressed at with little to no storage and random expansion. Less than half of the air consumed was regulated at a pressure lower than the primary compression pressure. The following are the categories of usage with descriptions:

1. Appropriate Production Usage - compressed air usage which is well applied and controlled at it's intended use pressure. This can include coincidental demand, critical pressure, high rate of flow, and high volume users which provoke the operating philosophy by the way that they effect the system and its pressure. A portion of the total appropriate users necessary to production will be regulated, while the balance will be unregulated.
2. Inappropriate Production Usage - applications that should be accomplished with either electricity, hydraulics, or mechanical power instead of with compressed air. Examples would be plant air for aspiration, agitation, aeration verses a single stage low pressure blower. Other examples would be air ejectors in place of simple vacuum or air verses electric vibrators. These are usually effortless applications of compressed air with no understanding of cost or consequences to avoid the purchase of alternative equipment to perform the same functional result.
3. Open blowing - plant air used for moving product, drying, wiping, cooling, part and scrap ejection as opposed to low pressure blowers or specialty nozzles which would have to be purchased and applied.
4. Drainage - this is when we use plant air in conjunction with either open valves, notched ball valves, motorized or solenoid operated drain valves to dispose of compressed air effluent such as water and or lubricant. This would be compared to automatic drain traps which do not use compressed air to dispose of effluent.
5. Leaks - this represents leaks which are internal to production equipment as well as in the general piping system from the internals of the compression equipment to the point of use equipment.
6. Artificial Demand - This is the excess volume of air that is created on unregulated users as a result of supplying higher line pressure than is necessary for the application. This includes all previously unregulated consumption including appropriate and inappropriate production usage, open blowing, and leaks.
7. Attrition - additional air consumption on applications as a result of unmanaged wear. Examples would be blast nozzles, textile machinery nozzles, etc. Unattended attrition can increase consumption by 50% volumetrically and frequently provokes the increase of pressure at both the point of use and at the supply. This can result in increases in requirement up to 100% of the original consumption.
8. Purge Air from Desiccant Dryers - this air is consumed in the process of stripping air dryers of moisture. This process can range from 3% to 14.7% of the total air systems capacity from one dryer type to another. There are specialty applications such as CDA 100 which is used for the microelectronics industry where purge can approach 25% of total capacity for the system.
9. Centrifugal Compressor Blow Off - when the demand for air in the system is below the minimum stable flow for this type of compressor or compressors, these compressors will blow off the difference between the minimum stable flow and the actual requirement. It is rather common that all centrifugals installed in an application can be blowing off simultaneously. The minimum stable flow depending on the design of the compressor can range from 60-85% of the full load capacity of this type of compressor. This is real demand which requires energy whether it is productive or not. The objective in operating a centrifugal should be to keep this unit fully loaded in base load.
10. Bleed Air or Control By Pass - this a point of use consumption where air is bled off the system or by passes an

application as a means of improving the accuracy of pressure and/or flow control . Where accuracy of pressure is important and there is considerably more power and/or higher than needed pressure on line, the pressure will fluctuate erratically or perturbate. There is normally a controls and/or storage associated problem that is compensated for in this manner. The most common usage of bleed air or by pass is where compressed air is used in simulation testing primarily in the aerospace industry.

In general the above represents the constituents of demand which were encountered in the audited systems. The last four categories, items 7 through 10, were only represented in 23% of all systems while the others are typical constituents. The following table is an attempt to illustrate the percentage of the total air consumption that was encountered for each of these various users of air relative to the total usage. The categories represent the minimum, average, and highest percentage that these values were represented. The total of these constituents are representative cumulatively of the typical system.

Table 1 - This is characteristic of 77% of the systems audited.

| Constituents of Demand | Low Usage | Average Usage | High Usage |
|---|---|---|---|
| Appropriate Production Usage | 19% | 37% | 57% |
| Inappropriate Production Usage | 3% | 10% | 26% |
| Open Blowing | 6% | 15% | 39% |
| Drainage | 0% | 6% | 16% |
| Leaks | 11% | 23% | 41% |
| Artificial Demand | 4% | 9% | 19% |
| | | 100% | |
| Total Kilowatts of Energy Consumed | 326.4 Kw | 1748.7 Kw | 11838.1 Kw |

The last four categories, items 7 through 10, are listed separately and are either industry or type of systems specific. These unusual constituents are representative of a percentage of the total volume in the systems in which they were audited. The four categories are not cumulatively representative nor do the typical users fit in these systems in the same manner as they do in the primary analysis.

Table 2 - These uses of compressed air were found in a smaller sample of the total systems audited and are not representative of what is typical. Their impact on the systems which were audited warrant mention.

| | | | |
|---|---|---|---|
| Attrition Wear | 2% | 7% | 38% |
| Purge Air for Desiccant Dryers | 3% | 9% | 14.7% |
| Centrifugal Compressor Blow Off | 0% | 12% | 38% |
| Bleed Air or By Pass for Control Apply | 0% | 16% | 31% |

## OTHER DEMAND INFLUENCES ON SUPPLY ENERGY

The amount of energy which is required to operate the system is not only based on how much consumption of air is used in demand, but how you use it. The relationship between the supply arrangement and the way that you use the demand will also determine energy consumed. In examining demand we must ask the question "why do we operate the system the way we do?" Our ability to breakdown the demand by issue provides us with the information to make the most informed approach towards managing the system efficiently. The following is a further evaluation of demand as it influences the supply energy with descriptions.

1. Minimum Load - although this is the condition with the least amount of energy requirement, it usually represents the most hours of operation per year in most systems. It is usually not evaluated and winds up being the step child when evaluating compressor sizes. There is usually a significant amount of part load of a larger than necessary compressor or compressors which which were sized for peak demand. When you combine the waste and the hours of operation, this is usually a major opportunity for savings. Leaks are usually the predominant user in this condition. As such this condition is an excellent tool for leak benchmarking. On a regular basis, typically every two weeks,

maintenance can bring the demand volume back to the previous benchmark period through selective leak management using a powerful ultrasonic scanner.
2. Base Load Demand- each of the conditions or shifts will have a base load demand that will not vary. The focus on servicing base load should be efficient compressors.
3. Trim Requirements- each of the conditions will have a variable portion of the demand above base load. This is called trim. We need to service trim demand with compressors that are capable of loading and unloading and turning the motor on and off as required. The speed of bringing the motor and compressor to full load can be critical. The focus on trim is smaller, faster compressors with flexible controls. Remember that no larger compressor, no matter how efficient part loaded, is as efficient as two smaller compressors with one off.

The first three items described provide the profile of usage across the conditions. There can be from one to five conditions in each system. There is often much sales talk about the efficiency of the compressors. When you thoroughly develop the anticipated profile, you may find that you will not generate enough hours in trim to rationalize more expensive and efficient trim units. The base load can and should be serviced by the most efficient compressors because of the number of hours of service verses the energy consumed. Do not forget the support of the low load. This will probably be supplied with one or more of the smaller trim compressors. Despite the sensibility of this, normally only the peak is considered. Several large compressors are installed with one extra which is loaded at the first inappropriate distress call from production. We then add another back up machine which gets turned on. Another tool used in sizing and configuring most systems is the ever popular “fudge factor”. Each step of the process of determining the demand and eventually the supply includes at least one fudge factor for either volume or pressure. Keeping in mind that we are expanding the gas to a variety of different pressures when using it, I am always surprised that when sizing the system users and industry representatives simply add up the volume as though there was no pressure and jack up the pressure without correcting the mass to a lower volume at the elevated pressure we are going to compress at. This allows us to start with much more supply energy than is anticipated. With no demand control, no waste management plan, and no information, you should not be surprised that with the first year virtually all of the systems need what they have and are shopping the next prepackaged solution to the poorly defined problem.

The next two demand items are the most pervasive of all demand issues and represent the primary reason why the system is operated in the manner that it is.

4. Demand Events that Create Peak Demand - All systems have events. These are typically high volume, short cycle air users which create the peak in the system. It is important to not only know the rate of flow, volume per cycle, the duration of the event, but also the recovery time available between events. If we ignored this event, the pressure would drop when it occurred. In most cases, the system is run at a high enough pressure all of the time so that when the event hits the system, we will stay above the minimum acceptable pressure. It requires additional power “on line” all of the time in order to operate in this method. This obviously not the best operating method, but is the typical approach. The highest demand event may be a single high user such as material transfer or dense phase conveying. Another major source of events is the coincidence of several large events hitting the system simultaneously. Typical of this would be the start up of a shift at a specific time. Typically this peak occurs at first shift start up. Smaller events occur at the return from breaks. In one case we shut off a 1500 bhp compressor by disconnecting the shift and break start up horn. Instead of 700 people hitting their equipment at one time, the shift started over a period of ten minutes. The breaks were split. The power required was significantly reduced. Another example of coincidental events would be several solenoid operated or motorized drain valves discharging at the same time. If there are enough of these drains, they are statistically going to overlap each other with some regularity. The more drains, the longer the open duration, and the shorter the intervals, the larger the event which will occur. Remember that the system sees events in real time at the rate of flow per event in cubic feet per minute. A 1/2” motorized drain valve may only be open for 5 seconds every 10 minutes. During the open time, it may discharge 40 cf of air at line pressure for 5 seconds, but it occurs at 477 cfm rate of flow. The supply system sees this as a requirement for 110 bhp of compressor for this short duration. Depending on how much storage capacity their is in the system, will determine how much the pressure will drop during the event. Imagine four or five of these valves opening at one time. Our experience is that this type of an event normally occurs in the compressor room and will occur sufficiently to prevent any compressor from unloading even when there is not enough demand to support the supply.

It would be unique if someone operating a compressed air system knew what the events were, how they influence the system, or what to do about them other than operating more compressors all of the time to handle the events once in a while. Events are the single most important issue in designing and operating an air system. There are many ways of managing events besides throwing power at them. We have included Attachment A titled " Sizing Control Storage " which will provide some insight into event management. Another way of better managing peak events in the system is Load Shaping©. This the development of high volume, high pressure storage which is created off the main air system with typically a very small 150-200 psig compressor/s. The air is then reintroduced into the system with a valve control system operated by a programmable controller which controls the pressure drop when the rate of change in the system exceeds a preset value normally commensurate with the events which occur. The idea of load shaping is to support events in the system while preventing larger compressors in the supply system from seeing the demand increase on a selective basis. The energy required is a function of the volume require times the use time divided by the available recovery time before the event reoccurs. 1

5. Critical or Highest Demand Pressure Required - most systems operate on an error response basis. If the pressure drops and someone complains, additional compressors are loaded to increase the systems pressure so that the calls will cease. The interesting thing about this is that when the call comes regarding insufficient supply (the most common diagnosis), it should occur to someone that the caller has operated at the same pressure for a long time with no reported problem. At 10:30 this morning, the same system's pressure was no longer sufficient. Is there something wrong with this picture. We find that most high, critical pressure users in the system have some rather common maladies. The most predominant is a regulator with an extremely high differential. Differentials on regulators show up on the upstream side of the pilot pressure they are trying to hold. If you have a 20 psig $\Delta P$, which is not unusual, and you are trying to maintain a pilot pressure of 90 psig on this application, you will have to maintain 110 psig in the overhead system and a higher pressure at the compressors. If your philosophy is keep them from calling, imagine the gyrations you will have to go through or the misdiagnosis in order to satisfy this kind of problem. Half of the plants audited felt that the main piping was undersized. In all of these cases the rational for this diagnosis was that a user in system could not hold 10 to 20 psig less pressure in the system on a critical pressure application. The real dilemma is the lack of problem definition. Another problem which can go hand in hand with the regulator problem is the point of use filter which is dirt loaded . As the filter gets dirty, the downstream pressure drops. It can run into the differential on the regulator. It will definitely change the way the air user is functioning. Since the user does not know why his air operated device does not work properly, invariably it is assumed that there is insufficient supply. Nine out of ten plants audited had never changed the point of use filter cartridges since they had been installed. They also had no replacement cartridges in inventory if they wanted to change the filters. In almost every system, the first two or three highest pressure users had between 15 to 30 psig of differential across the filter, regulator, hose, and disconnects. In most of these plants all point of use installations used the same size of installation components as mentioned regardless of the volume or pressure required by the air using device. Once you install the user, if it doesn't work, you just increase the regulator until it does. If this doesn't work, you add a compressor and elevate the entire system until that one user works. This is how we coop with differential. Most of the time, the differential at the point of use represents the highest pressure drop in the entire system. Sometimes the problem is another high volume user near the critical pressure application which causes the branch line or sub header pressure to drop into the critical application. Make the call. Add more power. Most of the time we fix $100 problems with $50,000 solutions. It sounds silly, but this is common place without investigation. We will struggle for months attempting to decide what brand and type of compressor should be used to fix a dirty filter. I hate to think of the tens of thousands of times we repiped the system to a larger size to fix an undersized regulator. In all cases the retrofit increase of the piping increased the storage capacity of the system although no one thought of storage as a solution. There are much less expensive ways to provide point of use storage than increasing the header size.

When you consider that it in most cases it will cost more to operate a compressor in the first year than what it costs to buy and install, adding another compressor is a serious decision. Even the most uninformed manager will balk at the capital expenditure if there is not a sound definition of the problem.In most cases,the decision to buy another box of compressed air will be sitting in the bottom of the "to do" pile. Eventually the problem will be frequent enough that production will support the purchase even though they also do not investigate the problem. The purchase, installation, and start up will occur. The pressure will be elevated a few psig and the complaints will cease for a period of time until we start the process all over again.In the audit process,we uncover these issues.The following will illustrate the effect that these demand events typically have on the amount of energy used in the forty two systems that were audited.To maintain continuity, they are presented as in a similar manner as Table 1 and Table 2. Table 3 - the following represents the percentage of total energy that was influenced by demand issues 4 and 5 in the forty two audited systems. Please keep in mind that the energy required to support the volume of these issues is only useful when the events occur. The vast majority of the time, this energy is waste. This only represents the effect on energy other than consumption.

| Demand Issue | Low % of Energy | Average % of Energy | High % of Energy |
|---|---|---|---|
| Demand Events | 0% | 16% | 33% |
| Approach Towards High Pressure Users | 4.5% | 18.3% | 24% |

In twenty nine of the forty two systems, there was an additional compressor or more on line to support one or both of these situations in the system. In the balance of the systems there were three or less relatively large compressors which would still be loaded even when these situations were corrected or serviced in a different manner.

It should be understood that there are a number of other consumers of energy in these systems which are not demand related. Although this report is pertaining specifically to demand in the compressed air system, we have provided Attachment B "Constituents of Supply Energy" to expand your understanding.

## Summary

Demand is the most misunderstood part of the compressed air system. Compressed air mass is what does the work. Only two of the forty two plants used mass. The majority used volume and pressure in separate context. Mass is not understood. There are no standards for the use of compressed air in regards to guidelines. Without information or education, none of this is perceived to be a problem because it can't be defined or quantified. The average usage cost was $1.665 per 100 cfm per hour of operation based on an average use pressure of 96 psig. On a three shift basis, five days a week, a 1/4" open blowing device @ 90 psig costs $9834 per year to operate. In all of the plants audited anyone could make this applications decision with no discussion or knowledge of the consequences. If this application requires the addition or loading of another compressor, the cost could increase by 10 times. Twenty eight of the plants audited currently have an air committee and have developed standards for the use of compressed air. They also have applied standards for allowable differentials at all applicable points from one end of the system to the other. They also view the addition of compressed air users in the system as a business decision as it should be. The average demand reduction in these plants was 43% although most admit that they are not finished. The average demand pressure requirement was reduced by 12 psig and many feel they can reduce this further. Seven have applied Load Shaping© to their system. Twenty six have in some manner, other than Load Shaping© more effectively learned to coop with events in the system. The average energy reduction is more than 51%. The average savings per year including all costs of compressed air were $486,360. The tough questioned that had to be asked in these industrial plants is how much production revenue must be generated annually in order to do nothing. As this is bottom line expense and directly impacts on operating income, the answer is the potential savings times the sum of the gross revenue divided by the operating income. In the average plant the answer was nearly $10,000,000 per year.

## Attachment A

### Control Storage Calculations

We need to determine the allowable pressure drop from the signal pressure when we begin to add the next compressor to the terminating pressure when we stop the decay. The amount of storage will determine how low the pressure will drop.

The factors that need to be considered are as follows:

1. The largest event in cf/sec that can occur in the system.
2. The slowest permissive speed of the compressors in the supply measured in seconds including the cold start of the motor and the internal permissives of the compressor required before it starts to discharge air into the system. Single and two stage rotary screws range from 6 seconds to 15 seconds with across the line starters. Recips range from 12- 18 seconds with across the line starters. Centrifugals range from 28-72 seconds with full voltage starters with hot start. Two stage dry screws can range from 12-28 seconds on

a hot start. You must then add the extra time required as the result of adjustment of a reduced voltage starter. This can take as long as an extra 12 - 18 seconds.

Note well: we are assuming that the slowest compressor will be able to satisfy the largest event. It doesn't have to do this in real time. It only needs to stop the decay at an acceptable pressure which could take much longer than the length of time of the largest demand event. Smaller, faster compressors will slow down the event and may outlast the event duration with less horsepower.

3. The allowable pressure drop. Once you have set up the compressors in their local supply pressure profile, the allowable pressure drop is the lowest acceptable pressure drop to neither load the next compressor unnecessarily or drop below the minimum acceptable pressure of supply to the system. Please do not forget the added pressure drop across the clean up equipment between the lowest P2 pressure and the the lowest P3 psig.

If the largest event is 600 scfm rate of flow, the scf/sec is 10 cf/sec. We will assume the time permissive is 15 seconds on the slowest compressor from a cold start. The allowable pressure drop is 3 psig either between the compressors' load pressures or below the last available compressor.

If the permissive is 15 seconds, the largest event will remove 15 sec X 10 scf/second = 150 scf from the system before the slowest compressor will begin to stop the decay.

If the allowable pressure drop is 3 psig, the question is "how much storage will we need to support a 3 psid pressure drop with 150 scf of volume reduction. 150 cf X [ 14.696 psia* ÷ 3] X 7.48 gallons/scf = 5496 gallons of storage.

You could put faster compressors in the trim position. We could also change the demand event by changing the ramp rate of the event or providing dedicated storage at the point of use. You could also increase the operating pressure of supply and keep too much energy on all of the time. This, of course, could cost a great deal more capital and and a significant increase in operating cost. Control storage is essential to all systems. Considerable thought should be given to its design and use.

* This assumes that the atmospheric pressure is at sea level. 2

## ATTACHMENT B

### Constituents of Supply Energy 2

Once we have determined the constituents of demand in the system, we need to determine how effectively we are using energy to support the usage. The demand usage is a constituent of the supply energy. There are a number of ways that energy is consumed in an industrial air system besides the obvious. Some of these are very interactive with each other and some with artificial demand. Although it is difficult to isolate their impact on an individual basis, we will attempt to do this to the best of our ability to help the reader understand the issues which must be coped with in a typical compressed air system. Please remember that air systems are extremely dynamic. The following are the constituents of energy in the typical system including descriptions and influence on total systems energy requirement:

1. Demand Usage - the amount of energy necessary to support the consumption assuming no inefficiency in the system.
2. Intake Air Temperature and Relative Humidity - using standard conditions as a normalized value, higher temperatures at the inlet of a compressor provide less dense air and result in less compressed air mass using less energy. Because the compressor produces less results in terms of mass or work energy, more energy is required to produce the identical results systemically achieved at lower temperatures. When the inlet air represented is based on volume with no regard to density, one can easily overlook this issue and the corresponding energy required. When the temperature drops the air is more dense and the compressor will produce more mass to the system using more energy. As work energy in the system is our objective, inlet density or mass is a necessary component of determining the power required, and the number of compressors to support all conditions relative to the system. At 0 ° F without the effect of relative humidity, you will produce close to 12% more air by mass and an equivalent amount of energy. At 100 ° F without the effect of relative humidity, you will produce more than 7% less air by

mass and an equivalent amount of energy. Higher relative humidity implies that there is more water present in the air at the intake of the compressor. As you cannot compress water, the water by percentage of total mass reduces the amount of net air that can be compressed. Relative Humidity can influence the net result by as much as 3.5% less displaced mass to as little as an immeasurable influence. When you combine temperature and relative humidity, you can have as much as a 22.5% swing in performance on the compressor/s in the system from 0 ° F @ 1% relative humidity to 100 ° F @ 100% relative humidity. When you compare the demand requirements including trim and conditional loads against the inlet condition profile, the amount of energy that you will need will be a function of the size of the compressors used. The larger the compressors as a percentage of the total requirement, the more part loaded a large unit will be depending on conditions and load. The smaller the compressors are, as a percentage of the total requirement, the less part loaded any one compressor can be. When properly controlled, the arrangement and size of the units verses the needs profile, can represent as much as 33% less power systemically at the lowest temperature and load.

3. Compressor Optimization - the objective is to get the most mass per kilowatt of electricity. The more mass that you can achieve in any one compressor in the system, the fewer compressors you will need to accomplish the same results. On positive displacement compressors, the volume is fixed within the operating pressure of the compressor. As you elevate the pressure within this range, the volume will remain constant as the pressure and power increases. This is an increase in mass. As you exceed optimum, the mass will become constant and/or the motor efficiency will begin to drop. Our experience is that optimum will be achieved within a compressor frame range at a higher pressure in the bottom of the frame, and at a lower pressure in the top of the frame. On centrifugal or other types of dynamic compressors, optimum is achieved in a slightly different manner. Optimum would be achieved at full load on the curve below the set pressure and above the choke zone. You would have to determine at what pressure you would displace the most mass per kilowatt of electricity. Unlike the positive displacement compressor, there will be a *portion* of the curve where you will achieve optimum rather than a specific pressure. The confusing issue with this type of compressor is that the curves moves with changes in inlet temperature. It will drop and move to the left as the inlet temperature increase, and rise and move to the right as the inlet temperature drops. This would require adjusting the operating pressure and the current limit adjustments on temperature change to stay within this optimum range.The number of stages and the design will determine at what range of pressure this can be achieved. As the pressure drops on a dynamic compressor, the volume will increase in order to maintain mass. As you drop below optimum moving down the curve, the volume will begin to diminish. At this point, you will begin to lose mass as the kilowatts continue to increase or become constant. If you continue down the curve, the volume will become constant as the pressure drops and the energy drops. This is referred to as the choke zone. In the choke zone, you lose the advantages of this type of compressor. Further on down the curve the volume will diminish as the pressure drops. This more than linear loss of mass is called "stonewall".

4. Compressor Cooling Temperature - all compressor performance is to a larger or lesser degree influenced by the temperature at which we cool the unit. There is a considerable difference in types of compressors. The displacement can be influenced by .5% to 3.5% of rated capacity for every 10 ° F increase over rated cooling media temperature. The inherent inefficiency, combined with the range of cooling media temperature and the maintenance condition of the coolers on the compressor, can effect the displacement efficiency by as much as 25% on the most temperature sensitive types of compressors.

5. Systems Storage verses the Rate of Flow of the Largest Event in the System verses the Time Required to Load the Next Available Compressor. The more storage capacity you have in the system, the less the pressure will fluctuate on any event occurrence in demand. This will allow you to maintain all of the compressors, that need to be "on", closer to optimum. The slower the speed that it takes to turn on the motor and load the next compressor, the more the pressure will drop. You should be able to add trim compressors with a minimum delay when they are necessary to the system. When this process doesn't work well, and the pressure fluctuates too much, the normal reaction is to put all compressors in modulation and keep on line regardless of demand. This will avoid the fluctuation or pressure decay, but not without a considerable increase in energy and operating cost.

6. Resistance to Flow in the System's Piping and Downstream Point of Use Components. The highest point of use pressure requirement is determined by the highest article or inlet pressure plus the highest installation differential across the point of use transmission components such as filters, regulators, lubricators, disconnects, hose, and fittings. Original equipment manufacturers install smaller transmission components with high $\Delta P$'s to control there manufacturing costs and expect the user of this equipment to provide a high initial pressures from the plant air system to compensate. The highest differential is achieved at the highest flow, highest inlet temperature, and the lowest pressure. Compressor manufacturers report that elevating the pressure 1 psig will increase the power by

1/2% of the total connected on board energy. If you are operating with the compressors in load-no load and the elevation of pressure does not increase the demand in the system, then this is true. Unfortunately, most systems are in modulation and do not have a demand control or expander, the elevated pressure will cause demand to increase. The demand increase will be a function of the percentage of unregulated demand including leaks and points of use with regulators adjusted to the max. The power will increase proportional to the pressure increase adjusted for the percentage of unregulated demand plus the 1/2% per 1 psig rise. If the increased demand does not require an added compressor, and the change in pressure does not effect the performance of the on line compressors, the influence on energy will be between .5% to 1.575% of the total connected bhp from 100% regulation at the point of use and no leaks in the system, to 0% regulation plus leaks respectively per psig. If you are in modulation, and you must add another compressor in order to increase the pressure, the new compressor will support a portion of the added load, but the total volume will be shared across all modulating compressors. This can be so inefficient, depending on the degree of part load prior to the add, that the effect of a pressure increase can be as high as 25% or higher for a 1 psig pressure increase if another compressor must be added. We haven't seen a system without leaks, nor 100% regulated below the lowest compression pressure. So much for the 1/2% per psig of pressure rise.

7. Differential Pressure Across Supply Components Downstream of the Compressor Control Signal Location - the differential influences systems energy in the same manner as in item 6. Filters that degrade will cause the downstream pressure to drop. Typical of these components would be aftercoolers, separators, filters, and dryers when the compressor signal is located upstream of the aftercooler. What is unique is that the differential will ride on the system's pressure and drive backwards into the compressor/s operating pressure signal. If the operating philosophy is to turn on compressors to maintain a system's pressure of 100 psig, the pressure drop across the clean up equipment will drive the control signal up accordingly. If the clean up ΔP is 10 psig, the signal pressure would have to be maintained at 110 to maintain a system's pressure of 100 psig. As you need more air, the differential will increase at a higher rate of rise than the dropping system's pressure. The more you need, the harder it will become to satisfy the demand, and the more likely you will turn on the next available compressor.

8. Higher Internal Pressures Resulting from Differentials Across Components Upstream of Compressor Control Signals. This is where the compressor control signal is downstream of the same components as in item 7. In this case, the differentials increase the internal pressure in the compressor. In this case only, the compressor energy will increase 1/2% per psig for this internal pressure rise. This is only true as long as there is motor capacity available. Once you have consumed all of the available energy, either the displacement will diminish, the motor will overload depending on the compressor type, or you will have to add another compressor. The differential will rise and fall with change in compressor demand, but the system will not see the effect of this, only the drive motor.

9. Resistance to Flow on Inlet Filters and Their Effect on Reduced Inlet Pressure to the Compressors. As the inlet filter dirt loads the dry inlet throat, pressure drops proportionately. If the compressor is not fully loaded, it will increase in load to achieve the same result at the reduced inlet pressure. The effect will be different depending on how the compressor is operating. If you are in load-no load, the increase in bhp will be proportional to the ratio of the inlet pressure reduction to the atmospheric pressure. If the compressor is in modulation, the effect can be from more than linear to less than linear depending on the load on the compressor at the time that the inlet pressure reduction occurs. Power is anything but linear in modulation. Based on manufacturer's recommendations for filter changes most systems will increase power by 2.3% to 3% between clean inlet filter and sufficiently dirty filter to require change. If this causes the need for another compressor, the influence increases the power dramatically.

10. Inefficiencies Resulting from How the Compressor Controls are Set Up and Their Effect on Unit Performance. The effect can increase energy from a modest amount of added energy to 33% of the total connected kilowatts. This is a very complex matter requiring a great deal of understanding. Please refer to the "Compressed Air Systems-Solution Series" section 7 on compressor controls. 2

## REFERENCES

1. Load Shaping© is a copyright and trademark of Applied Product Technology, Annapolis Junction, Maryland
2. The Compressed Air Systems Solution Series, R. Scot Foss, Published 1994, Bantra, Charlotte, NC