USING PRESSURE POWER GRAPHS TO ANALYZE COMPRESSOR SYSTEMS

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ABSTRACT OF A THESIS

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Masters of Science in Mechanical Engineering

Air compressors and air compressor systems have worked their way in and slowly become ingrained into the workflow of manufacturing plant life, and for better or worse, plants do not seem to be inclined to switch pneumatic processes for electric processes. This is better because, pneumatic systems are easy to implement, and easy to operate. This is worse because air compressors are quite complex and hard to operate ideally. An air compressor operating in an unideal state could rack up thousands of additional dollars in energy cost, and significantly reduce the life of the compressor. Air compressors and air compressor systems have so many different settings and possible control schemes, that it is often the case, that compressors will be set to the wrong control scheme.

The pressure power graph is a new style of graphing that plots the compressor output vs the compressor power input. Rather than a time dependent graph, this provides a control map of every possible location that the compressor could be operating. This operating map displays many different compressor settings that would not be obviously clear otherwise, and shows clearly what control scheme the compressor is operating in. The map provides information on what setting to change in order to improve the quality of air pressure and reduced energy cost of the compressor. More important though, this map show how to quantify exactly how much change these different settings will make.

CERTIFICATE OF APPROVAL OF THESIS

USING PRESSURE POWER GRAPHS TO ANALYSE COMPRESSOR SYSTEMS

by

Joshua D. Daugherty

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DEDICATION

This thesis is dedicated to my close family and friends

who supported me throughout my education.

Thank you for your support.

ACKNOWLEDGMENTS

I would like to acknowledge everyone who make this thesis possible. I could never have finished this on my own, and it is because of these people that I was able to finish. First, thanks to Dr. Glenn Cunningham, my advisor for teaching me about energy assessments, both in the classroom and in the field. He taught me all I know, and probably much more, about energy conversions and quantification.

Also thank you to Mr. Tony Taylor, who provided the thesis statement. He works in the industry with air compressor analysis and so his knowledge of air compressors provided clarity at times when it was most needed.

Last, thank you to the Industrial Assessment Center for hiring me, providing the funding needed for graduate school, and teaching me skills that have shaped me into the engineer I am today.

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CHAPTER 1: AIR COMPRESSORS TODAY

The use of compressed air can date back as far as one would care to go depending on the looseness of the term. This paper will not dive into the intricacies of how lungs are technically a compressor with a maximum load of approximately 0.08 Bar, or how a fan is a small-scale centrifugal air compressor. Instead, this paper will start with Viktor Popp, an Austrian engineer, who in 1888 built the first commercially useful 1,500 kW air compressor (Compressed Air Systems, 2016). After this, designs for centrifugal and screw air compressors came later on in the 20th century. Today, almost every industrial plant uses compressed air in some form or fashion, and from the benefits it's easy to see why. Pneumatic tools cost around half of the battery or motor competition. Pneumatic tools are lighter than the competition. Pneumatic tools don't spark, which can be necessary depending on the working location. Compressed air today powers hand drills, cyclone chillers, pneumatic transportation tubes, aerators, presses, plastics extruders, valve switches, cleaning air blasters, paint guns, and so much more (Oladner, 2019). In order to facilitate this load, most manufacturing plants will have a compressor or general maintenance room to hold all of the machinery required for compressed air. In general, "compressed air is used widely throughout industry and is often considered the 'forth utility' at many facilities. Almost every industrial plant, from a small machine shop to an immense pulp and paper mill, has some type of compressed air system" (U.S. Department of Energy Efficiency, 2003).

There are several different types of compressors. Centrifugal and screw compressors have already been mentioned before. There are also scroll compressors, which are common in AC chillers. Reciprocating compressors were more common 20 years ago, and are still widely used for smaller portable compressors. The different types of compressors, can more easily be described as a tree, shown in Figure 1 below (Madman, 2007).

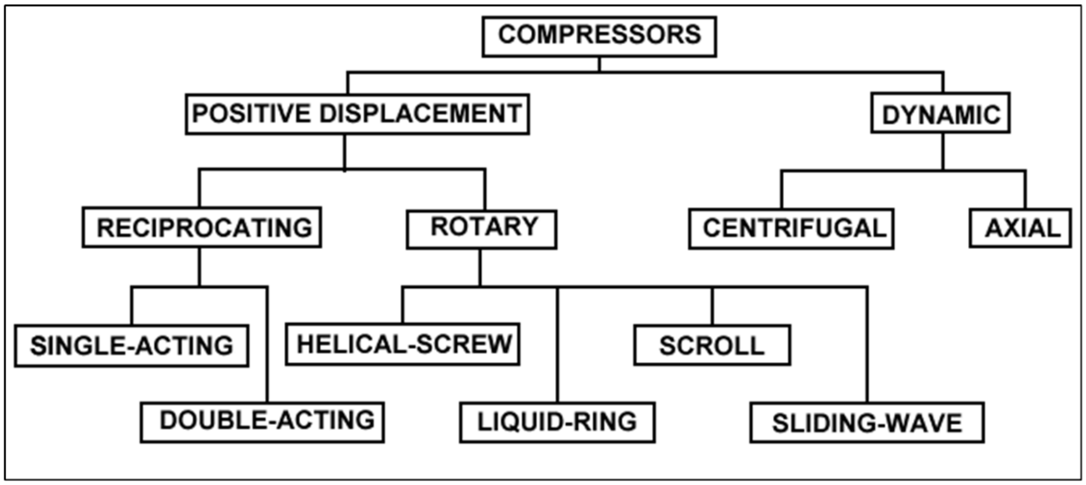

Figure 1: Compressors Family Tree

Here it can be shown that the first compressor distinction is between dynamic and positive displacement. Dynamic compressors use a combination of velocity and pressure to generate the required compression in the air. Dynamic compressors can be thought of as a giant high-speed high-pressure fan, that moves air from an area of low pressure to an area of high pressure. This thesis will not cover dynamic compressors. The other side is positive displacement. This style of compressor creates compression by shrinking the control volume holding the air, and displacing it into a state of higher pressure. The two main classifications for positive displacement is reciprocating and rotary compressors. Reciprocating compressors use a piston to pump air from low to high pressure. The piston will have a drive stroke and an intake stroke. The compressor will only additional compressed air during the drive stroke and for the intake stroke the load on the motor is significantly less. This creates vibration in the compressor and inconsistent air flow. This thesis will also not cover reciprocating compressors. Rotary compressors are significantly different from reciprocating compressors in that they use different styled dies that create consistent air flow. This also reduce vibration considerably. There are several different types of rotary screw compressors, but this thesis will focus entirely on the helical-screw style of rotary compressor (Madman, 2007).

Helical screw compressors use a matching male and female helical screw to create continuous positive displacement (U.S. Department of Energy Efficiency, 2003).. The male and female screw cross sections are shown below in Figure 2.

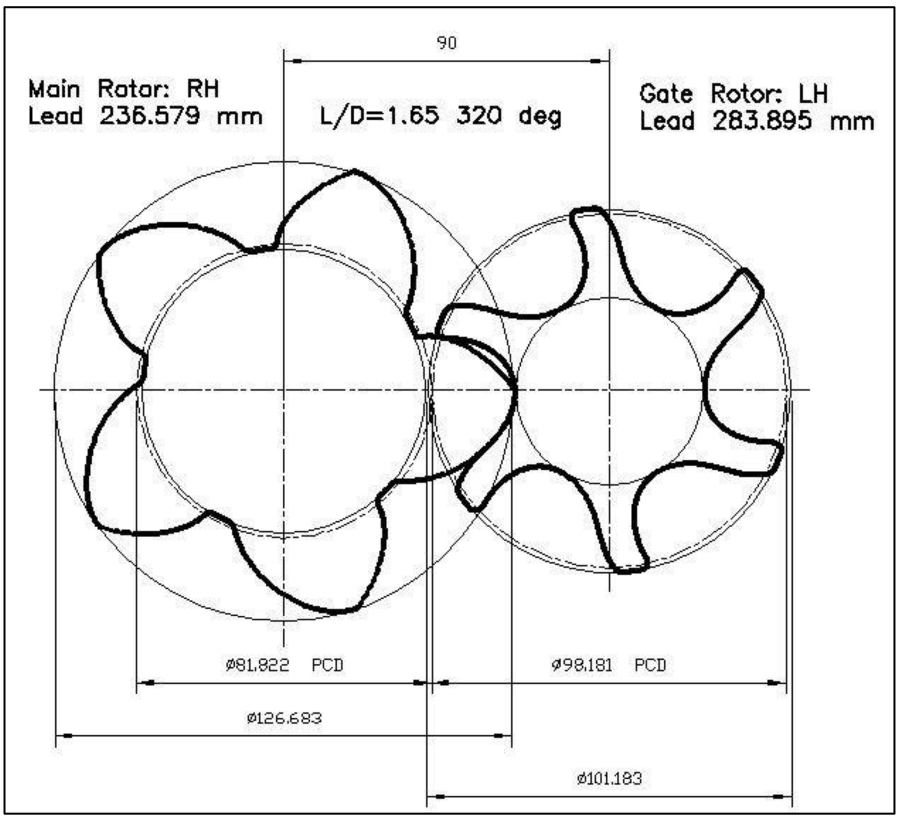

Figure 2: Compressor Screws-Cross Section

The helical screws change shape along the die causing the volume of the air cavity to constantly shrink until it has compressed the air to the rated pressure. Once the air is properly compressed, it is forced out through the high-pressure side of the die.

Compressors may also include inlet air filters for air purity, oil injection for cooling and sealing, one-way valves for improved performance, aftercoolers, to remove excess heat, and oil extractors for air quality control. These features, and other components shown below in Figure 3 are a short list of what make up the components and process of all screw compressors (Rotary, 2020).

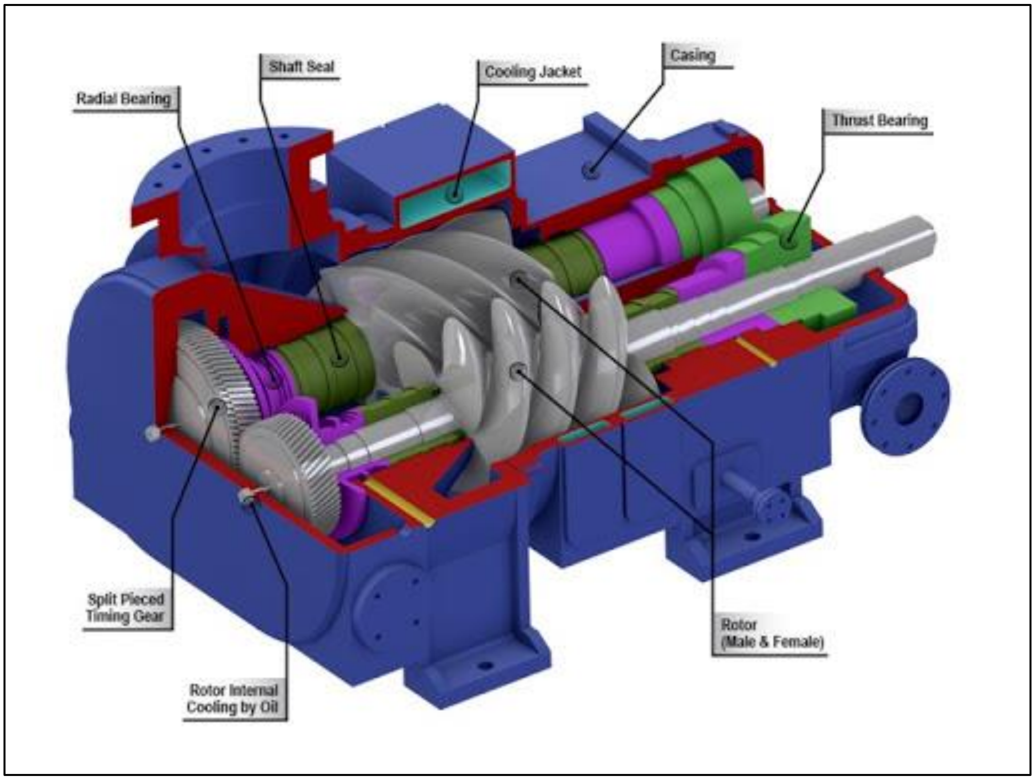

Figure 3: General Diagrams of a Screw Compressor

Table 1: Brief Component List

Item	Description	Notes
Inlet air filters	Cleans air into the compressor for compressor life	Not depicted
Timing Gear	Used to keep Male and female rotors in sync	Depicted
Cooling Jacket	Fits around Rotors, for heat and noise isolation	Depicted
Lube well	Holds lubricating oils for compressor rotors	Not Depicted
Rotors	Physical male & Female components that compress air	Depicted
One-way valve	Prevents backflow from high pressure side into screws	Not depicted
Oil filter	Reclaims oil and cleans compressed air	Not depicted
After coolers	Cool compressed air down to safe temperature, and remove extra moisture from air	Not depicted

The topic of this thesis is on capacity control. Variable production capacity is the root of complication and energy loss. During heavy production times, Plant "A" might use 650 SCFM. However, during break time, or if a line of production goes down, that number could drop to half or even less. In order to keep plant pressure during maximum compressed air consumption, the air compressor must be sized for the maximum possible usage of air. However, the plant will rarely use that much air, and will often need less, sometimes much less. Compressors must therefore be sized not only for plant demand, but also for plant variation. There are four main ways that compressors can vary their compressed air production, but before that, it is important to set in place metrics to measure and compare them.

Compressor Efficiency Versus Turndown Performance

Compressor efficiency and compressor turndown performance, while similar sounding, refer to two different measurements. Compressor efficiency is simple enough, and keeps in line with the general definition of efficiency: output over input. Compressor efficiency refers to the amount of energy required to power a compressor at full load per some fixed unit of output. Generally, the units of compressor efficiency are measured in kW/CCFM, or kilo-watts per 100 cubic feet per minute. A standard efficiency for screw compressors is around 19 kW/CCFM, although this can change based on the model, age, or rated compressor pressure. Compressor turndown performance refers to how well it keeps the efficiency as the compressor reduces load. This becomes clearer in a percent power vs percent load graph as shown below in Figure 4.

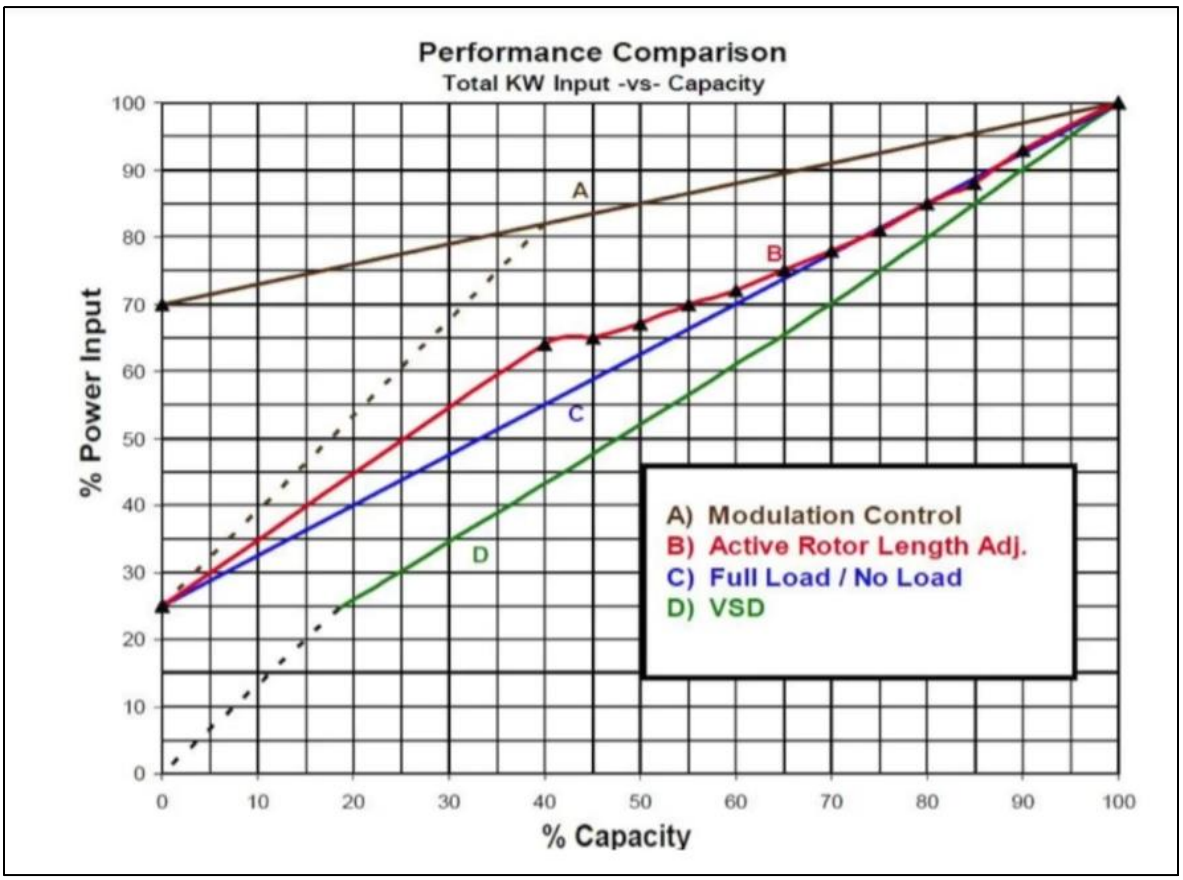

Figure 4: Compressor Preformance Comparison

This graph is normalized in both power and compressor capacity which allows it to represent any compressor size and any system consumption load. Each line represents how a compressor will perform when producing a below rated volume of compressed air. A perfectly ideal system, or perfectly efficient turndown performance could be represented by a line on this graph that is straight between the points (0,0) and (100,100), or in another way, if a compressor produces half of its rated compressed air, it will use half of its rated power. A perfectly wasteful system, or perfectly inefficient turndown performance, would be represented by a line that goes from (0,100) to (100,100), along the top of the graph. This would be a compressor that is always using its maximum rated power regardless of the amount of compressed air it produces. An example of this would be a compressor that runs always at full production, and when it begins to over pressurize the system, a safety valve opens allowing the compressor to vent excess air to atmosphere.

Screw Compressor Control Types

This thesis will cover the four main control schemes for screw compressors: Modulation, active rotor length adjustment, load-unload, and speed control (Roy, 2008). Figure 4 above shows how these control schemes compare to one another. The brown line shows modulation, the green line shows VFD/VSD control, the blue line shows a load/unload oil free compressor, and the red line shows active rotor length adjustment.

Modulation Control

Modulation compressors control volume of air production by controlling the volume of air available for the compressor. This is done with a compressor inlet valve.

As the compressor system requires less than the maximum capacity, the inlet valve to the compressor will begin to close off, throttling the system.

Figure 5: Modulation Inlet Valve

With modulation control, the inlet cavity created by the screws remains the same size. The control comes from reducing the mass flow into the compressor. Less mass flow means less compressed air produced, and less work for the compressor. As the valve closes, the screws generate an increasingly large vacuum on the inlet in order to fill the constant screw cavity size with the reduced air mass. The inlet valve into the air compressor is an example of exergy destruction, which directly effects total efficiency. On the outside of the inlet valve, you have atmospheric air pressure, usually around 14.5 psi, whereas, on the inside of the valve, you have a fairly large vacuum into the screw compressor. Across this valve, the air losses pressure, and generates no power or potential energy in the process. The screws must then work to pressurize air from as low as 1-2 psia back up to the original operating pressure. The reduction in mass flow slightly outweighs the decrease in energy, and the total energy consumed drops slightly. The brown line also shows a dotted line connected to it. The dotted line represents, a second strategy used by modulation compressors when the system consumption load becomes too small, called load/unload (U.S. Department of Energy Efficiency, 2003).

Load/Unload Control

A load/unload cycle is fairly straight forward, shown in Figure 4 in blue. The compressors will purposely over pressurize the system by five to twenty psi. Then, the compressor will turn off, or to an idling state, where the compressor doesn't produce any compressed air. With the compressor idling, the system pressure begins to falls back to the desired pressure. Once the system pressure has dropped back to the desired pressure, the compressor will come back on and start producing compressed air again. During the idling state, the compressor will still be using enough electricity to keep the compressor energized, because, it is damaging for compressor motors to turn on and off repeatedly, which is why in Figure 4, the load/unload cycle passes through 30% power usage at zero percent system consumption (U.S. Department of Energy Efficiency, 2003).

Pressure Band

With load/unload screw compressors, because of the nature of how this type of compressor functions, there is a parameter that is derived from the size of this cycle. This is the pressure band. The pressure band is the range at which the compressor will operate, between minimum pressure, when the idling compressor comes on, and the maximum pressure, when the loaded compressor unloads (Gopalakrishnan, 2014). An example of a compressor running the load/unload cycle is shown below in Figure 6 which plots the compressor operating pressure vs time.

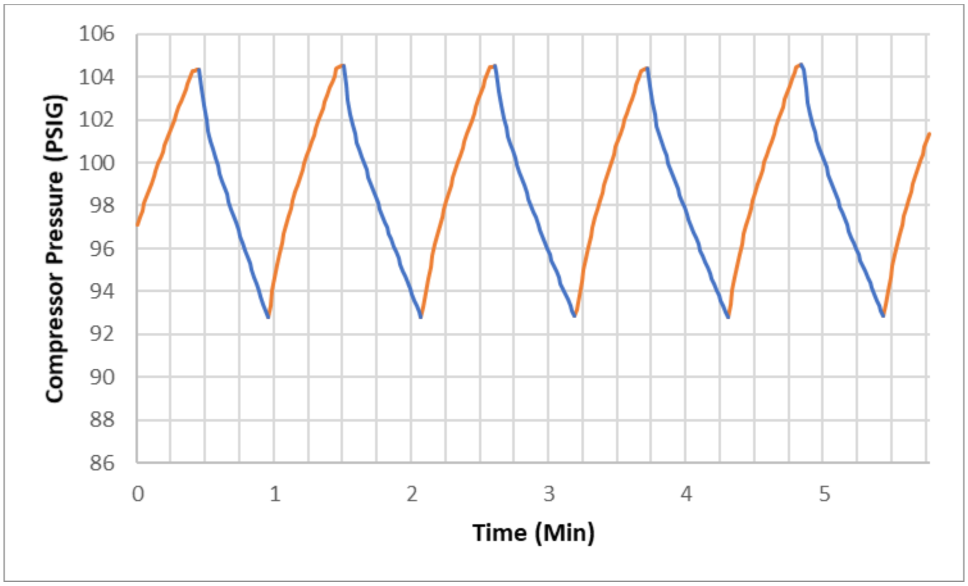

Figure 6: Simple Pressure Band

This pressure band is usually between 10 to 15 psi. In this case above, the pressure range goes from about 92.8 psig to 104.2 psig, resulting in a pressure band of 11.4 psig. In Figure 6 the orange line corresponds to the pressure when the compressor is loaded, and the blue line corresponds to the pressure when the compressor is unloaded. The reason pressure band is an important parameter is because the pressure of the system can impact both the energy consumption of the compressor, and the operation of the compressor system. Some pneumatic tools are calibrated so they can only operate on a very specific pressure. The system displayed in Figure 6, would not deliver sufficient pressure stability required for a tool like this. Decreasing the pressure band from the 15 psig down to 2-3 PSIG can have several different consequences though. The compressor will experience increased wear, as it is forced to cycle much more frequently, and the energy consumption will rise due to sump blow off.

Sump Pressure

Sump blow off is only an issue in the load/unload compressor style, and then only for lube injected compressor. Lube injected compressors are as simple as the name sounds; screw compressors with oil injected into the screw with the inlet air. This is for better sealing around the screw, better heat dissipation, and reduced friction. Oil free compressors alternatively do not use any oil for lubrication or heat dissipation in the screws, which results in less efficient compressors and hotter compressed air. Oil free compressors are however required in certain applications where the compressed air is required to be cleaner. Oil free compressors do have one significant energy advantage over lube injected compressors, which is in sump blow-off. Unlike oil-free compressors, the typical power consumption during idle is “15-30% of full load power consumption. However, for lubricated screw compressors, this low power level is reached only after the pressure in the separator has been relieved” (Mehltretter, 2014, p. 26).When lube-injected screw compressors unload, they can only reduce pressure in the screw chamber to a certain pressure, because of the high-pressure oil in the chamber. If the pressure on this oil is released too fast or too substantially, the oil can foam up and be blown out of the compressor with the compressed air. Oil free compressors, however, don’t have this problem because there is no oil to foam up, so instead, they can release all the pressure and idle with much less power usage (Mehltretter, 2014). Figure 7 below shows, the difference between the unload of a lube injected and an oil free screw compressor.

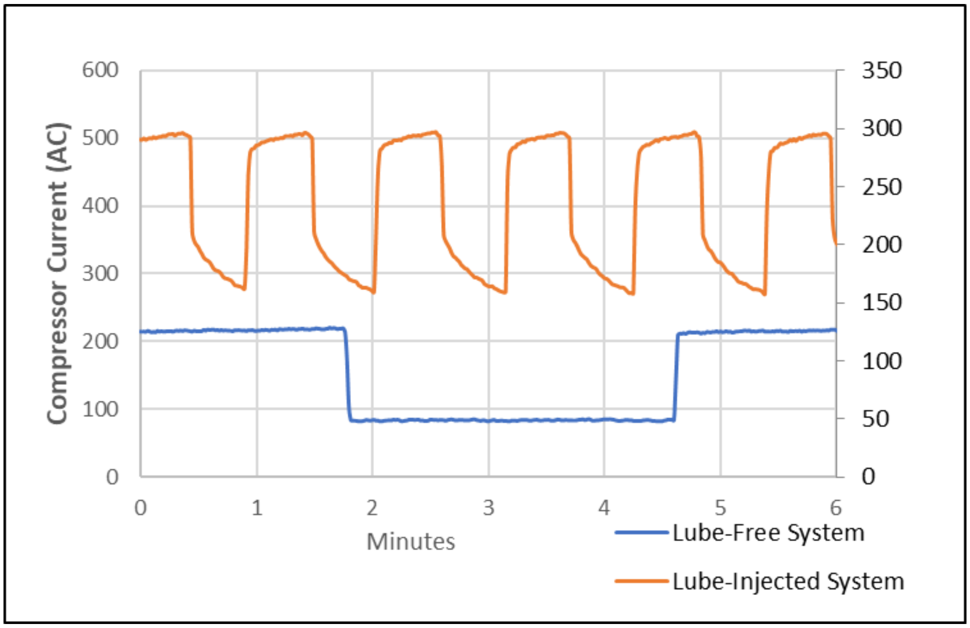

Figure 7: Sump Curves for Lube VS. Oil Free Screw Compressors

Active Rotor Length Adjustment Control

Active rotor length adjustment screw compressors operated in a slightly different way. These compressors have methods to shorten the length of the screw compressor. This is usually done by changing where the screw is separated from the inlet air cavity. For slider control more of the screw is exposed with a retractable manifold. The more the screw is exposed, the smaller the active section of the screw gets, and the total compressed air volume is reduced. Poppet valve control works in largely the same way. Poppet valves are positioned along the side of the screw manifold. The open valves give an escape to the air that would be compressed by the screws. The screws are unable to begin compression until after all of the open valves. Changing the screw inlet changes the size of the screw cavity. With a reduced screw cavity less inlet air is accepted to the screw, and the amount of compressed air is reduced. This control method is efficient for minor adjustments, but when the control reduction becomes half or more, the efficiency is reduced greatly (Ormer, 2006). This can be seen in performance graph from Figure 4. This is because the screws are sized for maximum compression efficiency. If half of the screw or less is used, the compression will not be as smooth, and there will be a greater generation of turbulence in the air. Other active rotor adjustments exist including step control (similar to valve control), spiral control and turn valve (both similar to slider control).

Variable Speed Control

The last type of screw control is called a VFD compressor (Variable Frequency Drive), VSD compressor (Variable Speed Drive), or sometimes just variable speed compressor. A variable speed compressor controls compressed air production by changing the speed of the motor driving the screw. A variable speed drive uses transistors and capacitors in a creative way to reduce standard 60 hz power, to any reduced frequency of power. Usually they have a minimum speed around 10 to 15 hz, but that will depend on the specific drive. By lowering the frequency of the AC power, the voltage is able to drop linearly with the power output of the motor. The motor can then run slower and use less power (Turkel). This means, the entire screw is still in use for maximum efficient compression. No exergy-destroying pinched valves are used, and there is no wear on the motor or sump curves to worry about. Variable screw compressors, are able to almost perfectly reduce max compressor power with compressor volume output, with only a few percentage points difference in efficiency between maximum compressor production and minimum compressor production. Variable speed compressors also have a limit for how low volume they can operate, set by the conditions of the compressor, but usually around 20 to 25 percent of maximum capacity (Mehltretter, 2014). Further reduced demand beyond, and compressor will be forced into either load/unload or start stop.

Thesis Statement

Air compressors are very complex. Many compressors come with the ability to switch between several different control settings as needed. For example, a compressor might operate in modulation control, until a maximum pressure and then switch to load/unload. A compressor might operate as load/unload, until a minimum set point and then switch to start/stop. Setting the proper control settings for maximum efficiency and turndown performance can be difficult, and is different for every situation, however, making sure air compressors are operating with the most efficient control scheme is vital for cost savings. An air compressor running with the wrong control scheme alone can cost a plant thousands of extra dollars per year, impact pressure stabilization, and even effect the life of the air compressor. Often, these issues are not noticeable, and a compressor can run in a non-ideal state for years with no problems.

This thesis will attempt to analyze the current, or power, and pressure data gathered from air compressors in a unique way. This unique style of analysis should display the cyclic nature of the compressor load cycle much more clearly. The thesis will go over how this style of analysis can show which control scheme a compressor is in, the efficiency of the compressor and the turndown performance, as well as many more specific features for each specific control scheme. The thesis will also go over the use of this type of analysis for fault and issue identification and quantification in the compressor system.

The proposed style of compressor analysis that will be discussed in this thesis is the pressure power graph, which represents the compressor operating state in a graph of compressor power, and system pressure. The pressure power graph can show air compressor cycling in a way that is more complicated to see in current air compressor analysis. Also, due to the cycling nature of the data, hundreds or even thousands of cycles can be placed on top of each other, without obscuring important information.

Thesis Limitations/Restrictions

This paper is not a complete guide to all compressor systems. As shown in the compressor tree figure before, helical screw compressors are a very small subset of compressor styles. However, because screw compressors have a high efficiency and excellent turndown efficiency, it is the main style of compressor used for many industrial applications. Notable additional styles of compressors are scroll compressors for air conditioning units, reciprocating, piston driven mobile compressors, and very large, centrifugal compressors, which all have significantly different compression mechanisms. These styles of compressors and other unique styles, will not be covered in this dissertation.

Conclusion

Air compressors operate in very complex ways, and each of the four control schemes can cause otherwise similar air compressors to operate in completely different ways. The purpose of this study is to try to identify patterns or meaning from air compressor data, that will allow air compressor data to be read more easily, and provide clearer and more quantifiable information.

CHAPTER 2: COMPRESSOR ASSESSMENT METHODS

Air compressor analysis is not a new field. Compressors have been analyzed as long as air compressors have existed. Compressors use a lot of energy, and any energy saving or conservation process can save thousands of dollars per year in energy cost. The first step to managing a compressor system is measuring the system. You can't manage what you don't measure. A larger data set, and more accurate data, yields a more accurate compressor system model, which means better recommendations for managing the system.

There are dozens of different compressor analysis methods. Some of them are specifically for one type of compressor, or one type of compressor control scheme. Some analysis methods give an estimation for the same compressor characteristics, but come from different types of measurements. It is not the purpose of this thesis to cover all of these methods. Instead, this thesis will cover three main types of analysis, how they are run, what they can measure, and some of the limitations that each method comes with.

Compressor Storage Size

The first analysis is over system storage. System storage is important because it dictates how the compressor will unload, and predicts the stability of the system pressure. Compressors with not enough storage capacity can run into problems like massive pressure drops when a pneumatic process uses a large volume of compressed air. Storage analysis is more difficult than it might sound. The storage volume is nothing more than the sum of the volume of every part of the pneumatic system. It is easy to add together the volume of the storage tanks in the system, but after that it gets more complicated. The storage volume is also made up of all the volume in the transfer pipes, any fittings, and any tool specific storage tanks or inlet valves. Sometimes, there will be more storage in the fittings and pipes, than volume in the storage tanks. It would be a nightmare to try to sum up the volume of every tube, fitting and tank. Luckily there are better ways. One way to measure the system storage is from a fully loaded compressor analysis. Based on how fast the compressor can fill the storage system, the volume of the storage system can be calculated. The output volume for a load/unload screw compressor is a fixed volume, and doesn't change based on system pressure. The only thing that changes is compressor power usage. This is because screw compressors are fixed volume machines. With that the storage volume can be found with the following equation.

$$SV = \frac{(FAD - SCD) * (FLT) * 7.48\frac{gal}{ft^3}}{\frac{UP - LP}{14.7}} \tag{1}$$

Where:

SV	=	The system storage volume (gallons),
FAD	=	Free air delivered, or compressor capacity (SCFM),
SCD	=	System consumption demand, (SCFM),
FLT	=	The time the compressor spends fully loaded per cycle, (min),
UP	=	The unload pressure of the compressor cycle, (psig), and,
LP	=	The load pressure of the compressor cycle, (psig).

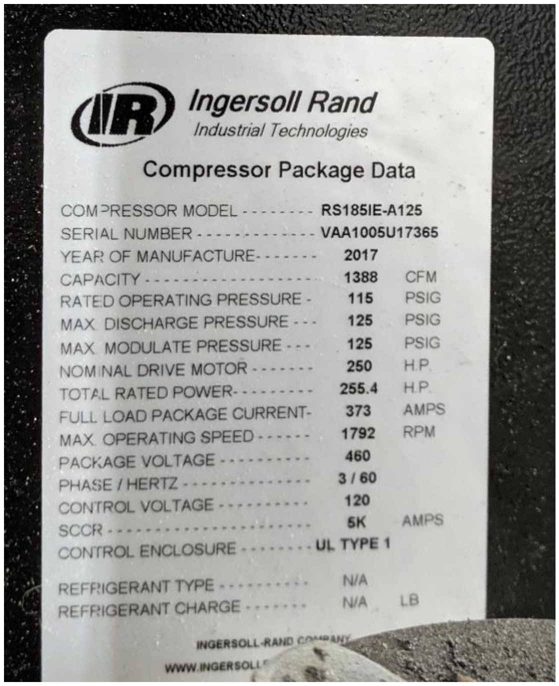

Figure 8: Example of a Compressor Spec Sheet

There is one variable missing from the equation above, which is the system consumption demand, SCD. This value is the average air consumption used by the compressed air system. This value while not a constant, will stay relatively constant through a compressor cycle. This value can be estimated from the average load cycle of the compressor, by multiplying the compressor capacity by the average load cycle over the average full cycle. This method of calculating the compressor system storage size can only be found if the compressor is running at full capacity. A load/unload control scheme always runs at full capacity, when running loaded, but there are many other control schemes which let the compressor run at a reduced rate. This method would not work for those compressor types. If during the data logging process, the compressor systems turn off, and the system pressure drops to zero, the other styles might be able to be estimated as the system re-pressurizes. When the pressure is below the control pressure of the system, the compressor will necessarily be running at full load. If this happens, this method could be used, even for a non-load/unload compressor system, as long as it is confirmed that the compressor is outputting its rated air volume.

Once the system storage volume is calculated, estimating possible energy savings measures is the next step. A standard process for estimating energy consumption, and potential savings is with a normalized storage graph (Marshall). An example of this graph is shown in Figure 9.

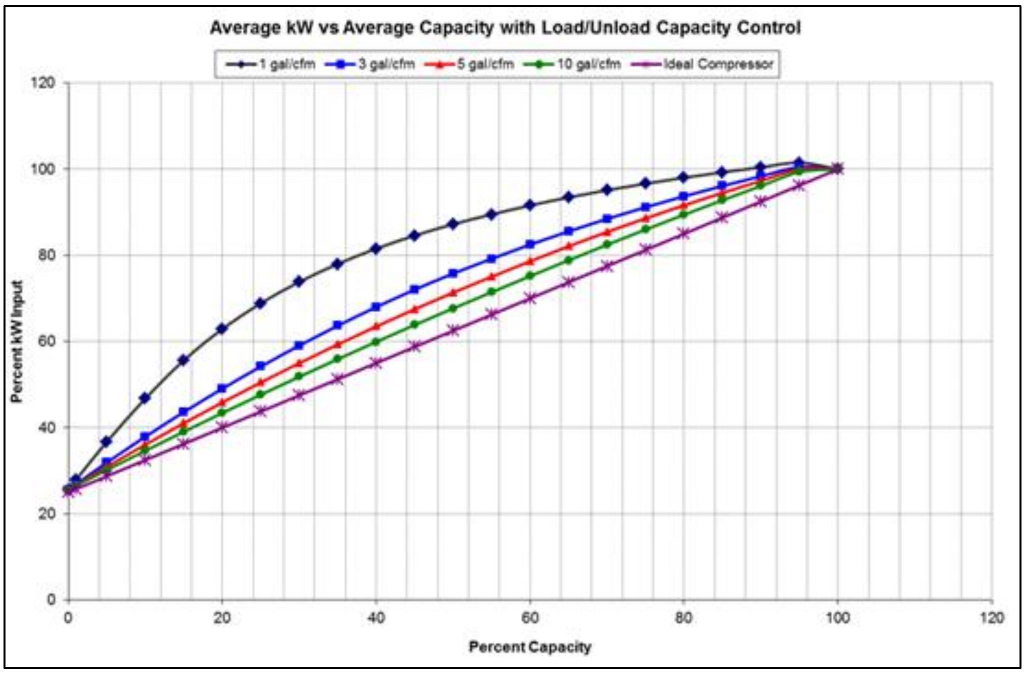

Figure 9: Load/Unload Turndown with Variable Storage

System storage is evaluated in Gallons per CFM, and the chart is in percent capacity of the compressor and percent consumption of the storage system. This makes the graph entirely non dimensional, meaning it can apply to any sized compressor, any sized storage system, and any size system consumption demand. With this chart, it can become easy to estimate how much energy reduction will be generated from an increase in storage volume. It is also clear from Figure 9, that with a system of 1 gal/cfm of storage, adding 1 gal/cfm is hugely beneficial. If, however, a system already has 10 gal/cfm, adding the same 1 gal/cfm is almost insignificant. The ideal case marked in purple represents an infinite volume of storage, and a compressor that is infinitely able to unload the sump pressure to a rated minimum pressure (Gopalakrishnan).

This form of analysis is very narrowly useful. For any compressor type other than load/unload control, added storage is mildly useful. The system storage volume is difficult to measure, deciding on a proper suggestion can be vague, and savings from the suggestion can be complicated estimate. However, when this method works well it produces accurate information about a complicated compressor issue.

System Pressure Efficiency

Many energy saving opportunities stem from changing the operating system pressure. The higher the pressure in the compressor system, the more work is required by the compressor to put the same amount of mass in the system. Pneumatic tools work best with a specific pressure. Below this pressure the tools will work less effectively or in some cases not work at all. To counter this, many compressor systems raise the pressure 10 to 20 psi higher than is required, not realizing that this action results in additional compressor work and added energy cost.

In order to calculate exactly how much additional energy is used for additional compression, the ideal gas equation shown below is observed.

$$Pressure * Volume^{n} = Constant$$

This equation accounts for how an ideal gas (air in this case), will heat as it is compressed. Each gas has a specific heat of compression which is based on how the velocity of the molecules increase when the volume decreases. Molecules with a higher velocity represent higher temperature, and additional pressure (What is Compressed Air).

For air, this heating results in n being set to 1.4 in the previous equation. The corresponding equation for pressure change can be given as:

$$PR = \frac{PP^{\frac{n-1}{n}} - AP^{\frac{n-1}{n}}}{CP^{\frac{n-1}{n}} - AP^{\frac{n-1}{n}}} \tag{2}$$

Where:

PR	=	Power change ratio,
PP	=	Proposed system pressure, (psia),
AP	=	The atmospheric pressure, (psia) and,
CP	=	The current system pressure, (psia).

For a compressor currently at 90 psi dropping to 88 psi, this would correspond to a power ratio of 98.99%. In other words, the compressor would reduce about 1 percent of the energy load for a 2-psi pressure reduction. In general, the 1 percent for 2-psi reduction is a good value to use for estimations for rotary screw compressors. This rule of thumb assumes no change in compressor efficiency. In some cases though, compressor efficiency may be highly dependent on the system pressure. In fact, some compressors may not be able to reduce pressure at all.

Compressor Control Scheme Identification.

The last type of analysis is with time dependent traces of the system pressure and compressor current load. This analysis can show what control scheme is running, and give some insight on how well the system is operating. It is important to first understand the distinction between current and power. Current is one of the variables that make up power. The full three phase equation for power is:

$$Power = \frac{\sqrt{3} * Voltage * Current * Power\ Factor}{1000\,\frac{W}{kW}} \tag{3}$$

Voltage should remain a constant and will probably be 480 volts, but could be anywhere between 110 and 4,160 volts. Power factor is affected by either an inductance or a capacitance load in the electrical system. Partially loaded motors are a large source of inductance, and so partially loaded motors can cause a variation between current load and power load. Luckily, most compressors have enough local capacitance built-in to correct any motor induced inductance, which should correct any potential power factor variation. Because of this, compressor current is assumed to be directly linear to compressor power, and representative variable for compressor power load (Khodapanah). Figures 10 and 11 below show examples of this type of analysis.

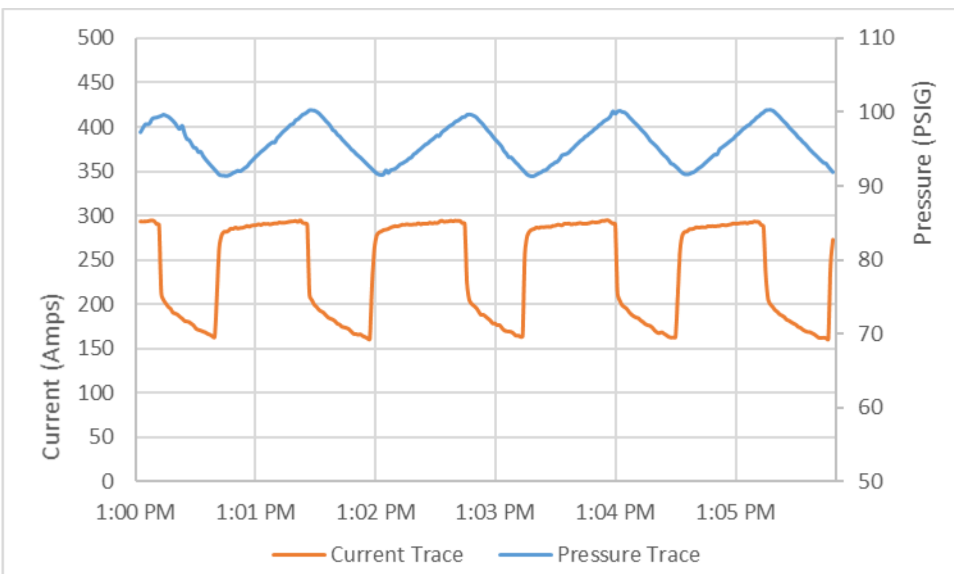

Figure 10: Load/Unload Control

Figure 10 shows an example of a screw compressor running load/unload. Load/unload control compressors will trace a very specific pattern. First the compressor will load to a full load amp rating. This is shown to be about 350 amps in the figure. While the compressor is at full load, the pressure in the system will slowly rise from a minimum system pressure to a maximum system pressure. This is displayed in Figure 10 by the blue line moving from about 92 psig to 101 psig. When the pressure reaches a maximum the compressor will unload, and the current will begin to fall along the sump curve. The time-dependent sump curve is displayed in Figure 10 by the orange trace. While the compressor is unloaded, the pressure will begin to fall back down to the minimum system pressure. This is displayed in Figure 10 by the blue line falling from 101 psig back down to 92 psig. Once the minimum system pressure is reached, the compressor loads again which completes the full cycle.

This style of analysis is very good at displaying some kinds of data. The pressure band is clear from this chart. Pressure band is an important characteristic of any load/unload compressor system because it dictates how the compressor will load, and affects compressor turndown efficiency.

The pressure current trace is also good at displaying the size of each cycle. In Figure 10, it is clear that there are just over 4 full compressor cycles. It is easy to tell about how long the load section of each cycle is, and from that it is easy to estimate how loaded the compressor system is. From the load/unload specific cycles, a lot of useful information about the compressor and about the compressor system can be determined.

The pressure current trace is also good at showing the sump curve. The sump curve is the section of the current trace (orange line) after the compressor has unloaded. The sump curve can look very different for each compressor, and analyzing its shape can help to identify potential problems or potential energy savings opportunities in the compressor system.

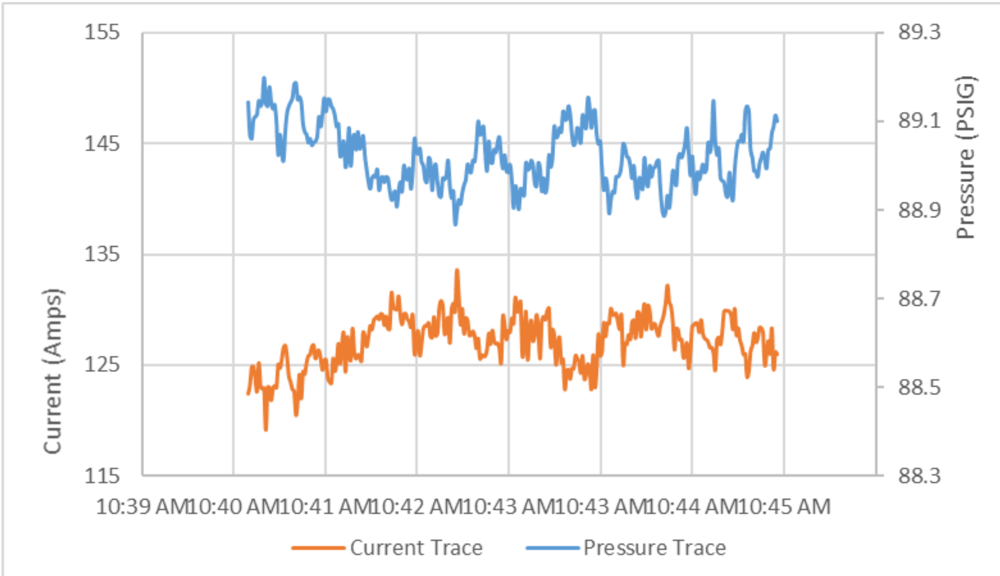

Figure 11: Variable Speed Control

The pressure current trace is also good at identifying variable speed compressor. Figure 11 shows an example of a variable speed compressor. This type of compressor control does not run in a cycle and the four stages that were seen in Figure 10 will not be displayed in Figure 11. In a pressure current trace of a variable speed compressor, the pressure trace will usually look like the inverse of the current trace.

The current trace of a variable speed compressor can show the range of system consumption. At minimum system consumption the current will be at the minimum, while at maximum system consumption the current will be at the maximum. This usually requires a very long trace to be accurate and the more data in the trace, the more difficult the trace becomes to read. On a shorter scale, the current trace can show the consumption stability. If there is a process in the system that uses a significantly large portion of the total air consumption, this would be seen either as a system pressure drop, or a responding compressor current spike.

Pressure current traces are very good for estimating several different compressor and compressor system characteristics. Generating pressure current trace graphs are relatively easy, and collecting data for this type of graph does not require complicated equipment or need very long sample times. There are some restrictions and limitations to the pressure current trace though. Pressure current traces are not designed to analysis days of day at a time. Figure 10 and Figure 11 both contain 5 minutes of data, which is usually an appropriate length for the trace data. If analysis was run for a full day, Figure 12 would be the resulting diagram.

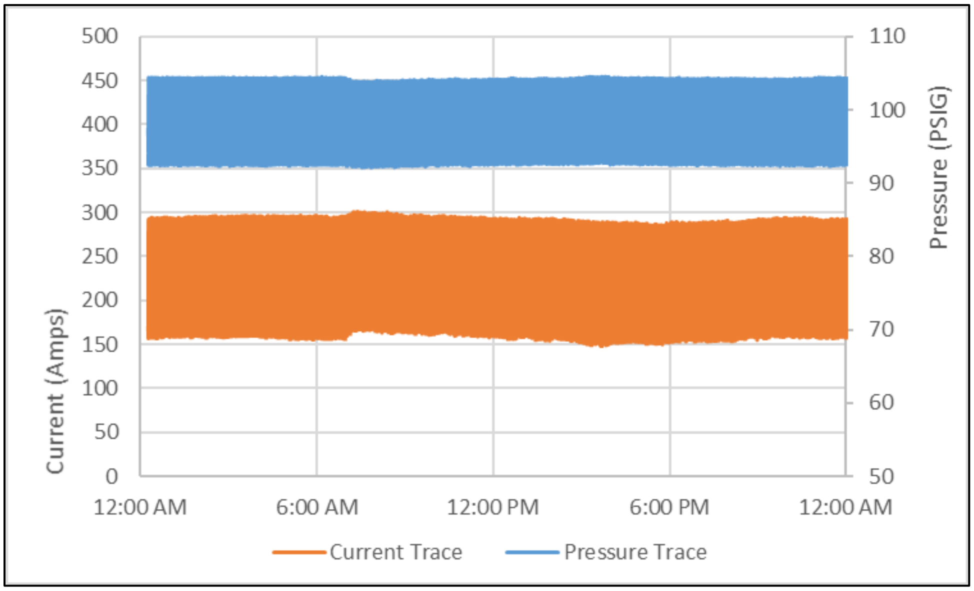

Figure 12: One Day Trace

This is just an example of one day of data, but there are time dependent processes in compressor systems that happen only once per week. The best analysis would cover one week of data, or 7 full days. These week dependent issues could be things like compressors unloading during the weekend, or a specific pneumatic process in the plant that only happens once per week. This type of analysis is not designed to display results for that much data at a time.

Another problem with this analysis process is that it is very confusing. A trained eye could look at a pressure current trace and determine what control scheme the compressor is running in, what set points are running on the compressor and many different characteristics about the compressor system. For an untrained eye, however, it is difficult to see what the compressor is doing during any specific time.

Conclusion

This is an incomplete summary of these three compressor analysis methods. Only the most important sections of each were covered. In addition, there are several other methods for analyzing compressors and compressor systems. The purpose of this chapter, however, is not to give a complete study on types of compressors and compressor analysis, but instead to illustrate what compressor analysis looks like, and to explain some of the common issues or difficulties with compressor analysis. Better understanding of modern analysis methods will help provide background for the actual study about pressure power graphs.

CHAPTER 3: METHODOLOGY OF DATA COLLECTION AND CODE DESIGN

The previous chapter talks about how current analysis of air compressors is performed. The usefulness and the short comings of each method were explained. The pressure power graph analyzed in this thesis uses the same two data inputs as previous compressor analysis methods: Compressor amp ratings (or compressor power) and compressor system pressure. The difference is that this analysis uses a computer to generate and analyze more compressor data than any human could ever dream of. This chapter will discuss why the data is processed the way it is, and cover some of the important differences between data selection and plot generation.

Computer Analysis Issues

Computers, while superior in processing power, are entirely stupid. Because of this, there are some major concerns that need to be addressed when processing data through a computer. These issues are so simple that for normal human analysis, they are not an issue, but for computers they must be identified and quantified clearly. The main three issues in question are outliers, insignificant data, and data overflow. Each of these three concerns need to be acknowledged and addressed.

Outliers

Outliers are easy to spot in real data and ignore, because other than these outliers, the data follows a specific curve. These outlier data points are infrequent, but differ significantly from the expected values. For computer generated graphs, extra precautions must be taken to removed outliers. Outliers can be caused by several different things. Inrush current is a major contributor to outliers because while loading the motor, the power can jump to almost ten times the max rated power on the compressor. This current spike only lingers for one or two seconds (OTRM 6). There can also be outliers due to faulty sensors. If the inrush current is normal, and the sensors are not misbehaving too badly, these outliers should never make up more that one to two percent of all data, and they shouldn't affect the general shape of the graph. Outliers can, however, cause disastrous changes to the maximum and minimum values recorded. For these reasons, extra precautions must be taken to identity outlier data and remove it from the analysis.

Insignificant Data

Insignificant data in this case refers to data where the compressor is not running, or the system is not pressurized. With previous methods of analysis, it is easy to custom select data where the compressor is running and avoid insignificant data. With automatically analyzed data, however, extra precautions will need to be taken in order to make sure the program can ignore insignificant data.

Overflow of Data

The benefit of looking at a week's worth of data, is that any process that happens, even if it only happens for a few hours will be documented. Previous compressor analysis methods would have no chance of finding a time dependent inconsistency unless every section of the data is analyzed individually. On an hour scale it is inconvenient, but on a week scale it is preposterous. A pressure power graph is designed to display a week's worth of data. A week's worth of data collected on a second interval totals to 604,800 data points which poses a problem. That many data points would make any graph unreadable.

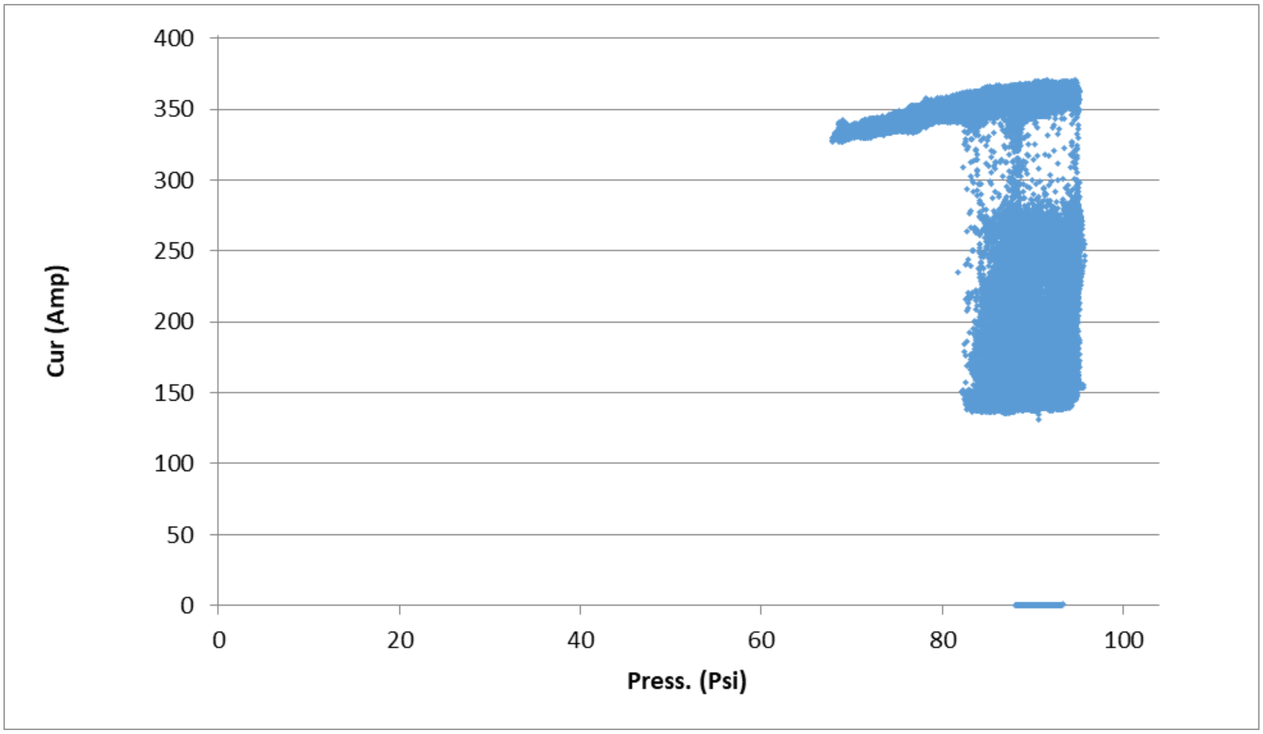

Figure 13: Pressure Power Graph with Over 600K Data Points

From this graph, some compressor operator setting values are clear, like pressure band and minimum sump current. However, so much data is in such a small space that the data begins to mask itself. There are several possible solutions. One is to shorten the time period that the data is collected. This, however would limit one of the pressure power graph's greatest strengths: to analysis as much data as possible. Another solution is to make the graph much bigger. This solution would probably work, but the graph would need to be quite large in order to properly space the data points, and it would reduce ease of use which is the pressure power graph's main goal. It also doesn't fix the problem that, plotting so much data is graphicly intense and difficult even for a computer. A third solution is to thin the data set, by only plotting some data points evenly throughout the data set. This is similar to the first suggestion but works much better because data set still represents each of the days from the sample time. Also, when enough cycles stack on top of each other, individual cycles become meaningless, and the average direction of the data can be easily visualized. Figure 14 shown below illustrates the same data plot as before but thinned down to 20,000 data points. For this data set, 20,000 data points represents 1/30th of the total data.

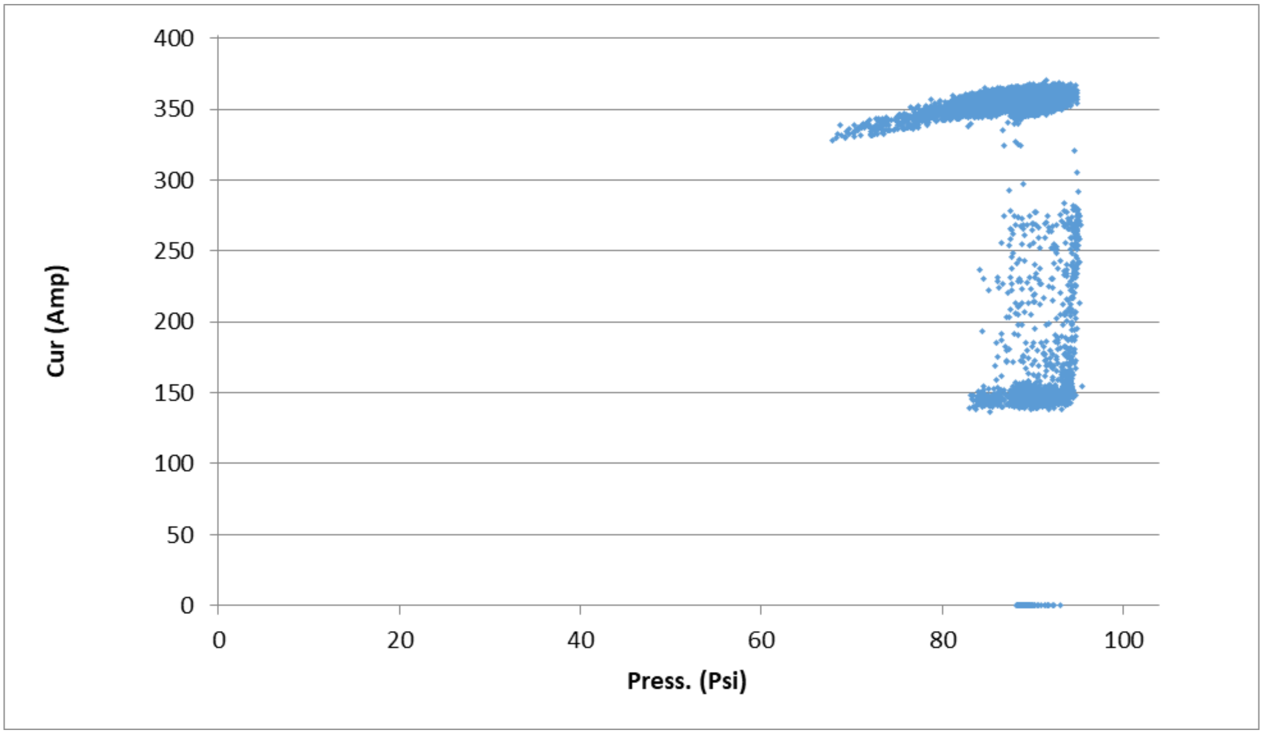

Figure 14: Properly Scaled Data

The graphing script is written in Visual Basic for Office 2010. The loading script file accepts .csv file type. The reason Excel and .csv are used is to make this code easily usable by other people.

The code is broken down into two script files. First is a load script file which loads a .csv file into the worksheet. The second is the analysis and graphing code which runs some data analysis and displays the proper graphs. The code is broken into two script files because, the .csv file could contain several different compressors worth of data, and a user might not want to reload data, but instead just reload the analysis with a different set of data.

Load Data Script

The load data script cleans up the excel file, deletes any old charts, and prepares to load new data. The script then prompts the user to pick a .csv file with data included. The data file should have headers and the data section should not contain blank spaces. If there are sections where no data is collected, those rows must be removed. All of these changes can be made after the data is loaded into the excel file. Excel 2010 has a set maximum number of rows at 1,048,576, which would result in 12.1 days of data collection at one second interval. For longer sample times than that, the data collection interval must be increased so that fewer data points are analyzed. A user who didn't have the data in a .csv file could manually load data by adding the data to a worksheet labeled, "Input Data"

Normalize and Plot Script

The normalize and plot script file can be broken down into three main sections: data recognition and loading, data processing, and chart plotting. This script also goes through some basics cleaning as well before it really starts. Once all output worksheet cells and charts are erased, the first section begins. Figure 15 gives a basic flow diagram of the script file.

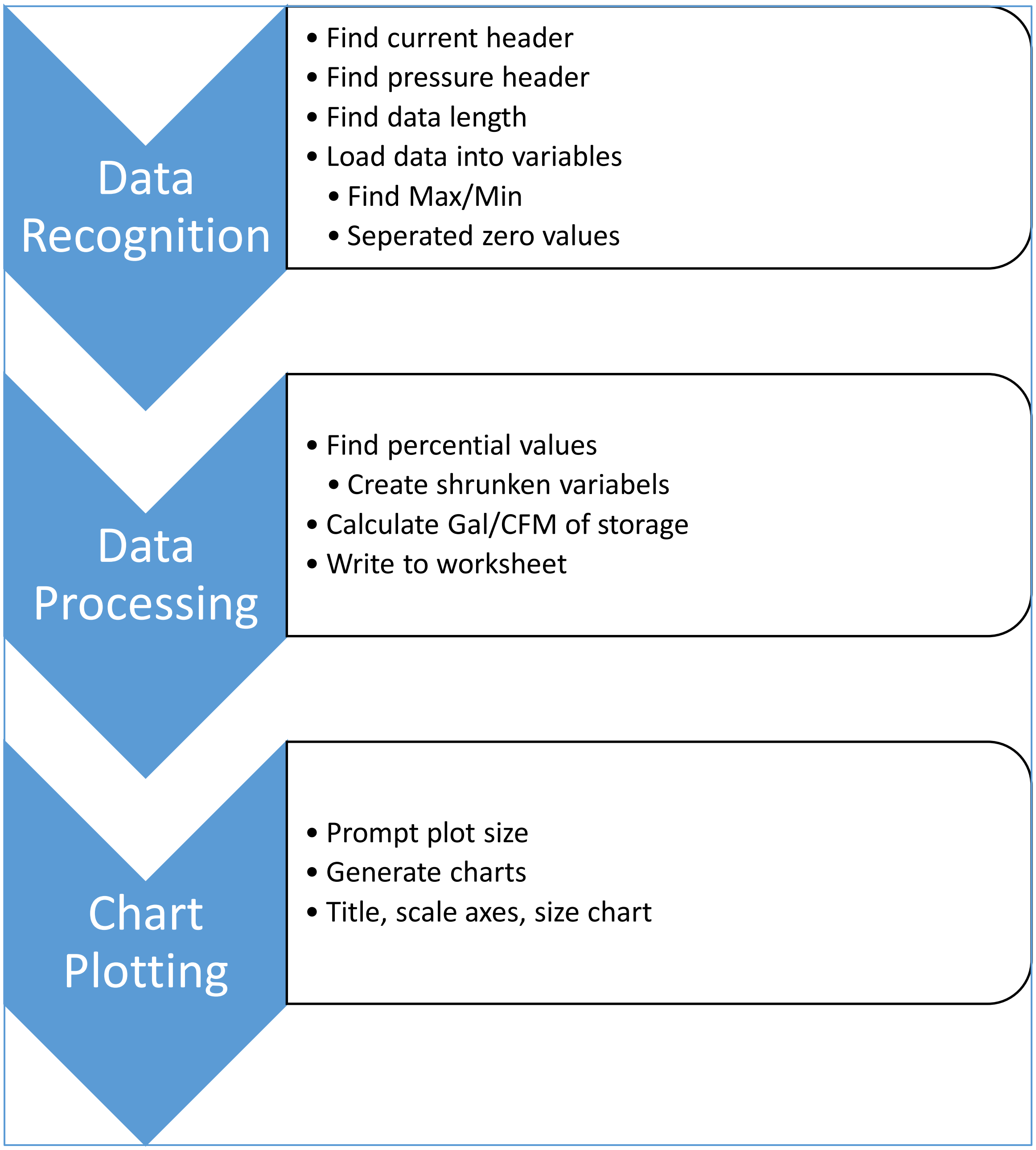

Figure 15: Script Process Diagram

Section 1: Data Recognition

In the first section, the script tries to find the current and pressure headers. For the AC current header, the script does a find command for any cell containing the string "AC" or "cur." This should pick up almost any variation such as: AC curr, Current, AC power, cur, etc. If for some reason, the current header does not contain a subset of "AC" or “curr”, or the script file finds more than one cell containing this string it will immediately force out of the if statement and prompt the user to give the exact cell address of the current header desired. This error textbox is shown in Figure 16 below.

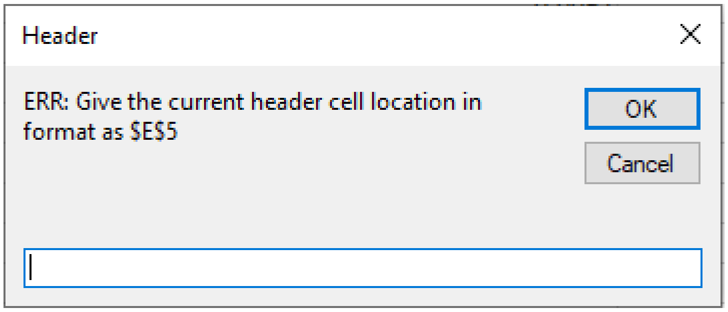

Figure 16: Current Header Error Textbox

The same process is then repeated for pressure using the prompt strings “psi,” and “pre.” Once the header address has been located, the length of the dataset is calculated by subtracting the header row address from the row address of the last row in the input data, which is stored. With the row headers and the data length found, the data can be retrieved from the input data worksheet and stored into vector variables. This is done using a do while loop to put cell data into vector cells individually. Once the data is stored into vectors, the script file will refer back to the data vectors to read data, instead of interfacing with the worksheet. This significantly increases the speed of the program because reading, manipulating or moving data into or out of the worksheet is very slow.

As was stated before in this chapter, it is desired to load data without insignificant points. It is assumed that if the current is below 5 amps, or the pressure is below 5 psi, the data is insignificant. The reason 5 amps is chosen instead of 1 or 0.1 is because when compressors are off, there is often still some power usage in the screens or internal computer. This generally uses between 0.5 and 2 amps, but is highly dependent on the compressor. The script file pulls values from the worksheet and determines if they are significant and belong in the corrected data vector with a few if statements. All data is stored in the regular data vector in order to compare data to useful data. In addition, in this loop, the max and min values are calculated in this do while loop. This is done by testing each current maximum or minimum value against each new iteration data point. The reason max and min are calculated directly in a do while loop is because the vector function application that would be used, has a max range of 16K data points. It is likely that most data sets will be in the 100K range of data points, so this is not a good method to find max and min values. This means the maximum and minimum values must be calculated directly in the do while loop as the data vectors are being loaded. In order to cut down on the min max find, vector load, and insignificant data recognition is all done in the same do while loop. In order to hold the generated data, four vector sets are created (current full, current corrected, pressure full, pressure corrected), the max and min values for pressure and current are recorded, and the corrected data length is recorded.

Section 2: Data Processing

In the second section of the code, the data that has been loaded into the script must be analyzed. The Application.Worksheet.Function class of functions are useful because this toolbox can be used on vector variables. This toolbox contains many different analysis functions, but the important one used here is the percentile function. Percentile function is important because it is a good way to determine a range for outliers. It was previously mentioned that the Application.Worksheet.Function class can only deal with vector sizes 16K or less. In order to get useful data out of the percentile function, the script in the following section thins the data sets to be 16K data points so the percentile function can be used. This is done with another Do While loop and it creates four new thinned vector variables (current thinned, current corrected thinned, pressure thinned, pressure corrected thinned). With these thinned variables, the percentiles can be calculated. The 98 and 2 percentiles are calculated for outlier purposes for each of the four thinned data sets, and these eight new values are stored. The next section of the code generates output data section titles, header and data set values. At this point the Maximum, 98%, 2% Minimum, and length values for the full and corrected data sets have been calculated, and so all of this data is put in the output worksheet.

The next step of analysis in the script is specifically for load/unload compressors. One of the more important operational characteristics for a load/unload compressor system is the storage volume. This was covered briefly in chapter two with analysis on storage volume and sump curves. The larger the volume of storage, the more time a compressor will spend idling, which allows the compressor sump to be reduced to its minimum. The size of the storage is expected to be easily apparent from the pressure power graph. In order to compare different load unload compressor systems, the storage volume needs to be recorded. The storage size is generally in the units of Gal/SCFM. Gallons refers to the volume of the storage tank and system piping and SCFM refers to load capacity of the operating compressor. Compressor storage size is reported in these units because it represents a volume independent value for system size, which means this variable can be applied to any sized compressor system. The equation for storage size is show below:

$$SS = \frac{ULT\ (\sec) * 7.48052\left(\frac{gal}{ft^3}\right) * 14.7\left(\frac{psi}{atm}\right)}{60\left(\frac{sec}{min}\right) * \left(LP(psig)\ - UP(psig)\right)} \tag{4}$$

Where:

SS	=	The system storage ratio, (gal/SCFM),
ULT	=	The time the compressor spends unloaded per cycle, (sec),
LP	=	The pressure that causes the compressor to load, (psig) and,
UP	=	The pressure that causes the compressor to unload, (psig).

This equation is very hard to use accurately, if not impossible with the current analysis because the unload time can change depending on the plant load. When the plant load is higher, the compressor will spend less time unloaded. Alternatively, when the plant load is lower, the compressor will spend more time unloaded. With computer analysis though, all the unload times can be accounted for and the median unload time can be used for a more accurate solution. The script file does exactly that. A vector variable is created and filled with unload times from the data. This script then runs through all of the data with a do while loop and records all of the unload times from each of the compressor cycles. Afterward, the median unload time is used. The median is used because sometime the compressor may turn off, which would give the script an artificially high mean unload time. The median value will not be affected as much so this value is used to estimate system storage size. The storage size is calculated and then put in the output worksheet.

Section 3: Chart Plotting

The last section of the codes plots the data: The full dataset and the dataset with insignificant data removed. In order to properly plot the two graphs, the data must be properly thinned to a readable scale. The user is prompted to choose a plot size. The suggested size is 20K data points, which fits well in a graph sized for a word document. The real data and corrected data are then thinned to 20K data points with a do while function. In a while loop, the full data is transferred to the thinned data vector, and the corrected data is normalized before it is transferred to the thinned corrected data vector. The current data is normalized based on the 2 and 98 percentiles of the current, and the pressure is normalized to atmospheres. Having normalized data like this will remove many of the differences between different sized compressors and allow the pressure power graphs to be compared more easily. The charts are then generated to the proper size for a word document, the charts are populated with data, proper axes are labeled and scaled, and the graphs are titled. When run properly, the resulting output worksheet should look like Figure 17 below:

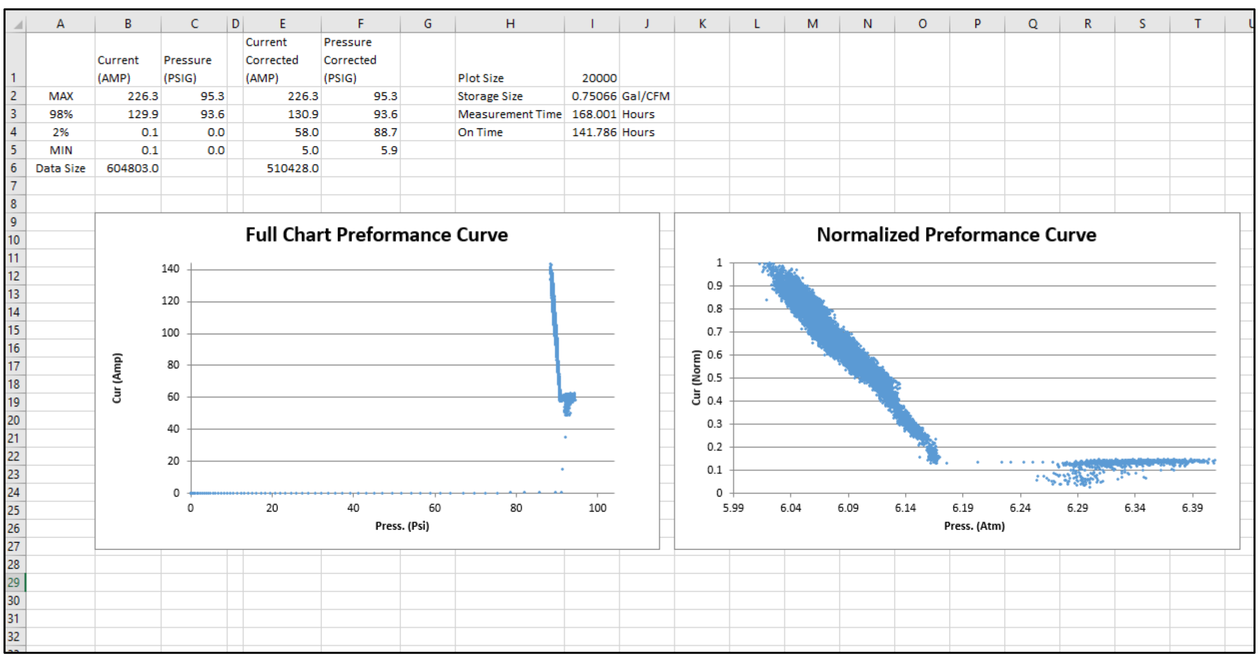

Figure 17: Proper Script Output

The full code including comments for both script files is in Appendix A and Appendix B

CHAPTER 4: THE CURVES AND THE CHAOS

In this chapter, each of the four compressor types will be covered. The full shape formed from the pressure power graph will be explained with examples. In some cases, there will be several different possible shapes, or different features from the same compressor control style. The meaning behind each of these features, and any variation on the base shape formed will be addressed for easy recognition. Any features that display characteristics for the compressor or compressor system will be identified and the importance of these features will be explained in full.

Pressure Power Graph's Special Axes

The curves shown in these pressure power graphs are quite unique in the fact that they do not display time on an axis. This can be confusing at first, because most other compressor analysis methods plot data with a time axis. Because of this, it is extra important to remember what data is displayed, but more importantly what data is not displayed. In pressure power graphs, there is no time-axis. This also means slopes on this curve do not symbolize time rates. Some time analysis is still possible, but it must be done indirectly with time as opposed to directly with the time axis. For example, system pressure change is not instantaneous but instead takes time. This means horizontal lines displayed in the graph, or sections where pressure change is significant, must have taken a lot of time for the compressor curve to trace. Contrarily, vertical lines in the curve where the pressure change is minimal could have happened much more rapidly. These lines are seen during compressor load and unload which takes 1 or 2 seconds. Thinking about the graph in this way can be confusing. But remembering what each axis represents should keep things clearer.

Load/Unload Screw Compressors

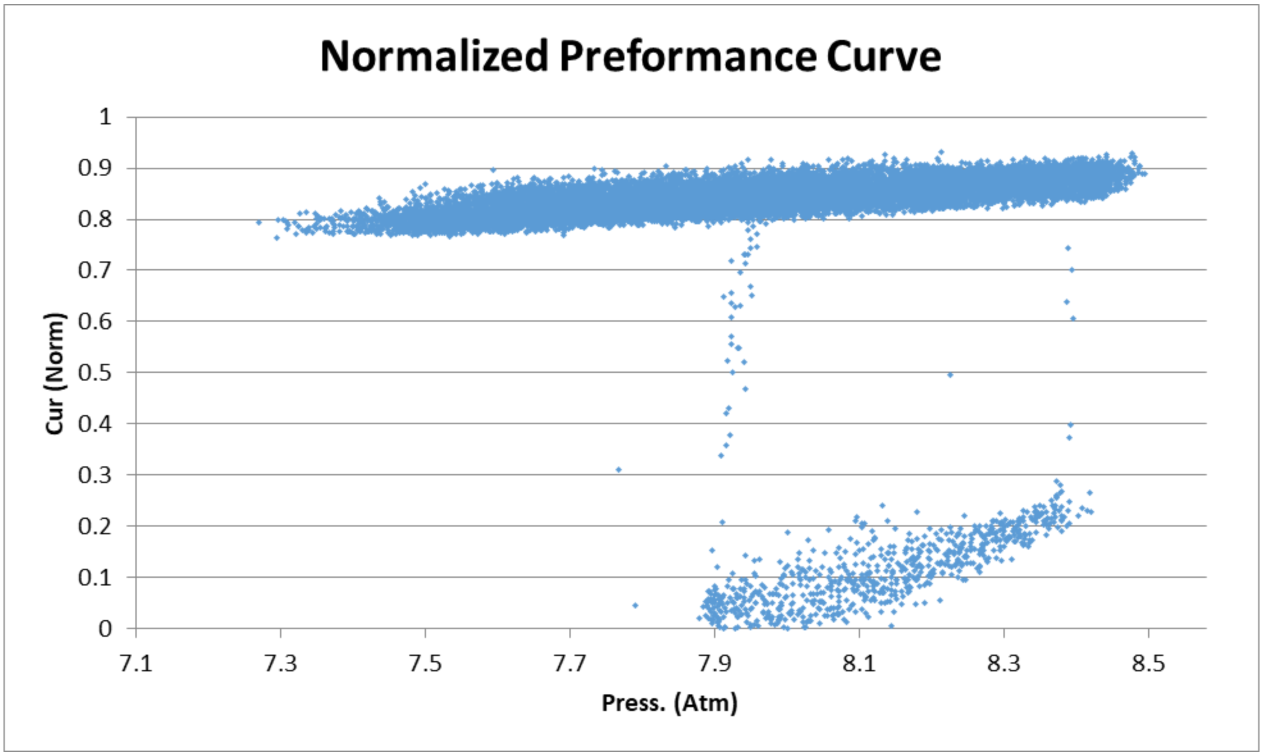

Figure 18: Load/Unload Compressor Example 1

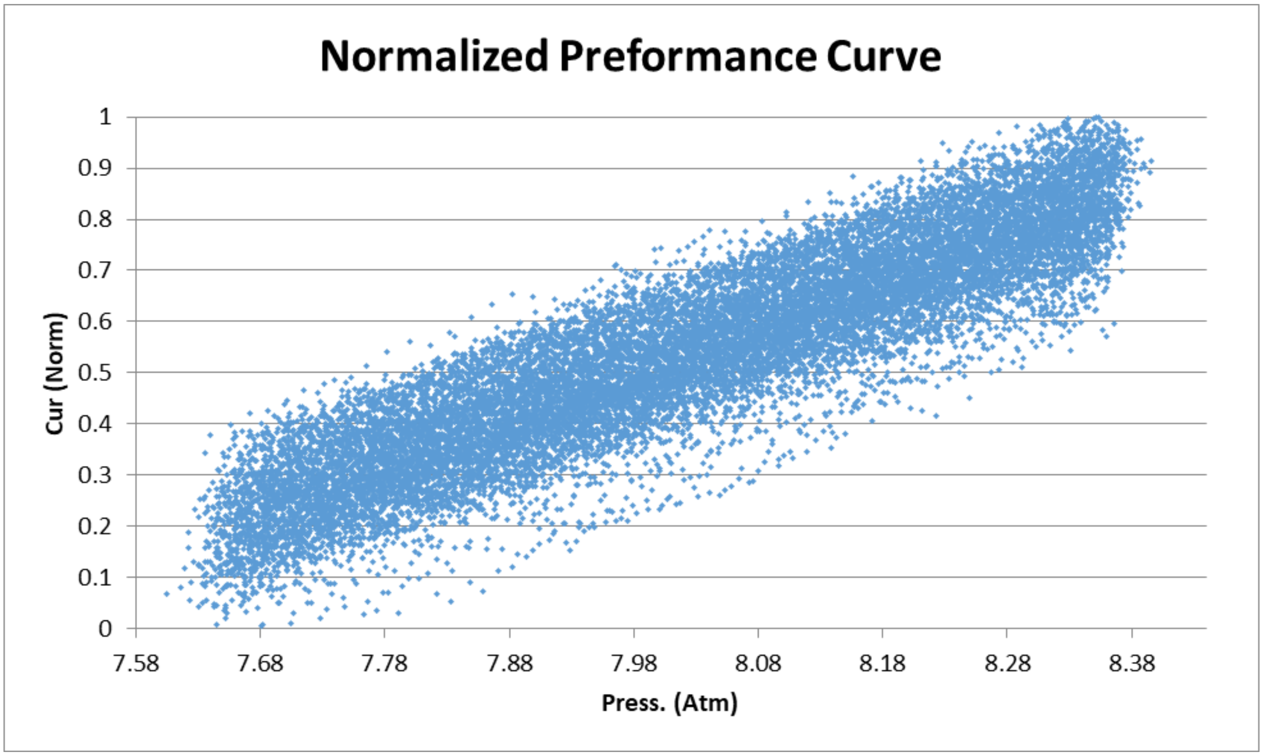

Figure 19: Load/Unload Compressor Example 2

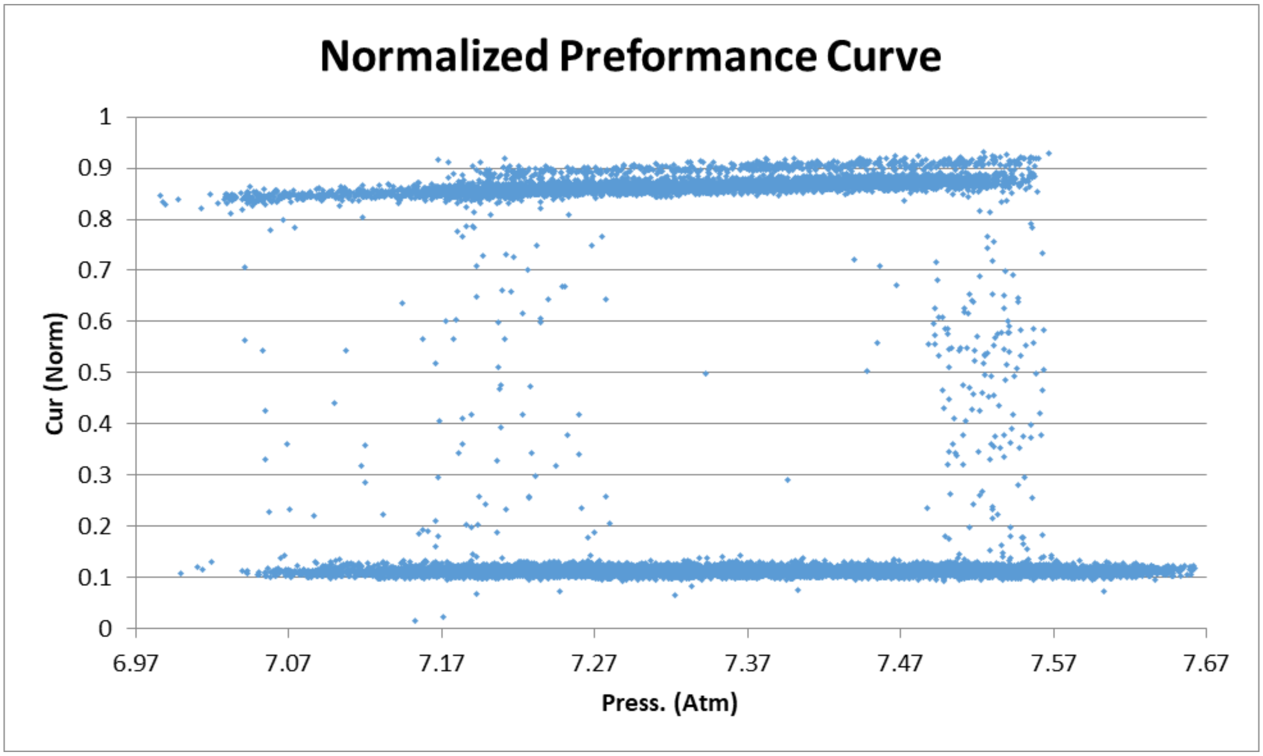

Figure 20: Load/Unload Compressor Example 3

The three pressure power graphs display compressors running in load/unload control. The first is a fairly typical lube injected compressor trace. The third is a load/unload oil free compressor, which means no sump curve. The second compressor never unloads and so the full cycle is never performed. Instead, only the top section of the cycle is performed and traced. This is fairly uncommon because compressor systems are almost always sized to be bigger than the plant demand, however, in cases with a multi-compressor system this type of trace can occur. Figure 19 is a case where having a normalized graph that is based on zero current rather than minimum current might be better for analysis. Figure 21 shows an example of this curve normalized through zero amps instead.

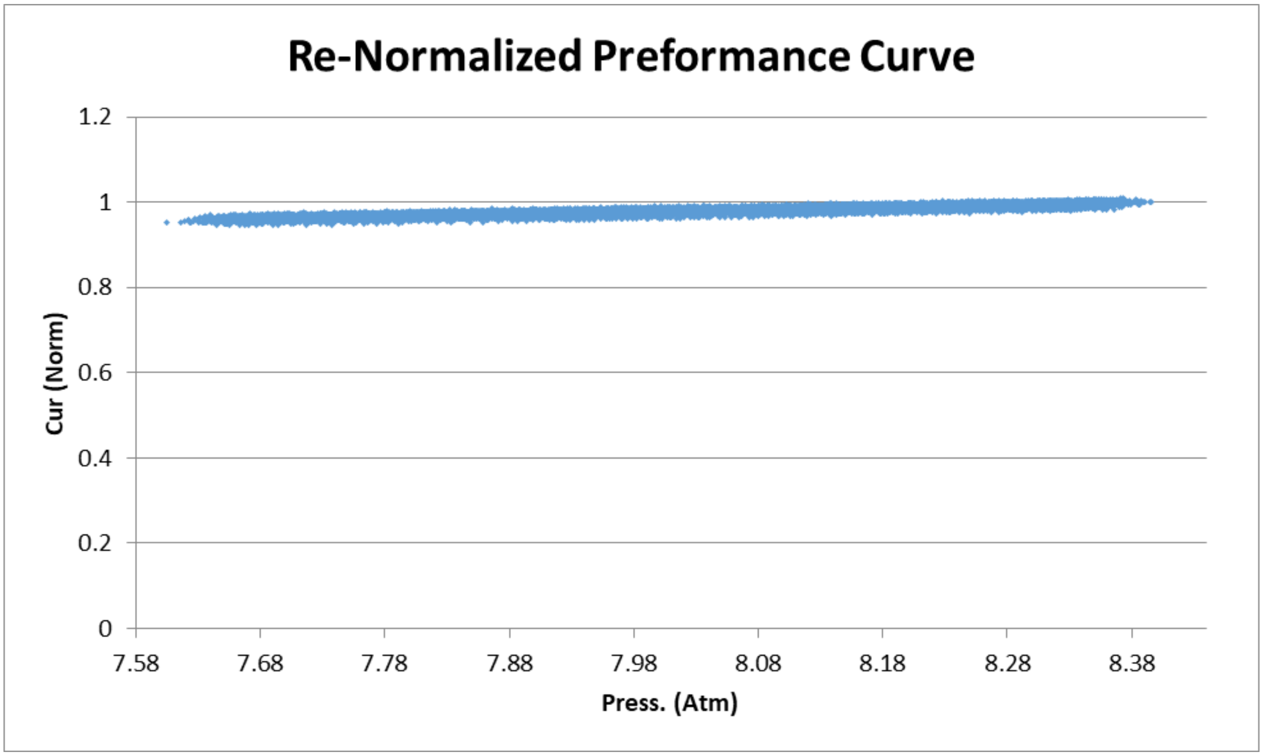

Figure 21: Figure 19 Normalized Through Zero Amps

The basic shape of the cycle in a load/unload pressure power graph is made up of four sections. The first section is the compressor load. This is the leftmost vertical line. A vertical line is created by a rapidly changing current load but a relatively constant system pressure. The compressor loading phase takes at most a few seconds so the trace of this line can be difficult to see sometimes because there might not be enough data points. In cases like Figure 18 it is fairly easy, but in cases like Figure 20 it is more difficult to see. Next, the compressor operates at full load as the pressure slowly rises. Compressors spend a lot of time in this stage and so this line is much easier to see. This is represented by the slightly inclined top horizontal line. Sometimes, the load of the system is greater than the full load capacity of the compressor, and the line can actually drop below the load pressure. This is displayed in Figure 18, where the load pressure is around 7.9 atmospheres, but the full load line drops all the way to 7.2 atmospheres. The third section of the cycle is the unload phase. This section is represented by a rightmost vertical line, where the compressor goes from fully loaded to an idle setting. The current drops considerably while the pressure remains constant. Like the compressor load phase, this phase can be difficult to see clearly sometimes because it happens so fast and there are few data points that capture it. For Figure 18, this phase drops the current all the way down to a normalized value of 0.25. For Figure 20, this phase drops the current all the way down to a normalized value of 0.1. Figure 20 drops to a lower normalized current because the compressor is running oil free, which means no sump load. The fourth stage of the cycles is the idle phase. For an oil free compressor this is represented by a horizontal line where the current remains at an idle state and the system pressure slowly drops back to the load pressure. For lube injected compressors, this is represented by a curved line where the current continues to approach a minimum idling current while the pressure slowly drops back to the load pressure. At the load pressure the cycle starts over again.

Full Load Section Analysis

The slope of the curve along the fully loaded stage is important. This stage represents the only section where the current should be a directly function of the system pressure. Because of this fact, the fully loaded section is always very consistent and clean. The higher the pressure is, the greater the pressure difference is across the screws in the compressor and more power the compressor must use to compress air. The average slope for this part of the curve is highly dependent on the compressor model and how well the compressor handles additional pressure. From data this slope was anywhere between 0.07/Atm, and 0.15/Atm in the normalized compressor graph. This value would be more important in a non-normalized graph because it can make calculations for potential energy savings for reducing compressor system pressure very simple. This is an example of a current type of compressor analysis that was discussed in chapter two. Pressure power graphs show very clearly how fully loaded power is directly based on system pressure, and shows how fully loaded power would change based on a system pressure change. The current method of energy savings for reducing compressor system pressure is by using the ideal gas law, but this estimation does not take efficiency changes or screw cooling into account. The ideal gas compression equation results in an approximation of 1% of compressor energy reduction for every 2 psi decrease in the compressor system. More detail on this method was covered in chapter 2. Some of the findings of this study support this number very closely, however, several compressors analyzed support a number closer to 1% per 4 psi decrease. Different compressors handle pressure changes very differently. Pressure power graphs offer very clear and reliable results, in order to find a more accurate approximation for the effect between full load power and system pressure.

Pressure Band Analysis

The pressure band is a very important setting for load/unload compressors. If set too narrow, the idle time will be too short to allow the sump to properly degas, and the compressor performance efficiency will suffer. In addition, excess load/unload cycles will begin to wear the compressor. If set too wide, the compressor will lose efficiency from having to compress pressure much higher than is actually needed in the system in order to reach an unload pressure state. In multi-compressor systems, having improperly set pressure bands can cause compressors to fight one another. Pressure bands are also not always constant. In some cases, the pressure band will change throughout the week with changing system load requirements, as is shown in Figure 22 below. Here a clear load pressure is shown around 7.50 atmospheres, but a second slightly less developed pressure load set point is displayed around 7.73 atmospheres.

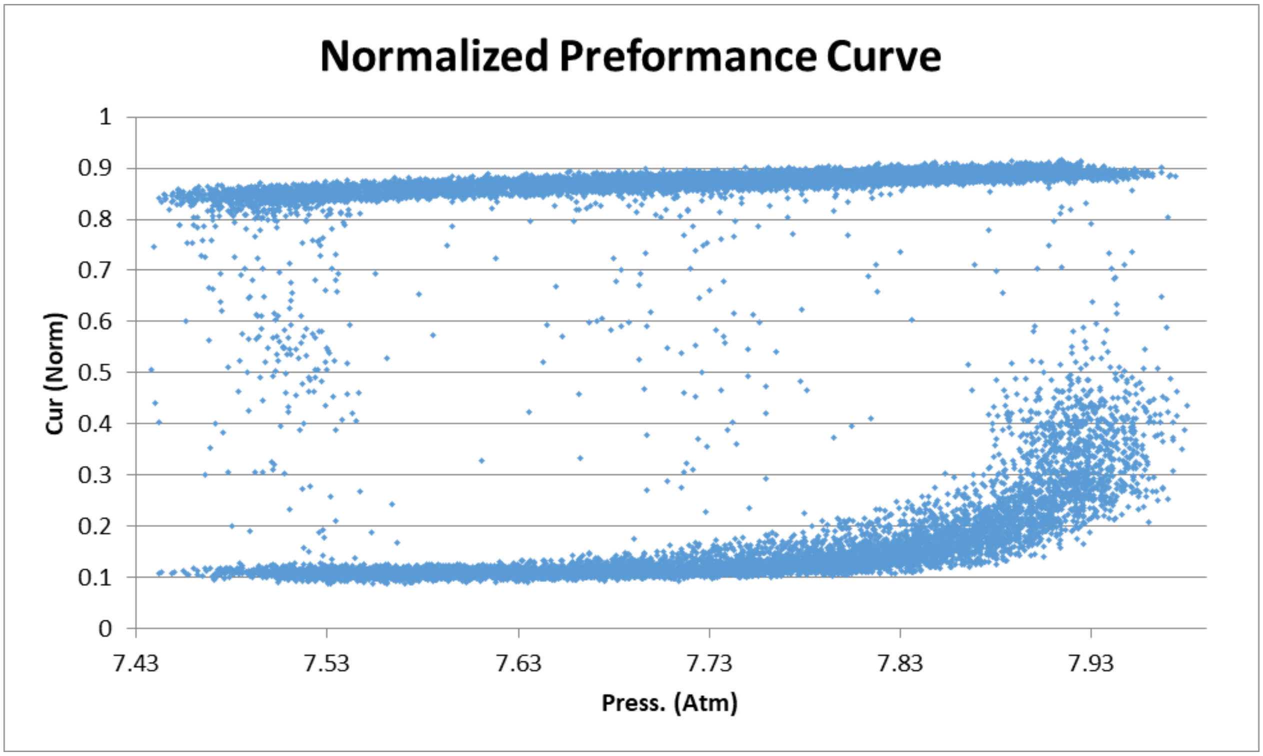

Figure 22: Changing Pressure Band Settings

The pressure band consistency is usually difficult to measure. With a pressure power graph, accurately determining the pressure range becomes much clearer and more accurate.

Unload and Sump

After the compressor reaches a maximum pressure and switches to an idle phase, the compressor current drops instantaneously. After the unload point in the cycle is reached, the compressor current is a direct function of the sump pressure. For oil free compressors there is no sump to worry about and the current drops to the minimum load required to keep the motor idling. For lube injected compressors, the current drops also, but not to a minimum load, because lube injected compressors need to worry about oil foaming up and getting sucked out with the compressed air. For the load/unload compressors analyzed in this study, almost all compressors drop instantaneously to a normalized compressor current load of between 0.4 and 0.5. From that point, the compressor current begins to fall more slowly as the pressure on the sump is slowly released. In both styles of compressor control, once the compressor starts to idle, the system pressure begins to fall. From this point, the current in the system is based on the sump pressure, which reduces at a specific rate, based on time. As the sump pressure is reduced the compressor does not need to work as hard to keep the chamber pressurized. The sump pressure reduction is consistent for every cycle regardless of the system pressure so, 10 seconds after compressor unload, the sump will be at the same pressure, and the compressor will be operating with the same current load every cycle. Pressure reduction however, is not directly time dependent. If the system is extremely loaded. 10 seconds after compressor unload, the system may have lost 8 psig. Contrarily, if the system is quite unloaded, 10 seconds after the compressor unloads, the system may have only lost 2 psig. The pressure reduction is as much a function of system load as it is of time. The system load is constantly changing, as tools startup, production goes online, or during lunch break. While this system air demand varies constantly, it usually doesn’t vary much within the time span of a single cycle. Even if there is significant variation in the consumption during a single cycle, when analyzing thousands of cycles on top of each other, the average data does not contain much pressure variation between cycles. Because of this, the sump curve in the pressure power graph looks very similar to the sump curve in a time axis graph, with one difference. The sump curve in a pressure power graph traces a wider section, the larger the variation in the system air demand. This is not always the case though. Sometimes there is so much variation in the system that a recognizable sump curve is not formed. This could be caused by a pneumatic process that uses a significant proportion of air capacity in one instant. Another case could be a multi-compressor system where the compressors are fighting each other to maintain control. Figure 23 below shows a load/unload compressor where after switching to idle the pressure continues to climb because of a second, still running compressor.

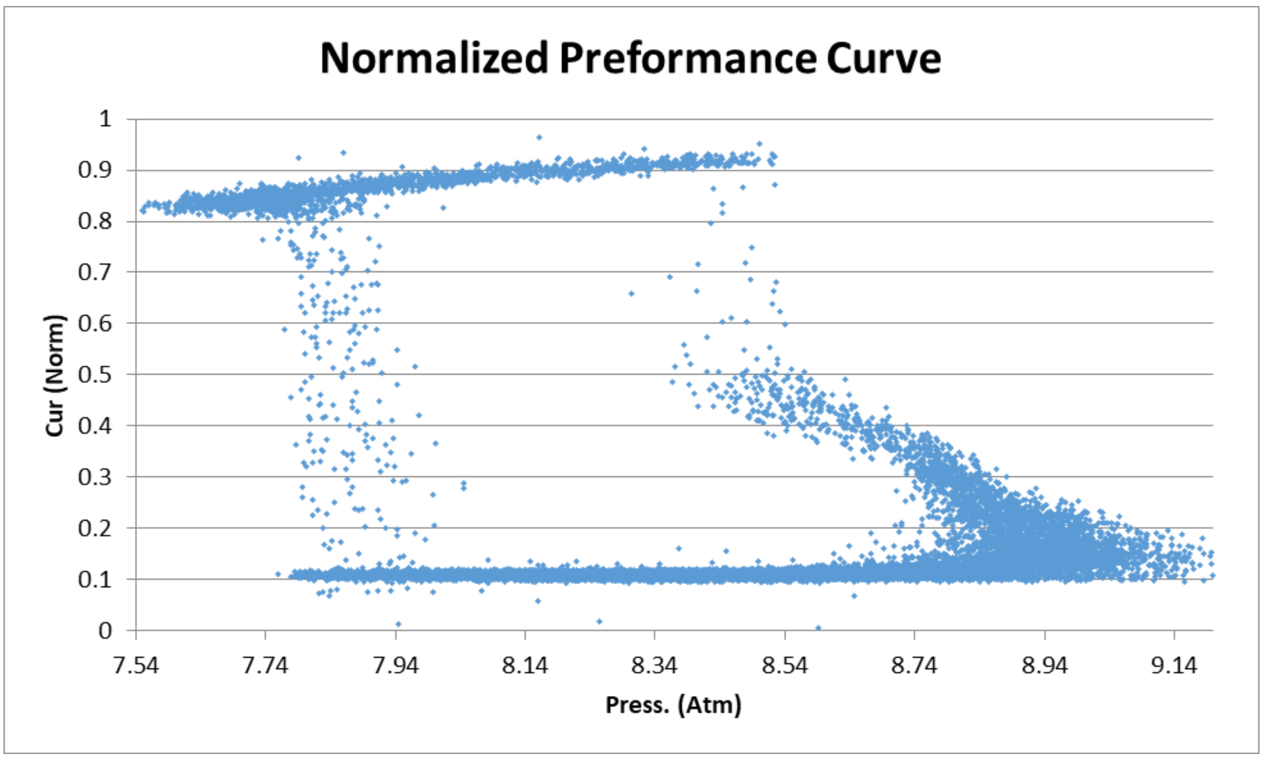

Figure 23: Compressors Fighting in Multi-Compressor System

Ignoring a few isolated cases, however, the sump curve on load/unload lube injected screw compressors looks very similar on a pressure power graphs as it does in a time axis graph. Each compressor sump curve looks different. Some sump curves look very asymptotic as they approach a minimum current load and a minimum sump pressure. Other sump curves seem to drop quite linearly with no indication of a minimum sump pressure. Figure 24 and Figure 25 below display the two different styles of sump pressure reduction.

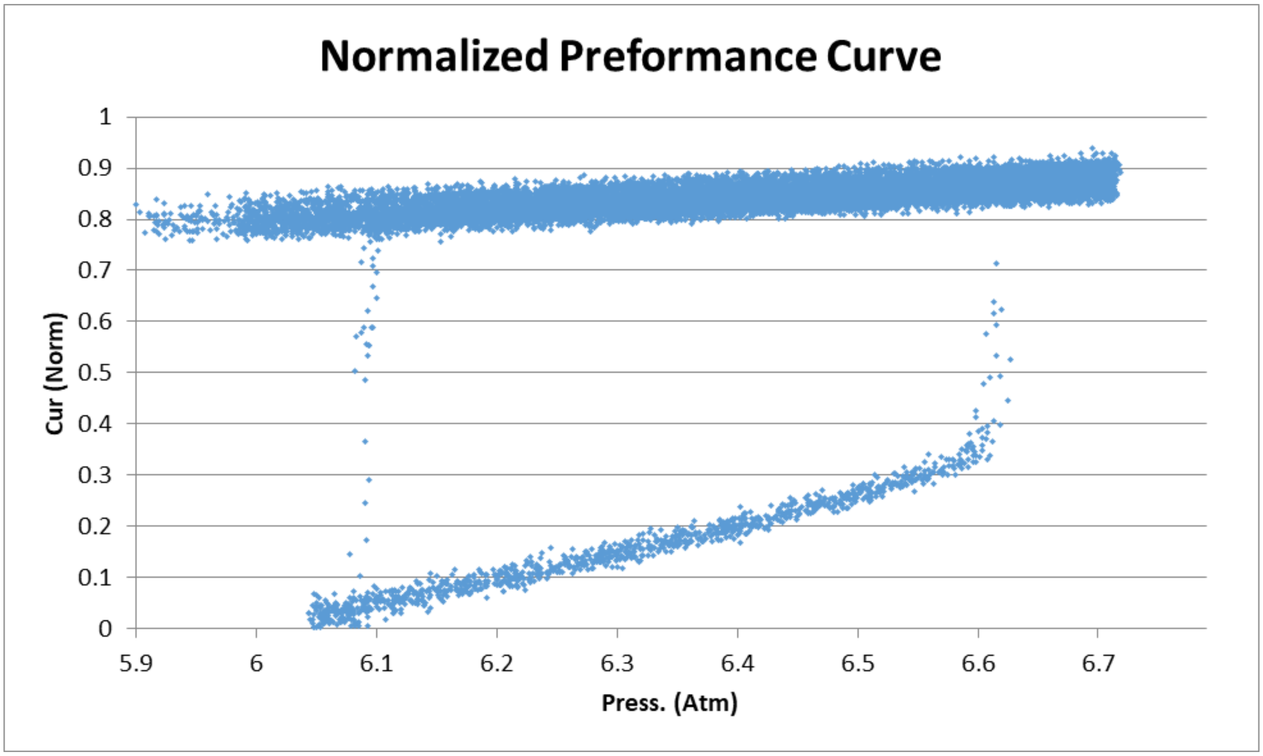

Figure 24: Pressure Power Graphs with Straight Sump Curve

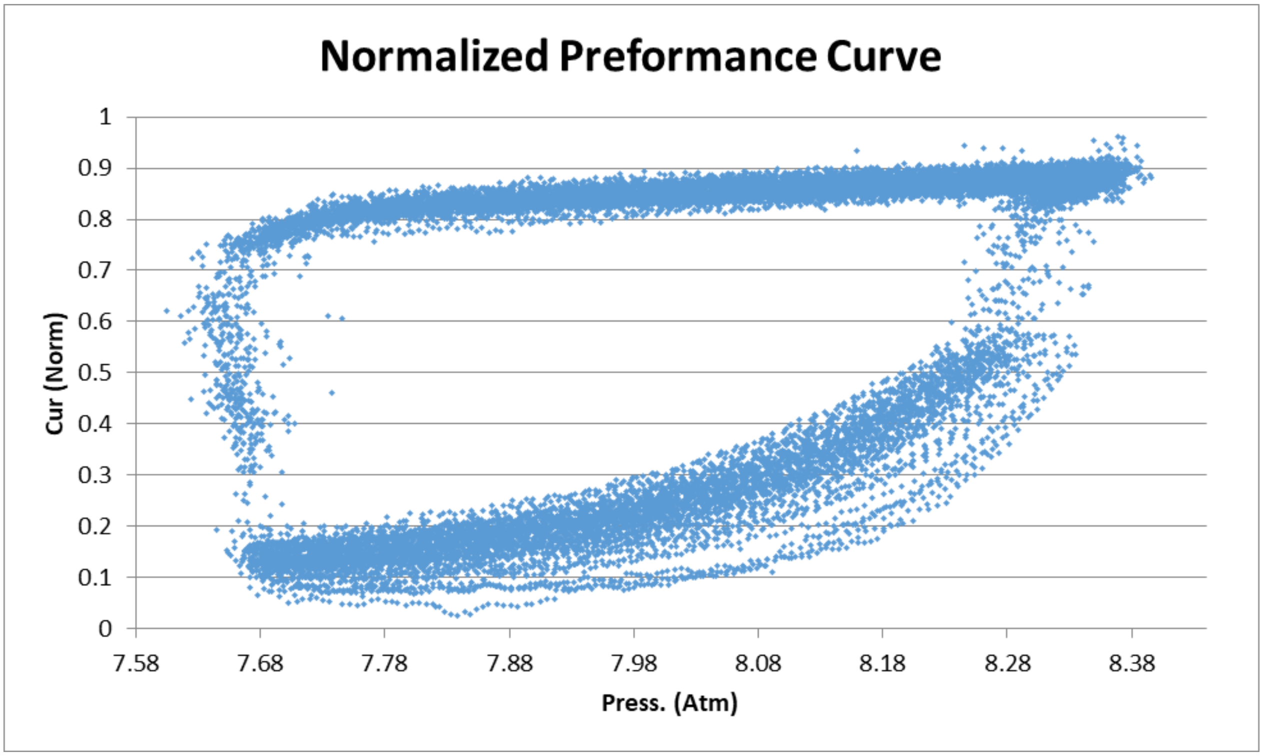

Figure 25: Pressure Power Graph with Asymptotic Sump Curve.

Sump Analysis

The variation of compressed air demand used by the system can also be indirectly shown on the pressure power graph. While the compressor is loaded, the current usage is directly a function of the compressor system pressure. This means the system pressure can increase, hold, or decrease, and it will be impossible to tell from the pressure power graph, because the trace will go back and forth over the full load section, but still stay in the full load band. During unload, however, the compressor current is based on sump pressure, which is a direct function of time since compressor unload. In a single compressor system, the pressure reduction is also fairly dependent on time, as was explained before. Using this information, Figure 26 shows a pressure power graph with appropriate bounds placed on the sump curve.

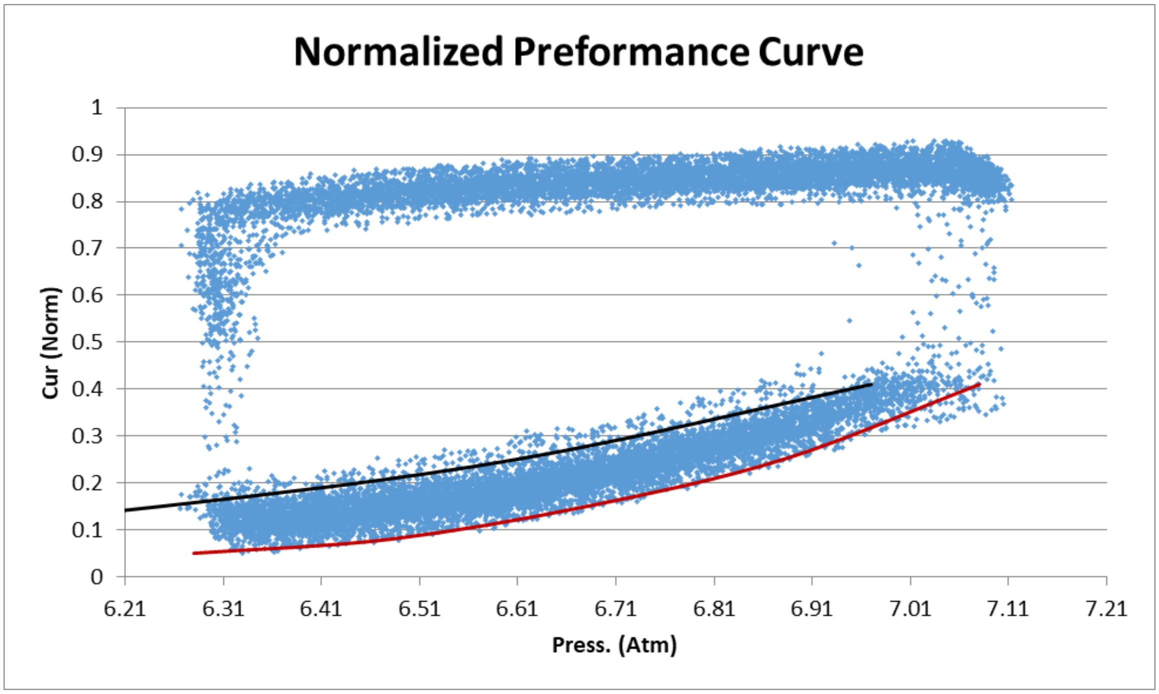

Figure 26: Upper and Lower Bounds on Sump Curve

In this graph, the lower bound marked by red line represents the system minimum air consumption load. This lower bound is the time when the compressor spent the most time in unload, and the compressor current load was able to drop lowest. The maximum system air load is marked with the black line. This curve fit uses the red line, but shifted and stretched in order to fit the upper bound on the sump curve. This can be done because the time-axis sump curve should be the same for both minimum and maximum system consumption setting. The only difference is the system pressure rate of reduction, which causes the sump curve to be stretched on the pressure power graph. This transformation can be calculated with the following equation.

$$UB\ (Atm) = UP(Atm) - UV(Atm) - (UP(Atm) - LB(Atm)) * CV \qquad (5)$$

Where:

UB	=	The upper bound data point, (Atm),
UP	=	The unload pressure setting of the compressor, (Atm),
UV	=	The unload pressure variation/ range of pressure at unload (Atm),
LB	=	The lower bound data point measured from the graph, (Atm) and,
CV	=	The consumption variation of air usage in the compressor system.

An example for calculating the second data point is shown below. All other data points are recorded in Table 2.

$$6.608\ atm = 7.08atm - 0.11\ atm - (7.08\ atm - 6.88\ atm) * 1.81 \qquad (6)$$

Table 2: Table Data for Sump Transformation

	Minimum System load	Maximum System Load	Transformation values	
Current Load	Measure Pressure	Generated Pressure	unload variation	consumption range
	Atm	Atm	0.11 (Atm)	181%
0.41	7.08	6.97		
0.25	6.88	6.608		
0.15	6.68	6.246		
0.08	6.48	5.884		
0.05	6.28	5.522		

Because the pressure power graph is normalized, it cannot tell what the actual consumption is, but it can tell the variation in air consumption. From this transformation, it can be approximated that the maximum system air consumption is about 181% that of the minimum system air consumption.

System Storage Estimation

The shape of the sump curve can also give an idea about how much storage the compressor system has, and help estimate how much additional storage would help. The following three figures contain measured storage ratios of 3, 5 and 10 gal/SCFM respectively. In each, as the storage ratio increases, the shape of the slump curve begins to flatten out and approach the minimum current load.

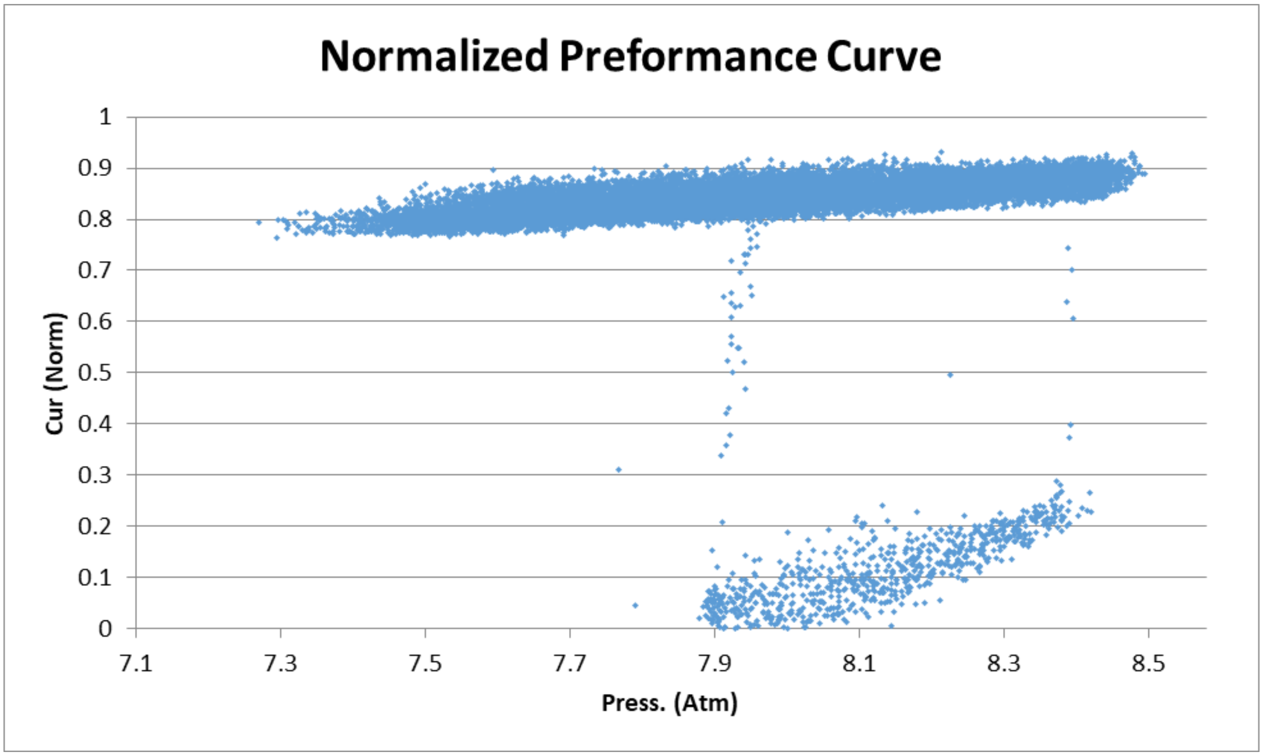

Figure 27: Load/unload Compressor with 3.2 Gal/SCFM of Storage

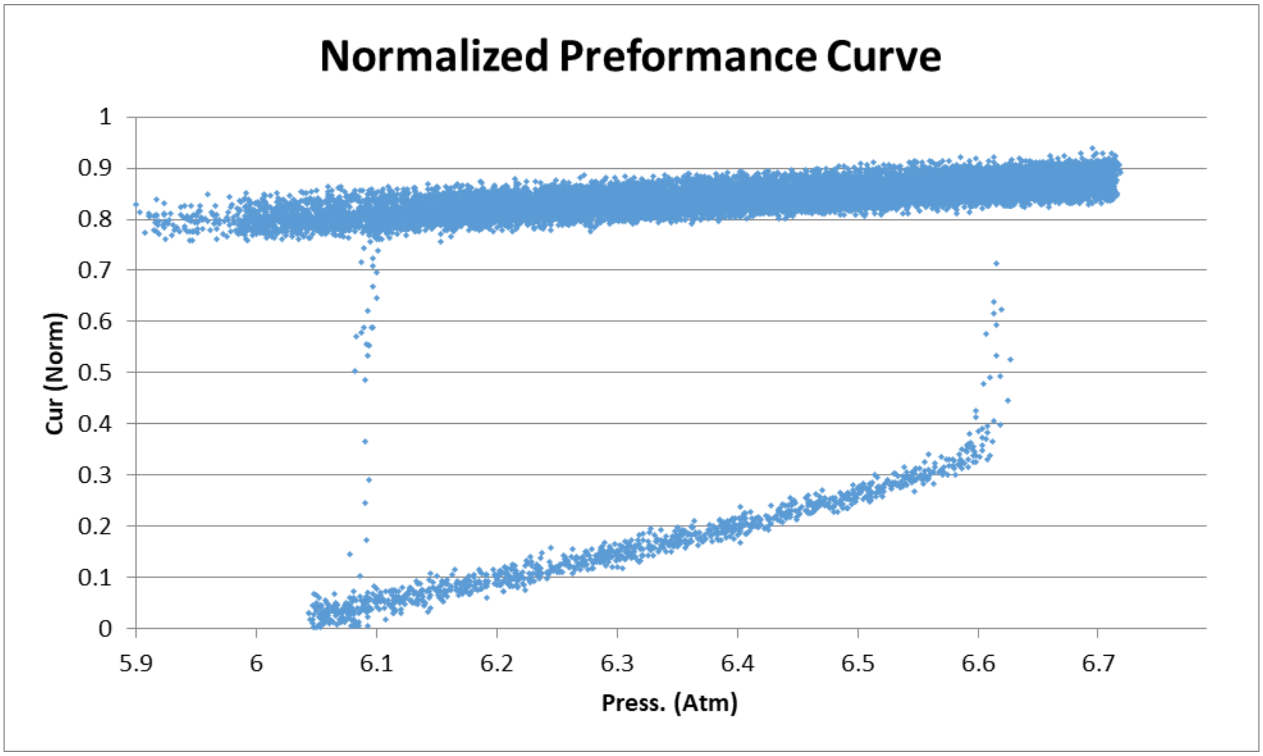

Figure 28: Load/unload Compressor with 5.1 Gal/SCFM of Storage

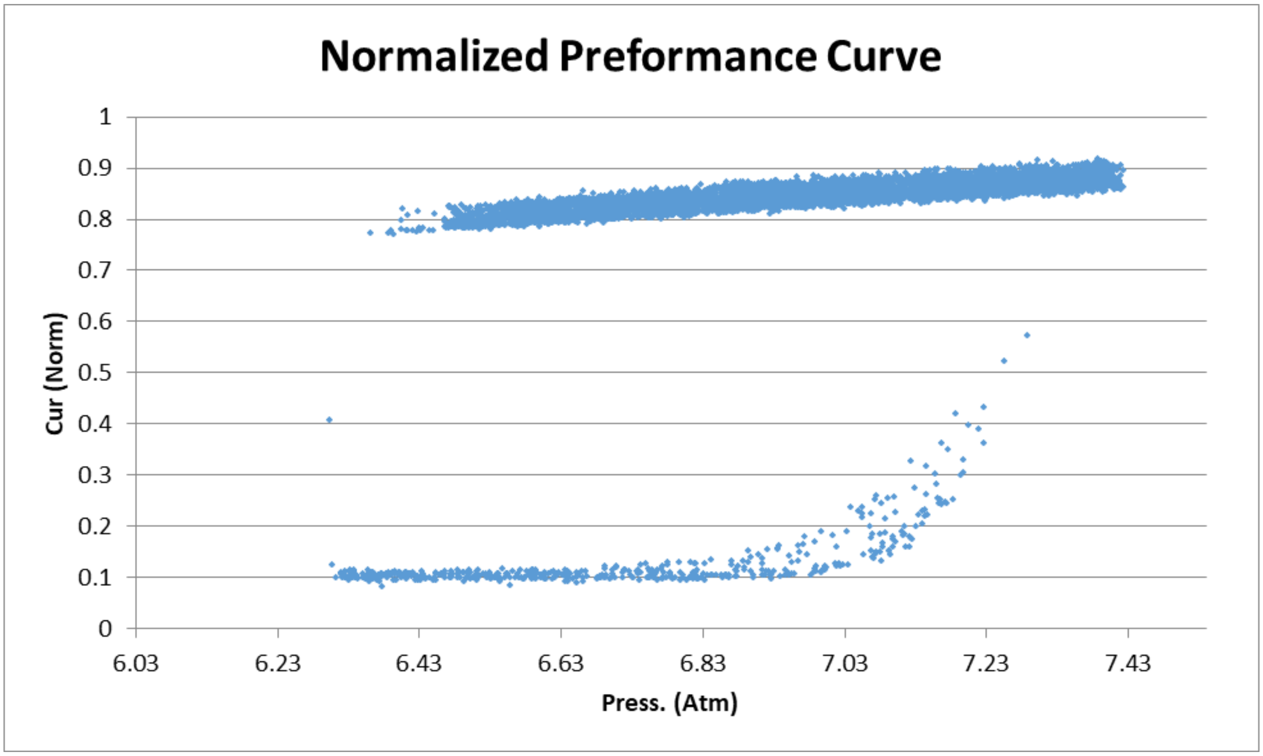

Figure 29: Load/unload Compressor with 10.9 Gal/SCFM of Storage

The graph can definitely say when the storage is large enough because the sump curve becomes completely flat. Further than that, the compressor storage size is more difficult to see than hoped from the pressure power graph. This is because, the pressure band also plays a factor in the compressor storage value. If, for example, a compressor has a pressure band that is extremely small, around 2 psig, and a storage volume of 10 gal/SCFM which is generally consider state of the art, the compressor would only stay unloaded for about 11 seconds. If alternatively, the compressor pressure band was around 25 psig, and the system had a compressor storage volume of 1 gal/SCFM, generally considered a very bad amount of storage, the system would stay unloaded for about 14 seconds, or three more seconds than a state-of-the-art system, with a bad pressure band. Pressure band range and volume storage are both important for slump curve reduction.

There are several other features seen in misbehaving load/unload compressors, but for properly operating compressor, this is a comprehensive list of every found in this study.

Variable Speed Compressors

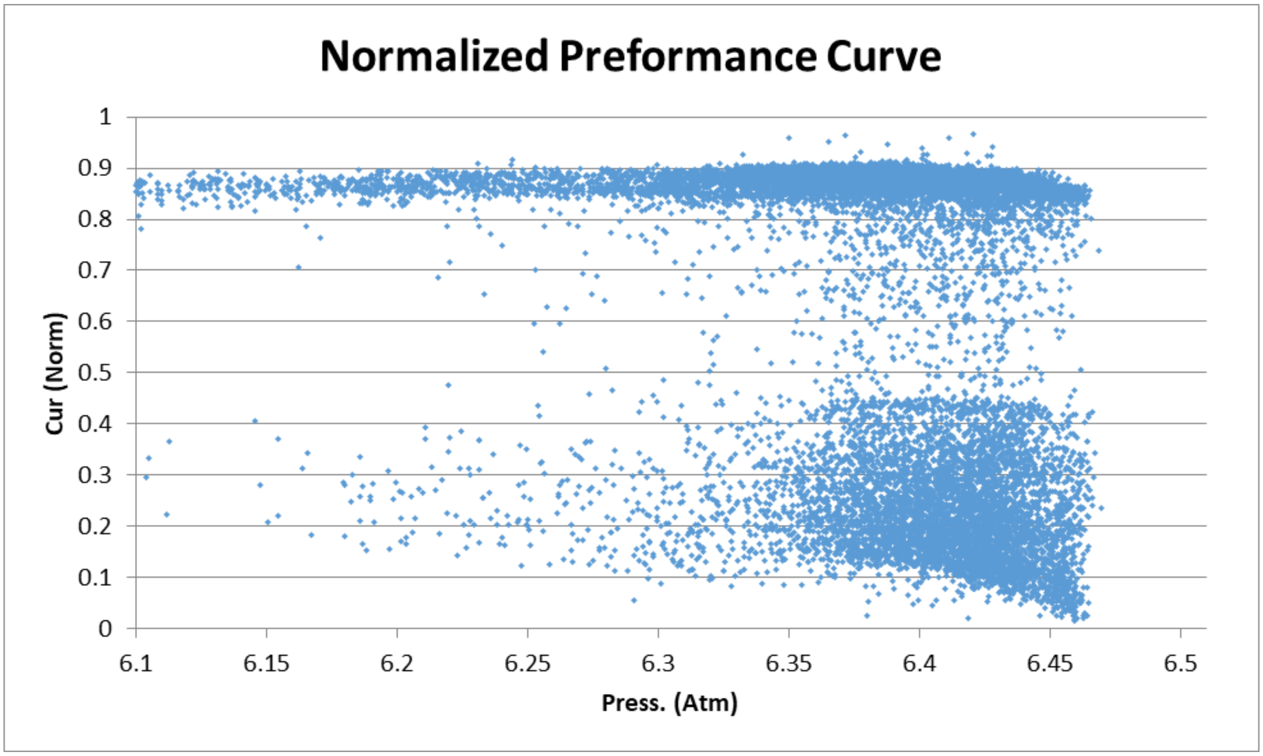

Figure 30: Variable Speed Example 1

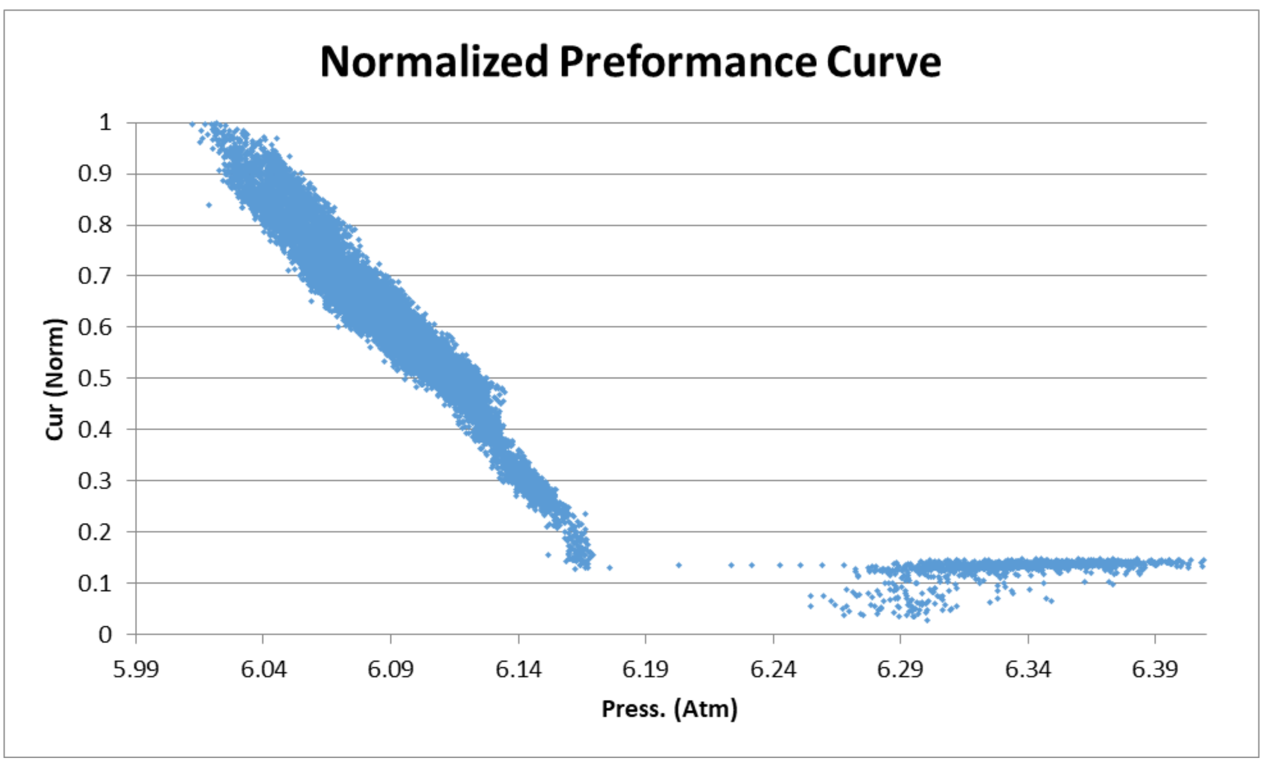

Figure 31: Variable Speed Example 2

Importance of Measurement Location

The two figures above show examples of what a variable speed pressure power graph could look like. The difference between these two examples is dependent on the location where the pressure is measure. If the pressure is measure right at the outlet of the compressor, the graph will look more like Figure 30. If the pressure is measure after that, like in the first storage tank, the pressure will look more like Figure 31.

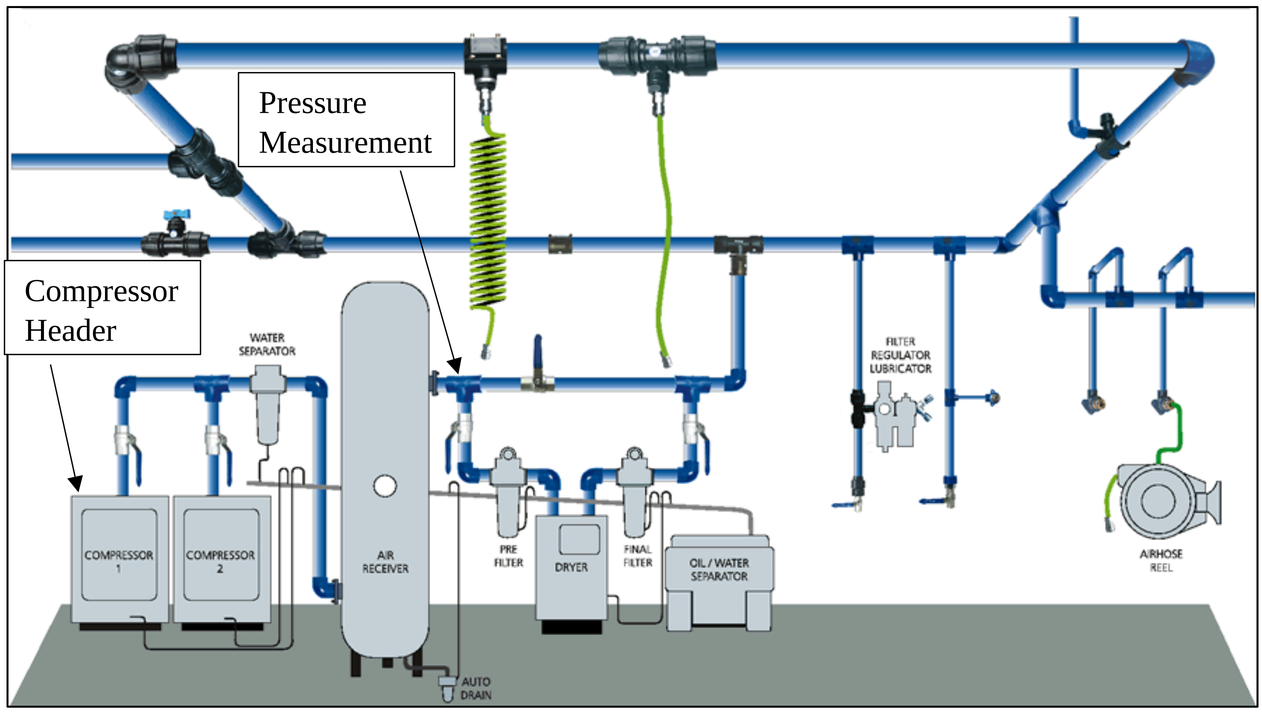

Figure 32: Example Compressed Air System

Variable speed compressors are slightly different from load/unload compressors because they do not have to follow a cycle. Instead, the operation point slides up and down as it responds to the system load demand. In Figure 31 the pressure is measured after all of the air treatment. Because of this, in the curve, the pressure and the current seem to drop together. In this case, the compressor is actually maintaining perfect pressure control, but there is pressure drop between the compressor output and the pressure transducer.

According the fan affinity laws the pressure drop should be linear to the square of flow rate, and in variable speed compressor, the flow rate is linear to the compressor current.

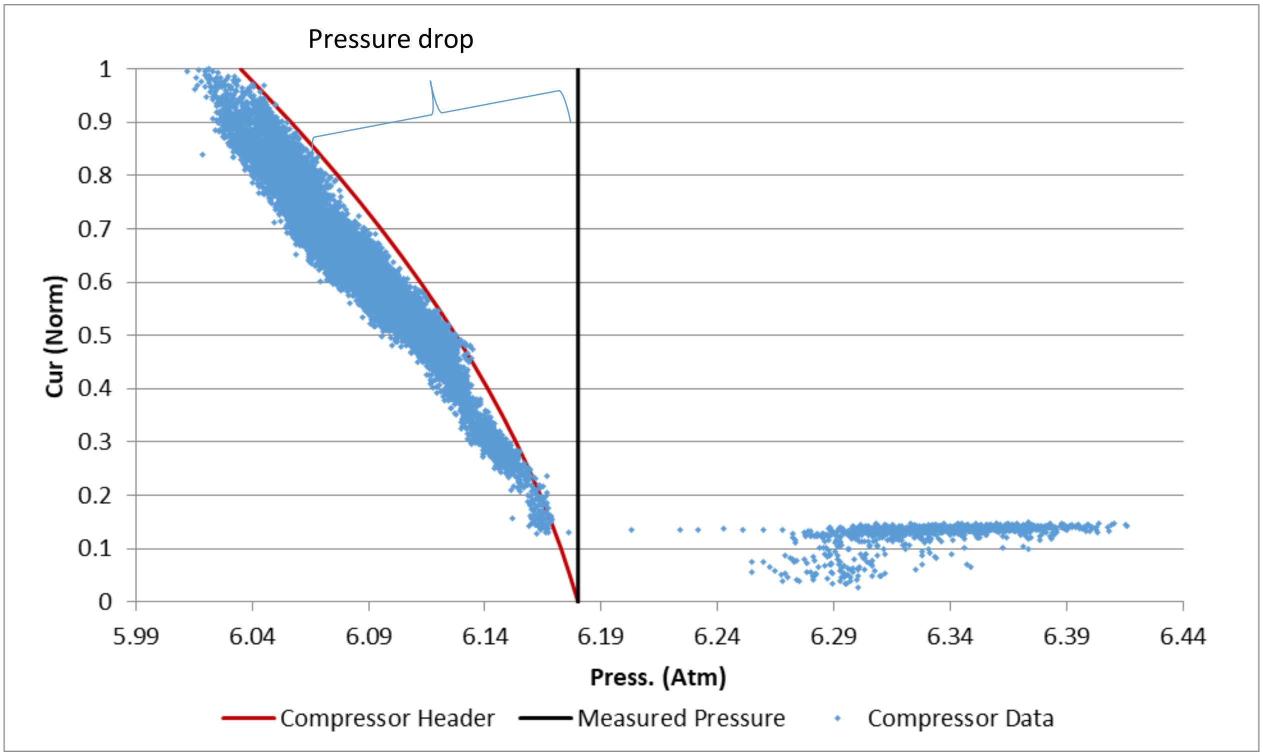

Figure 33: Pressure Drop for Variable Speed

Figure 33 shows the pressure drop between the pressure transducer, shown by the red line and the compressor header, shown by the black line.

The other shape a variable speed compressor can form is shown in Figure 30 above. In this figure the pressure is taken right at the compressor outlet. Here the pressure stays constant between 6.36 and 6.46 atmospheres, and the current slides up and down to match the compressed air load from the system. In addition to the control section described, a variable speed compressor may contain a tail at lower pressure than the control section representing a full load setting, and a tail above the controls section representing a minimum load setting.

Variable Speed Tails

The full load section in a variable speed compressor, where the operating current is directly a function of the system pressure. This section will only happen in a variable speed compressor if the system pressure drops below the control pressure and begins to compressor operates at full load. This will take the shape of a tail on the left side of the graph. As with the other compressor control types, the slope of the full load section is important because it shows the compressor efficiency with respect to power. This is explained in detail in the load/unload compressor section. The pressure power graph in Figure 30 clearly has this section while the pressure power graph in Figure 31 does not.

If the system pressure continues to rise beyond the desired compressor operating pressure, even with the compressor operating at minimum flow, a tail will form to the right side of the compressor control section. This is clearly displayed in Figure 31 while not in Figure 30. This minimum flow rate is determined by the compressor manufacture but for lubricated screw compressor it is around 20-25% of maximum rated volume. If the pressure continues to rise too high, it will hit an emergency stop pressure where the compressor will turn off entirely and wait for the system pressure to return to normal.

The other thing to note is on all of the other pressure power graphs the pressure range is on the order of 10 to 15 psi. For variable speed compressors, the pressure range should be much smaller. For these two figures, the control range is 3 and 2 psig respectively.

Setpoints

The pressure setpoints can be found from the pressure power graph of a variable speed compressor. These are important because they show how the compressor is actually preforming and show how consistently the compressor stays in the desired pressure boundary. The first important pressure setting is where the maximum current is located. This should be at the transition between the full load slope section of the graph and the variable speed control section, shown in Figure 30 to be 6.41 atmospheres. In Figure 30 this represents the actual desired compressor operating pressure, but for the diagonal style of graph this would represent pressure at the point of measurement, which is the pressure after the pressure drop across the air quality equipment. The compressor operating pressure for the diagonal control graph would be on the bottom end of the diagonal line between the control stage and the minimum load stage, shown in Figure 31 at about 6.17 atmospheres. The last important pressure setpoint is the compressor emergency stop pressure. This is the pressure where the compressor will not continue to run, even in a minimal flow state. This is shown in Figure 31 at 6.4 atmospheres. Not all variable speed compressors include the emergency stop section as a regular part of the compressor cycle. Generally, this only happens when a VFD compressor is part of a multi compressor system, and two compressors start fighting each other, or if the minimum air demand in the system is extremely low.

Active Rotor Length Adjustment

Active rotor length adjustment can take on two very different pressure power graph shapes. The first shape is for slider, spiral, and turn valve control. This is shown in Figure 34.

Slider, Spiral and Turn Valve Control

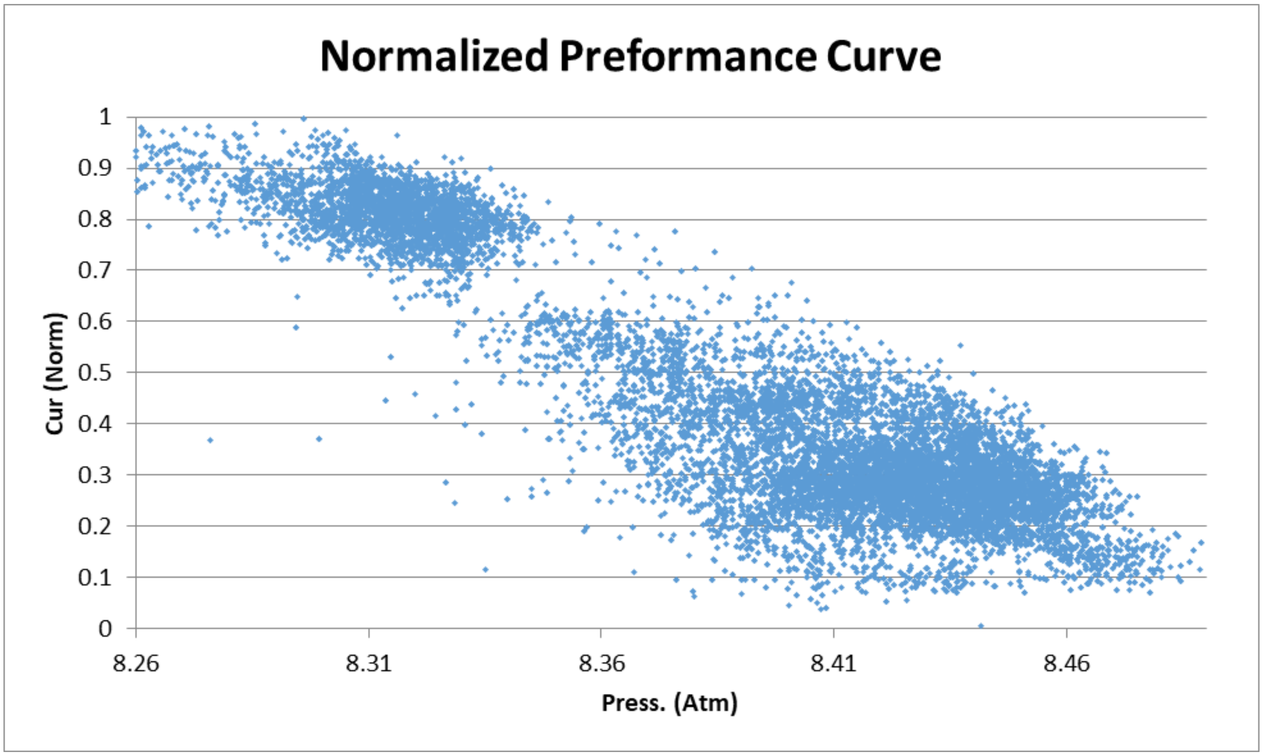

Figure 34: Active Rotor Length Example 1

Slider control tails

Normally this curve would be split into three sections. A full load section below minimum desired pressure, and control section, and a minimum flow section. Figure 34 only shows the control section because the entire range of the system consumption demand is in the control range of this compressor. If the system air consumption were to become larger the compressor would run at full load, and a full load section tail will develop in the top left corner of the graph. This is shown in green in Figure 35. The slope of the full load section is important because it shows the compressor efficiency with respect to power. This is explained in detail in the load/unload compressor section.

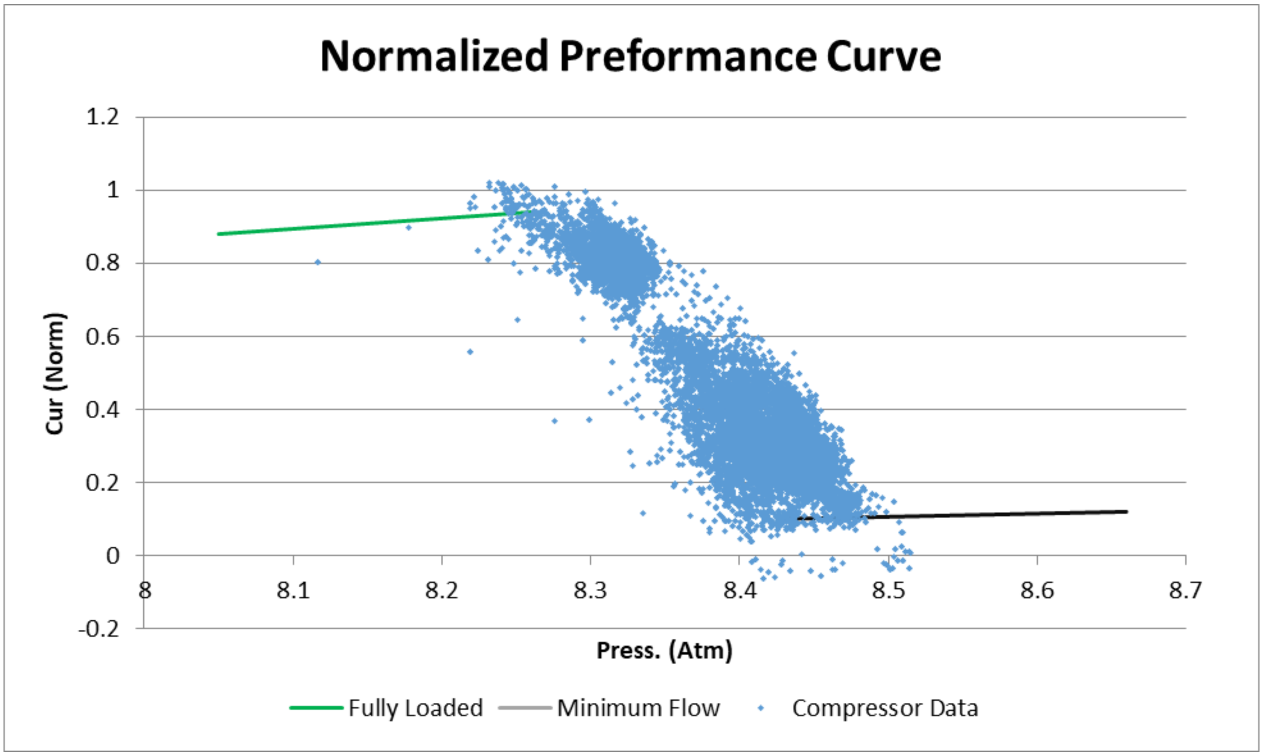

Figure 35: Active Rotor Length Adjustment with Example Tails

In addition, if the system air consumption were to become much smaller, a tail to the right would develop off of the bottom of the control section where the minimum flow of the compressor is. This is shown in black in Figure 35. The main difference between this graph and the pressure power graph of a variable speed compressor is the variable speed compressor can have a control phase with a current reduction of 50 to 70%. A control phase for an active rotor length adjustment compressor can only reduce by 30 to 40%.

As with the variable speed control, the location of the pressure measurement can change the shape of the trace. In the case of Figure 35, the pressure is measured after the control so the diagonal control shape is created by a pressure drop across the air quality equipment, between the compressor outlet and the pressure transducer.

PID Controller Error

Slider valve compressors, like variable speed compressors, use PID feedback loops in order to determine the proper volume of compressed air required. Often, compressors operators will leave off the "D" or derivative component when tuning the controller. This results in control that is less than perfectly accurate. Specifically, this results in control that is better at different flow requirements. Figure 34 above is an example of this. This controller is tuned so that the compressor preforms best at high consumption loads. For lower consumption loads, the pressure variation is much wider. In the higher load, the pressure variation is around 0.6 psig. As the load drops, the pressure variation grows to around 1.4 psig. PID feedback loops are found in both active rotor length adjustment and variable speed control, so this phenomenon can occur for either control type.

Slider Control Setpoints

The pressure set points can be found on the pressure power graph of an active rotor length adjustment compressor. These are important because they show how the compressor is actually preforming, and show how consistently the compressor is staying in the desired pressure boundary. The first important pressure setting is where the maximum current is located. This should be at the transition between the full load and control sections of the graph just like with variable speed control. For Figure 34, this would actually be the maximum-current system pressure, because it takes into account the pressure-drop through the air quality section. The next important setpoint would be the end of the control section. This would represent the actual compressor operating pressure. The last important pressure setpoint is the compressor emergency stop pressure. This setpoint is not displayed in Figure 34 because the compressor never reaches the shut-down pressure, but it would be the end of the black line in Figure 35. Not all active rotor length adjustment compressors will have the shut-down pressure section it the compressor cycle.

Active Rotor Length - Poppet and Step Control

The second common shape for active rotor length adjustments is shown in Figure 36.

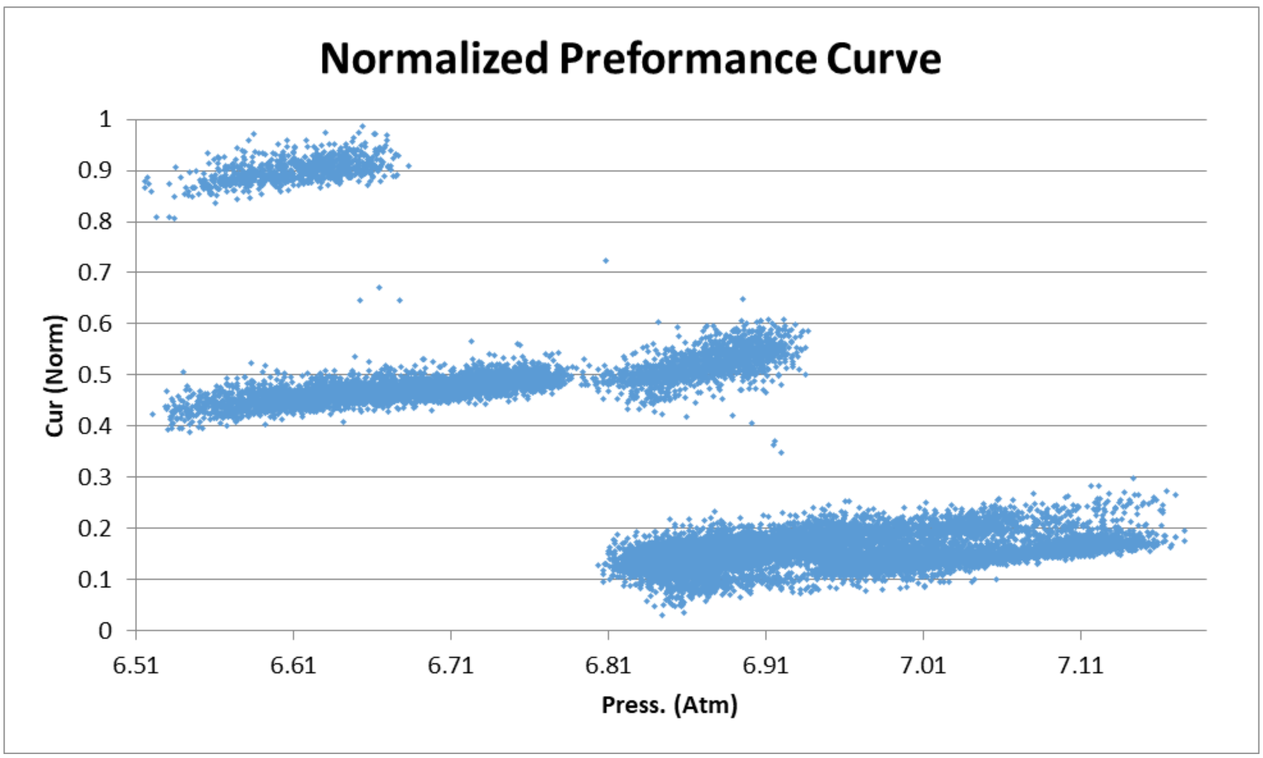

Figure 36: Active Rotor Length Adjustment Example 2

This graph is representative of poppet and step control. This type of active rotor length is represented by several different relatively straight lines. These lines look like the full load section from load/unload compressor control because that is really what they are. Opening or closing valves changes the size of the compressor but does not change the fact that the compressor is still running fully loaded. Instead it just creates a smaller fully loaded compressor. Each of the lines represents an additional valve that can be opened. Figure 36 contains 1 additional operation line that got cut off because it represents less than 2% of the data. This means there are four different settings the compressor operates on, corresponding to four different valves.

Step Control Setpoints

For this style of compressor, the pressure power graph can very clearly show where each of the pressure set points are for each of the compressor settings. Table 3 shows all of the load and unload pressure setpoints.

Table 3: Poppet Pressure Setpoints

Load %	Load pressure	Unload Pressure	Compressor Efficiency
100	6.52	6.64	0.40/Atm
75	6.81	6.93	0.29/Atm
50	6.99	7.13	0.20/Atm
25			0.14/Atm

The slope of each of these sections is also important, because each of these setting operates as a fully loaded compressor, the slope of each section represents the efficiency of the compressor with an increased operational pressure. Because each valve that opens changes the geometric size of the compressor, each compressor pressure efficiency should change too. These efficiencies are reported in Table 3. These compressor efficiencies would probably have more meaning if the graph was normalized through zero amps. As it is, these distinct compressor efficiencies are only meaningful when compared to each other.

Modulation Screw Compressors

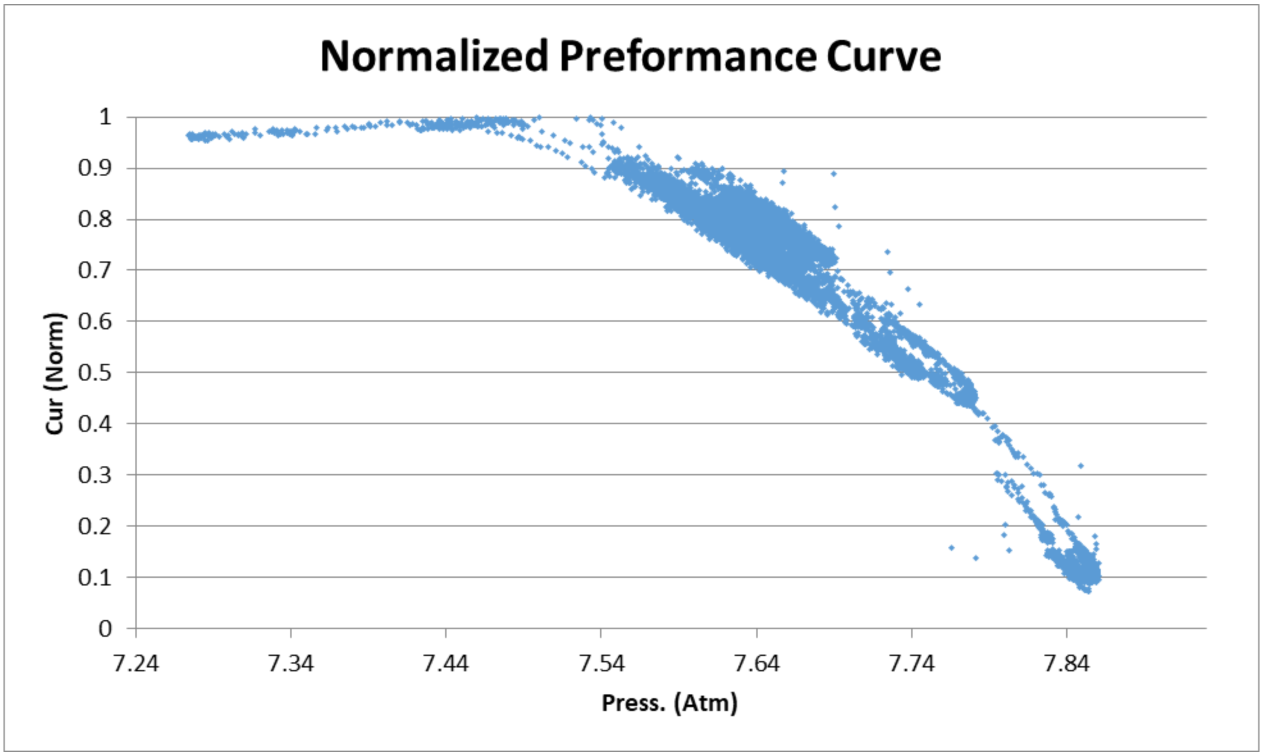

Figure 37: Modulation Example 1

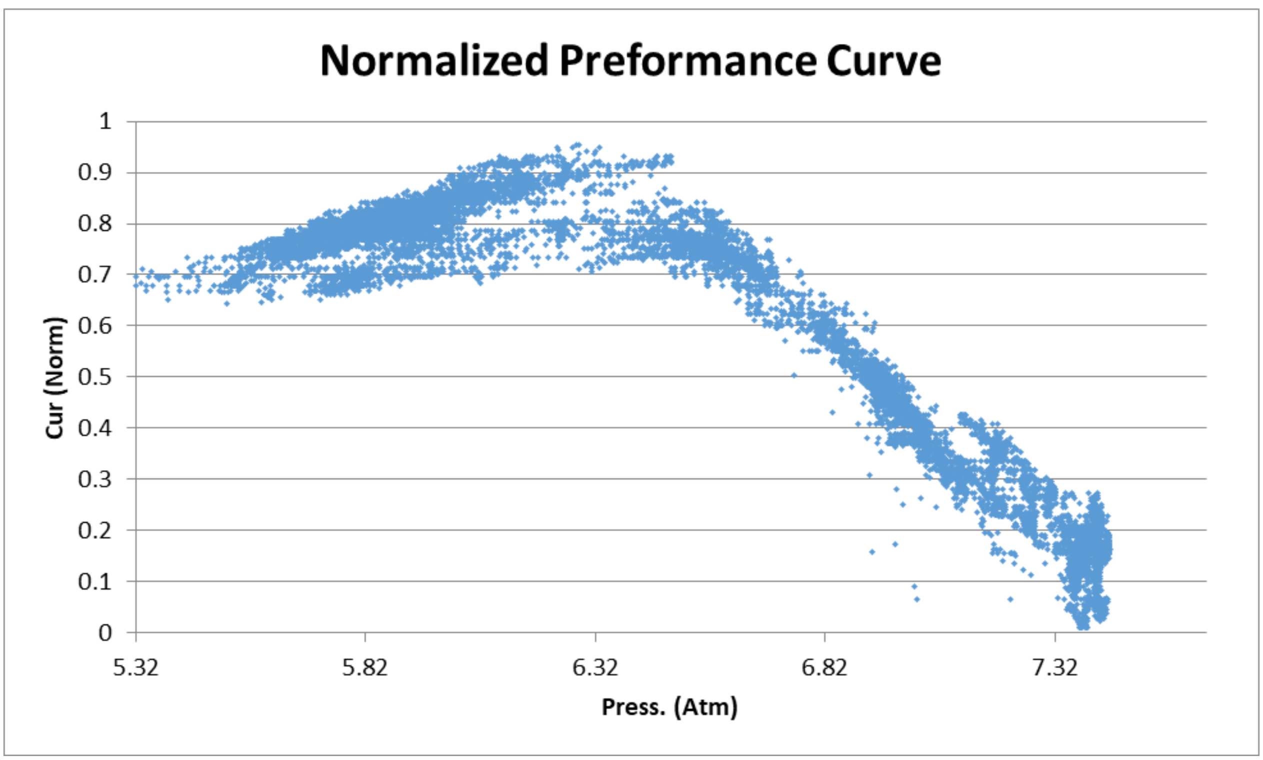

Figure 38: Modulation Example 2

The two figures above show what modulation control on a pressure power graph look like. Modulation control usually contains two or three states of operation: Full load operation, modulation control and a third load/unload slump curve that will cause the trace to form a cycle. In the first section the full load operation is represented by a straight line. The slope of the cycle while in full load is important because it shows the compressor efficiency with respect to power. This is explained in detail in the load/unload compressor section. The second state of operation is the modulation control. Here the compressor uses modulation control to reduce the volume of compressed air produced in order to keep system pressure. The second state of operation is represented by the diagonal line downward on the right side of the graph. This is the control section.

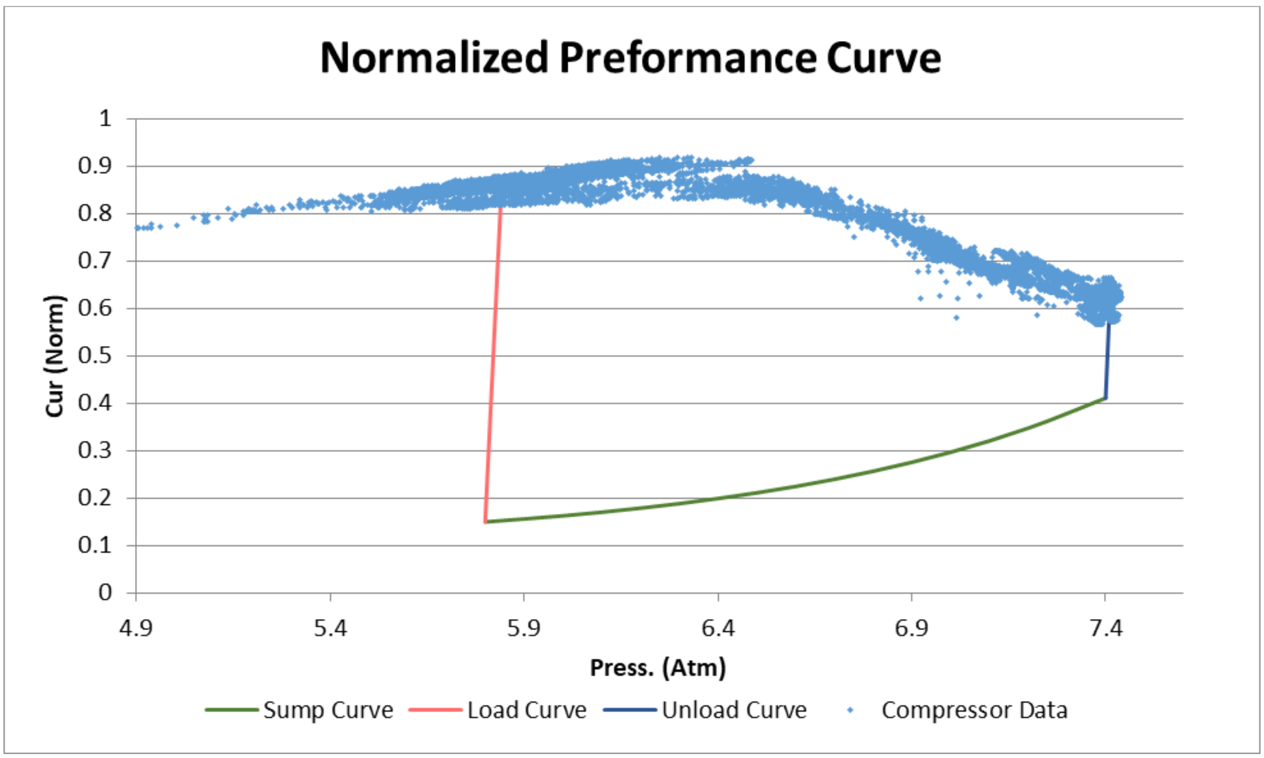

Figure 39: Modulation with Example of Load/Unload

The third section is only for modulation compressors that also run load/unload control. A representation of this is show in Figure 39. A pressure power graph for a compressor operating in this state would have an additional sump curve develop from the highest point of pressure after the modulation control is at a maximum. The slump curve would look exactly the same as the slump curve in a pressure power graph, from a load/unload compressor. The slump curve would run down to minimum pressure and a load stage would complete the cycle from the end of the slump curve to the start of the fully loaded section.

Modulation control compressors are much less common than any other type of compressor control. Because of this, only three compressors from the entire study operate with modulation control. None of the three operated with load/unload characteristics, but instead, all operated with a full modulation control scheme.

Setpoints

One of the most important characteristics for modulation control compressors on the pressure power graph is the pressure setpoints. These points include the minimum pressure where the compressor loads, the pressure when the compressor switches from fully loaded to modulation control, and the pressure when the compressor switches from modulation control to load/unload control. Of these setpoints only the pressure setpoint where the compressor switches from fully loaded to modulation control is displayed. The location of the minimum pressure is where the compressor curve switches from compressor load to fully loaded. The location of the full load maximum is where the compressor switches from the inclined fully loaded section, to the declined modulation section, and the absolute maximum pressure, if depicted, is where the compressor section switches from modulation control to the sump section.

Minimum Flow Analysis

The current value of the maximum pressure is also an important characteristic. In general, modulation compressors ramp down to about 70% full load power at 0% flow production. Finding the minimum current load at the maximum pressure will give a value for estimated compressor production at the compressor full load power. For modulation compressors operating load/unload, this is only slightly important. This estimation would be the minimum flow the compressor with operate before switching to load/unload. For compressors operating entirely in modulation, this value will give an estimate for minimum system load which is significantly more important. This minimum flow metric can be found with a pressure power graph normalized through 0 amps, or a non-normalized pressure power graph.

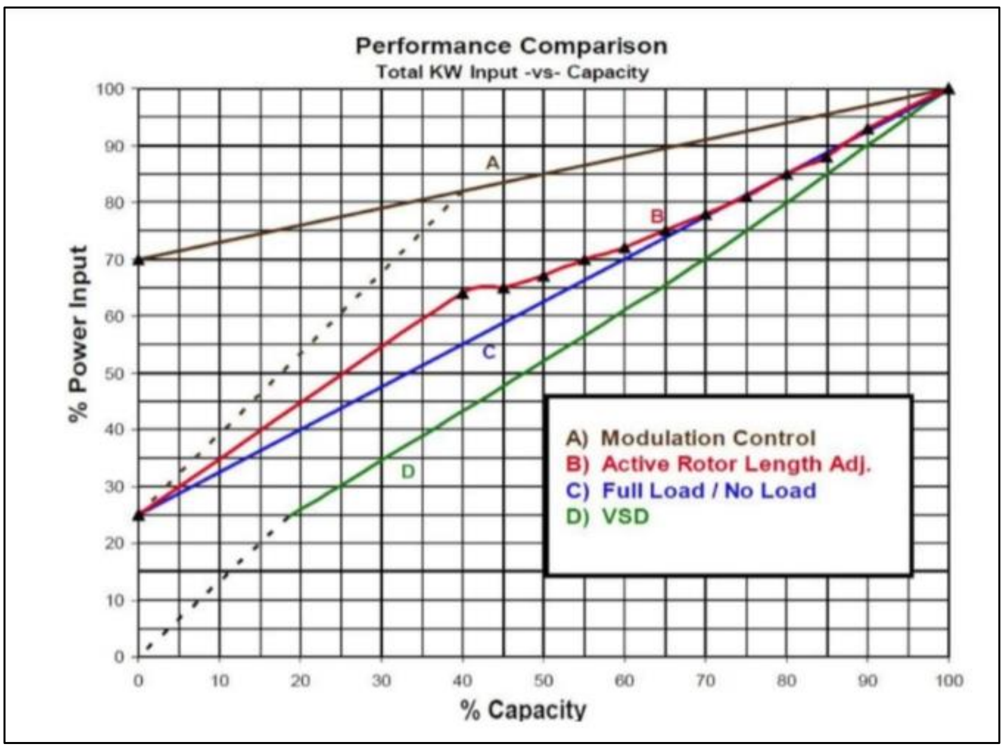

Figure 40: Compressor Preformance Comparison

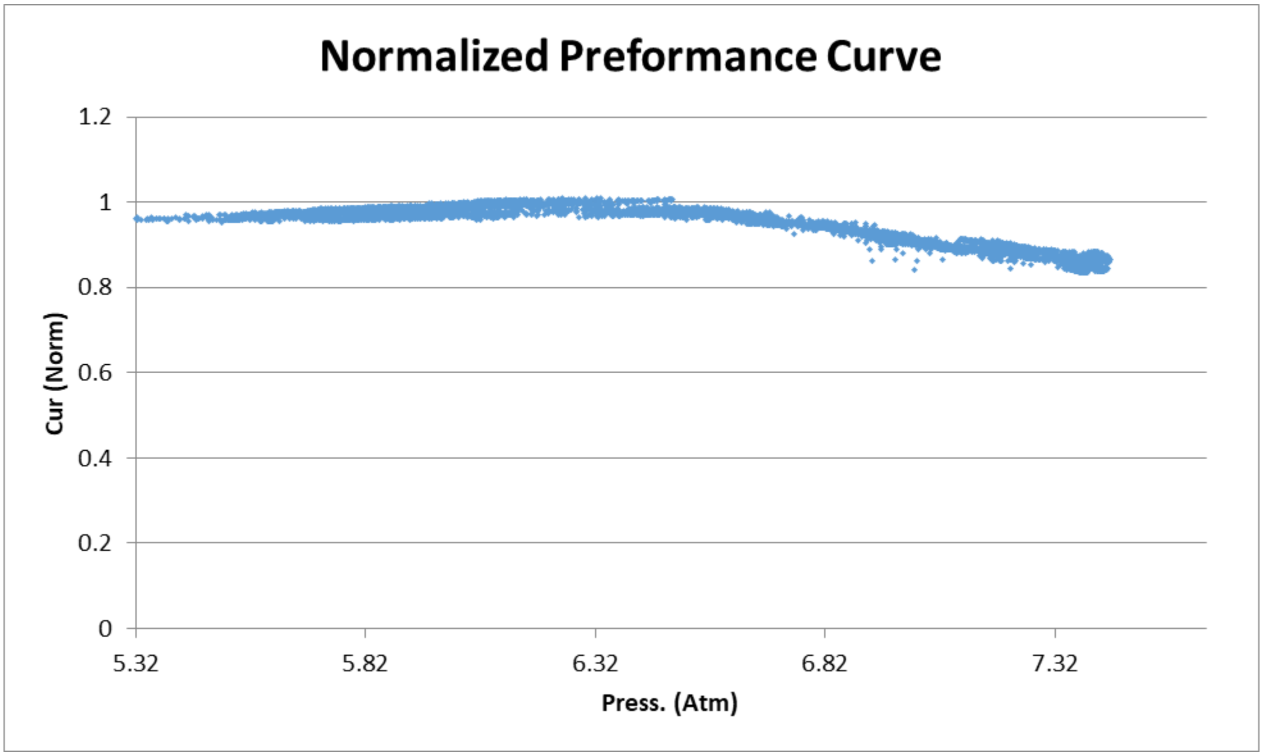

Figure 41: Non-Normalized Modulation Graph

In modulation control, the reduction in compressed air volume is linear to the reduction in compressor power, and a complete reduction in compressed air should correspond to a 30% reduction in compressor power. From this information, the minimum load on the compressor can be calculated with the following equation.

$$MF = \frac{MPC - 0.7}{0.3} \tag{7}$$

Where:

MF	=	The minimum system flow in percent of max rated compressor out,
MPC	=	The normalized current at the maximum pressure.

$$CV = \frac{0.84 - 0.7}{0.3} = 0.467 = 47\% \tag{8}$$

This 47% is an estimate and so unusual circumstances could case this measure to become inaccurate. This represents the minimum observed air production of the compressor. Because this compressor does not run load/unload control, this 47% also represents the minimum system demand load, in terms of the compressor operating capacity. If the compressor displayed a load/unload cycle, then a calculation like this would only tell the minimum air production of the compressor, before the compressor switches to load/unload control.

CHAPTER 5: CONCLUSION

Pressure power graphs illustrate another way that compressors can be analyzed. Pressure power graphs use current and pressure data from compressor systems, and provide a clearer representation of what cycling compressor systems look like. For load/unload compressors, this graph shows various kinds of information about how the compressor is preforming. For the other types of compressors, this graph shows pressure setpoints, load times and compressor operation stages.

The pressure power graphs outperform modern compressor analysis in three main sections. First, pressure power graphs can analyze an entire week of compressor performance data in one graph. Other types of analysis could never do this. Analyzing an entire week of data provides useful information. Glitches, errors, or bugs that occur with the air compressor do not necessarily happen when expected, and so increasing the data recording time as much as possible is a crucial part to a better compressor analysis. In addition, some compressors operate differently during the weekend or at night. Capturing the operation during these times could be crucial when determining the proper energy saving recommendation.

The second way pressure power graphs excel is in simplicity. Compressor controls that operate in a cycle, like load/unload, generate a pressure power graph with a loop. Compressor controls the operate without a cycle, like variable speed, generate a pressure graph without a loop. Current analysis that generate traces with respect to time do not show this cycle as a looping feature. This is helpful when learning about how compressor operate.

Last, pressure power graphs are very good at showing which compressor control scheme is in operation. Modern analysis can distinguish between some different styles of compressor control, but even then, it takes a trained eye, and careful evaluation.

Pressure power graphs also perform well in other smaller ways. Compressor system storage estimations for load/unload compressors becomes more easily identifiable. Compressor pressure set points, and pressure bands become more readable, and the variation on these values becomes more quantifiable. Compressor continuity, or how consistent the compressor keeps to a control scheme is also made clear over long periods of time which modern analysis has difficulty measuring.

Limitations

Pressure power graphs are not a silver bullet. These graphs show some compressor features clearly but in some regards they are more limited than current analysis methods. Pressure power graphs do not show data well in respect to time. It is difficult to see what day or time of day the data observed is displaying. In fact, the data displayed will probably be from multiple days. Consumption demand and compressor control systems may change throughout the week, and a pressure power graph can absolutely tell that change has occurred. Telling when change occurred or for how long it persisted, it another matter. Pressure power graphs have difficulty when analyzing the cycle length. In other forms of analysis, it would be easy to estimate a cycle time length. With the pressure power graph, this is all but impossible. Pressure power graphs also have difficulty sorting through noise. Before the sensor is recording, and after the sensor stops recording, the logging software will still record data. Usually this data is noise that strays anywhere from minimum to maximum sensor output. This data is easy to remove manually because it looks significantly different from real compressor data. It is difficult however, for a computer to identify this data as insignificant because this type of data is not constrained to a specific range.

The range of this thesis covers the pressure power graph's analyzing potential for screw compressors running the four main types of control: Modulation, active rotor length adjustment, load/unload, and variable speed. This thesis does not cover the pressure power graph analyzing potential for centrifugal compressors, scroll compressors, reciprocating compressors or any other style of compressor control for screw compressors. For these and other types of compressors, the pressure power graph needs more analysis and research. However, most air compressor systems in manufacturing facilities are powered by one of the four compressor styles discussed in this thesis, and so the results of this thesis should be applicable to many systems.

Future Work

There are a lot of different directions future work could take from this study. More research could be devoted to improving and expanding upon the current analysis code. During the study, it became clear that while normalizing the data around the minimum data helped for some recognition, normalizing the data through zero current would be helpful in some analysis procedures. Changes like this, or others could be made in order to show additional compressor characteristics.

A different direction for future work could be into the field of computer image recognition. Since much of the analysis in this field so far is devoted to computer simulation and graph generation, computer recognition software could be added to the script to allow the computer to automatically recognize patters, and find compressor operation setpoints. Computer pattern recognition could also be used to identify potential errors in the compressor settings, or inefficiencies in the operating schedule. Computer pattern recognition is a relatively new field of research and it is not clear how effective or how easy to use it will become in the following years.

A final direction future work could take is the continuation of analysis for different types of compressors not analyzed in this study, or for analysis on multi-compressor systems. Very limited research has gone into multi-compressor analysis for this study, but it is hypothesized that applying the pressure power graph to multi-compressor systems in some creative way might provide useful information.

Closing Statements

Pressure power graphs can change how air compressors are analyzed in plants, but they will not replace all other forms of compressor analysis. For total compressor analysis and for the greatest reliability in results, pressure power graphs should be used side-by-side with other analysis methods. Pressure power graphs are also simple to understand and help to visualize what actually happens in a compressor control cycle. Because of this, pressure power graphs would be useful as teaching material to describe why air compressors behave the way they do, and what can be done to improve performance, increase compressor life, and reduce energy cost to the plant.

So many compressor systems run in an unideal control state because the operator set up the controls in the wrong way. Many compressors are set to run with load/unload control when the compressor is designed to run with the more efficient variable speed control. With better data visualization, and clearer explanations, compressor systems can be understood, and mistakes like these can be avoided and compressor systems can run more efficiently. System performance and compressor life can be improved.

APPENDIX A: LOADING MACRO

```
Sub Load()

'Clean data from Input and output Worksheets

Sheets("Input Data").Cells.ClearContents

Sheets("Output Data").Cells.ClearContents


'Create empty chart for delete to have something to delete

Dim Chart3 As ChartObject

Set Chart3 = Sheets("Output Data").ChartObjects.Add(Range("I9").Left,
Range("I9").Top, 400, 300)


'Clear Charts from output worksheet

Sheets("Output Data").ChartObjects.Delete


'Move to Input Data Worksheet

Worksheets("Input Data").Activate


'Download data from computer (works for officer 2010 windows)

Dim ws As Worksheet, strFile As String

Set ws = ActiveWorkbook.Sheets("Input Data") 'set to current worksheet name

strFile = Application.GetOpenFilename("Text Files (*.csv),*.csv", , "Please select text
file...")
```

```
With ws.QueryTables.Add(Connection:="TEXT;" & strFile,
Destination:=ws.Range("B1"))
    .TextFileParseType = xlDelimited
    .TextFileCommaDelimiter = True
    .Refresh
End With
End Sub
```

APPENDIX B: NORMALIZING MACRO

```
Sub NormalizingMacro()


'Clear cells from Output Worksheet
Sheets("Output Data").Cells.ClearContents


'Create blank chart to keep delete charts from erroring
Dim Chart3 As ChartObject
Set Chart3 = Sheets("Output Data").ChartObjects.Add(Range("I9").Left,
Range("I9").Top, 400, 300)


'Delete all charts on Output Data
Sheets("Output Data").ChartObjects.Delete


'Move back to Output data Worksheet
Worksheets("Input Data").Activate




'Start of Macro
'Find Current header from data
    'Look for a single case of a cell containing Cur or AC in initial cells error case prompts
user for location
```

```
    Dim cell1 As Range

    Dim cell2 As Range

    Dim cell3 As Range

    Dim cell4 As Range

    Dim CaseNum


'Set Location case as error case to default

CaseNum = 3


'Long compicated if-nest that selects best guess for current cell header location

Set cell1 = Range("A1:Z5").Find("Cur")

If cell1 Is Nothing Then

    Set cell3 = Range("A1:Z5").Find("AC")

    If Not cell3 Is Nothing Then

        Set cell4 = Range("A1:Z5").Find("AC", After:=cell3)

        If cell3.Address = cell4.Address Then

            CaseNum = 2

        End If


    End If

Else

    Set cell2 = Range("A1:Z5").Find("Cur", After:=cell1)

    If cell2.Address = cell1.Address Then
```

```
        Set cell3 = Range("A1:Z5").Find("AC")
        If cell3 Is Nothing Then
            CaseNum = 1
        ElseIf cell1.Address = cell3.Address Then
            Set cell4 = Range("A1:Z5").Find("AC", After:=cell3)
            If cell3.Address = cell4.Address Then
                CaseNum = 1
            End If
        End If
    End If
End If
Dim CurHeader As Range

'Based on Case determined from if statement, Current header location
'is automatically selected or user is prompted for the location, and then stored
Select Case CaseNum
Case 1
Set CurHeader = cell1
Case 2
Set CurHeader = cell3
Case 3
Range("A1").Select
```

```
Set CurHeader = Range(InputBox("ERR: Give the current header cell location in format
as $E$5", "Header"))
End Select

'Find Pressure header from data
    'Look for a single case of a cell containing Cur or AC in initial cells error case prompts
user for location

    Dim cell5 As Range
    Dim cell6 As Range
    Dim cell7 As Range
    Dim cell8 As Range

'Set default selection case to manual selection
CaseNum = 3

'Long compicated if-nest that selects best guess for pressure cell header location
Set cell5 = Range("A1:Z5").Find("Pre")
If cell5 Is Nothing Then
    Set cell7 = Range("A1:Z5").Find("Psi")
    If Not cell7 Is Nothing Then
        Set cell8 = Range("A1:Z5").Find("Psi", After:=cell7)
        If cell7.Address = cell8.Address Then
```

```
            CaseNum = 2
        End If
    End If
Else
    Set cell6 = Range("A1:Z5").Find("Pre", After:=cell5)
    If cell6.Address = cell5.Address Then
        Set cell7 = Range("A1:Z5").Find("Psi")
        If cell7 Is Nothing Then
            CaseNum = 1
        ElseIf cell5.Address = cell7.Address Then
            Set cell8 = Range("A1:Z5").Find("Psi", After:=cell7)
            If cell7.Address = cell8.Address Then
                CaseNum = 1
            End If
        End If
    End If
End If

Dim PresHeader As Range

'Based on Case determined from if statement, pressure header location
'is automatically selected or user is prompted for the location, and then stored
Select Case CaseNum
```

```
Case 1
Set PresHeader = cell5
Case 2
Set PresHeader = cell7
Case 3
Range("A1").Select
Set PresHeader = Range(InputBox("ERR: Give the Pressure header cell location in
format as $E$5", "Header"))
End Select

'find the length of the dataset from difference between top and bottom cells
Dim Data_length As Long
Data_length = PresHeader.End(xlDown).Row - PresHeader.Row

'With data set length and the pressure and current headers
'the actual data can be inported from excel worksheets into an array
'Often much off the data will be useless because current or
'Pressure is zero. This data can be corrected by erasing it.
'This program assumes that if the pressure or the current is below 5psi/5AC
'the data can be ignored. The corrected data will be stored in seprate arrays.

'Dimensioning all data arrays
ReDim Pressure_Data(Data_length) As Single
```

```
ReDim Current_Data(Data_length) As Single
ReDim Pressure_DataC(Data_length) As Single
ReDim Current_DataC(Data_length) As Single

Dim Counter As Long
Counter = 0
Dim Data_lengthC As Long
Data_lengthC = 0

'Application.Function.Worksheet functions have a maximum range
'of around 16000 data point. Many of the data sets used have on the
'order of 500k to a million data points. The max and min values of the data arrays
'are calcuated from below, while the 98 and 2 percent percentials are
'calcuated in a slightly different way later on.

Dim Pressure_Max As Single
Pressure_Max = 0
Dim Pressure_Min As Single
Pressure_Min = 1000
Dim Current_Max As Single
Current_Max = 0
Dim Current_Min As Single
Current_Min = 1000
```

```
Dim Pressure_MaxC As Single
Pressure_MaxC = 0
Dim Pressure_MinC As Single
Pressure_MinC = 1000
Dim Current_MaxC As Single
Current_MaxC = 0
Dim Current_MinC As Single
Current_MinC = 1000

Do While Counter < Data_length
    Pressure_Data(Counter) = (Range(PresHeader.Offset(1 + Counter, 0).Address))
    Current_Data(Counter) = (Range(CurHeader.Offset(1 + Counter, 0).Address))

    If Pressure_Max < Pressure_Data(Counter) Then
        Pressure_Max = Pressure_Data(Counter)
    ElseIf Pressure_Min > Pressure_Data(Counter) Then
        Pressure_Min = Pressure_Data(Counter)
    End If

    If Current_Max < Current_Data(Counter) Then
        Current_Max = Current_Data(Counter)
    ElseIf Current_Min > Current_Data(Counter) Then
```

```
    Current_Min = Current_Data(Counter)
End If

If Pressure_Data(Counter) > 5 And Current_Data(Counter) > 5 Then
    Pressure_DataC(Data_lengthC) = Pressure_Data(Counter)
    Current_DataC(Data_lengthC) = Current_Data(Counter)

    If Pressure_MaxC < Pressure_DataC(Data_lengthC) Then
        Pressure_MaxC = Pressure_DataC(Data_lengthC)
    ElseIf Pressure_MinC > Pressure_DataC(Data_lengthC) Then
        Pressure_MinC = Pressure_DataC(Data_lengthC)
    End If

    If Current_MaxC < Current_DataC(Data_lengthC) Then
        Current_MaxC = Current_DataC(Data_lengthC)
    ElseIf Current_MinC > Current_DataC(Data_lengthC) Then
        Current_MinC = Current_DataC(Data_lengthC)
    End If
    Data_lengthC = Data_lengthC + 1

End If
```

```
    Counter = Counter + 1
Loop

'In the previous loop, the data length of the corrected data is calcuated
'The following arrays can now be re-dimensioned
ReDim Preserve Current_DataC(Data_lengthC) As Single
ReDim Preserve Pressure_DataC(Data_lengthC) As Single

'The percential functions can only run on about 16k data points, so the
'four data arrays are thined down to 16k points and stored in four additional
'data arrays
ReDim Current_DataCT(16000) As Single
ReDim Pressure_DataCT(16000) As Single
ReDim Current_DataT(16000) As Single
ReDim Pressure_DataT(16000) As Single

Counter = 0
Do While Counter < 16000
    Pressure_DataCT(Counter) = Pressure_DataC(Int(Data_lengthC / 16000 * Counter))
    Current_DataCT(Counter) = Current_DataC(Int(Data_lengthC / 16000 * Counter))
    Pressure_DataT(Counter) = Pressure_Data(Int(Data_length / 16000 * Counter))
    Current_DataT(Counter) = Current_Data(Int(Data_length / 16000 * Counter))
    Counter = Counter + 1
```

```
Loop

'Now the percential 98 and percential 02 can be calcualted and stored as variables
Dim Current_98 As Single
Dim Current_02 As Single
Dim Pressure_98 As Single
Dim Pressure_02 As Single
Dim Current_98C As Single
Dim Current_02C As Single
Dim Pressure_98C As Single
Dim Pressure_02C As Single

Current_98 = Application.WorksheetFunction.Percentile(Current_DataT, 0.98)
Current_02 = Application.WorksheetFunction.Percentile(Current_DataT, 0.02)

Pressure_98 = Application.WorksheetFunction.Percentile(Pressure_DataT, 0.98)
Pressure_02 = Application.WorksheetFunction.Percentile(Pressure_DataT, 0.02)

Current_98C = Application.WorksheetFunction.Percentile(Current_DataCT, 0.98)
Current_02C = Application.WorksheetFunction.Percentile(Current_DataCT, 0.02)

Pressure_98C = Application.WorksheetFunction.Percentile(Pressure_DataCT, 0.98)
Pressure_02C = Application.WorksheetFunction.Percentile(Pressure_DataCT, 0.02)
```

```
Worksheets("Output Data").Activate


'The next section of the code rebuiled the entire output worksheet including
'headers titles, and values
Range("B1").FormulaR1C1 = "Current (AMP)"
Range("C1").FormulaR1C1 = "Pressure (PSIG)"
Range("E1").FormulaR1C1 = "Current Corrected (AMP)"
Range("F1").FormulaR1C1 = "Pressure Corrected (PSIG)"
Range("A2").FormulaR1C1 = "MAX"
Range("A3").FormulaR1C1 = "98%"
Range("A4").FormulaR1C1 = "2%"
Range("A5").FormulaR1C1 = "MIN"
Range("A6").FormulaR1C1 = "Data Size"



Range("B2").Value = Current_Max
Range("B3").Value = Current_98
Range("B4").Value = Current_02
Range("B5").Value = Current_Min
Range("B6").Value = Data_length


Range("C2").Value = Pressure_Max
```

```
Range("C3").Value = Pressure_98
Range("C4").Value = Pressure_02
Range("C5").Value = Pressure_Min

Range("E2").Value = Current_MaxC
Range("E3").Value = Current_98C
Range("E4").Value = Current_02C
Range("E5").Value = Current_MinC
Range("E6").Value = Data_lengthC

Range("F2").Value = Pressure_MaxC
Range("F3").Value = Pressure_98C
Range("F4").Value = Pressure_02C
Range("F5").Value = Pressure_MinC

'This section of the code is applicatable for load/unload compressors only
'one very important piece of data for load/unload compressors is the compressor
'system storage often measured in units of Gal/CFM
'This is calculated using conversions between gallons and ft^3 and the average unload
'time of the compressor.
'AS OF NOW THE STORAGE METRIC IS NOT FULLY TESTED AND
UNRELIABLE
Dim Cycle As Long
```

```
Counter = 0

Dim Timer As Long

Timer = 0

Dim Normal_Storage As Single

ReDim CycleTimeData(Data_lengthC) As Long


Do While Counter < Data_lengthC

   Timer = Timer + 1

   If Current_DataC(Counter) > (Current_98C + Current_02C) / 2 And Current_DataC(1
+ Counter) < (Current_98C + Current_02C) / 2 Then

      Timer = 0

   ElseIf Current_DataC(Counter) < (Current_98C + Current_02C) / 2 And
Current_DataC(1 + Counter) > (Current_98C + Current_02C) / 2 Then

      CycleTimeData(Cycle) = Timer

      Timer = 0

      Cycle = Cycle + 1

   End If

   Counter = Counter + 1

Loop

If Cycle = 0 Then GoTo Line1

ReDim Preserve CycleTimeData(Cycle - 1)

Normal_Storage = Application.WorksheetFunction.Median(CycleTimeData) / 60 /
(Pressure_98C - Pressure_02C) * 7.48052 * 14.7
```

```
Line1:

Range("H1").FormulaR1C1 = "Plot Size"
Range("H2").FormulaR1C1 = "Storage Size"
Range("I2").Value = Normal_Storage
Range("J2").FormulaR1C1 = "Gal/CFM"
Range("H3").FormulaR1C1 = "Measurement Time"
Range("I3").Value = Data_length / 3600
Range("J3").FormulaR1C1 = "Hours"
Range("H4").FormulaR1C1 = "On Time"
Range("I4").Value = Data_lengthC / 3600
Range("J4").FormulaR1C1 = "Hours"

'Many of the data sets are expected to be very large >>100k data points
'It can be difficult to plot so visulaize plots when ther are so many
'data points. Also, that many data points will take a long time to graphically
'render. Therefore, the next section of the script allows the user to change
'the number of data points be graphed in each of the plots. Currently it is set
'on a default of 20k
Dim Plot_Size As Long
Plot_Size = InputBox("Choose a Data Plot Length." & vbCrLf & vbCrLf &
"Recommended Sizing is: 20000 Points", Default:=20000)
```

```
Range("I1") = Plot_Size

Counter = 0

'The same scaling process as before when scaling for the
'percential function happens here except with a variable size
ReDim Current_DataT(Plot_Size) As Single
ReDim Pressure_DataT(Plot_Size) As Single
ReDim Current_DataCT(Plot_Size) As Single
ReDim Pressure_DataCT(Plot_Size) As Single


Do While Counter < Plot_Size
    Current_DataT(Counter) = Current_Data(Int(Data_length / Plot_Size * Counter))
    Pressure_DataT(Counter) = Pressure_Data(Int(Data_length / Plot_Size * Counter))
'    The corrected data will be scaled based on certain condtitions in order to plot
'    a normalized plot that should standardize all plots based on pressure and compressor
size
    Current_DataCT(Counter) = ((Current_DataC(Int(Data_lengthC / Plot_Size *
Counter)) - Current_02C) / (Current_98C - Current_02C) * 0.8) + 0.1
    Pressure_DataCT(Counter) = Pressure_DataC(Int(Data_lengthC / Plot_Size *
Counter)) / 14.7
    Counter = Counter + 1
```

```
Loop

'Ploting charts
'Chart 1 is a non-normalized chart scaled from 0 to 111% (10/9) of 98 percential of
'both non-corrected current and pressure
Dim co1 As ChartObject
Dim ct1 As Chart
Dim sc1 As SeriesCollection
Dim Ser1 As Series

Set co1 = Sheets("Output Data").ChartObjects.Add(Range("B9").Left, Range("B9").Top,
470, 280)
    co1.Name = "Full Chart"
    Set ct1 = co1.Chart
With ct1
    .HasTitle = True
    .ChartTitle.Text = "Full Chart Preformance Curve"
    .HasLegend = False
    .Axes(xlValue, xlPrimary).HasTitle = True
    .Axes(xlValue, xlPrimary).AxisTitle.Characters.Text = "Cur (Amp)"
    .Axes(xlCategory, xlPrimary).HasTitle = True
    .Axes(xlCategory, xlPrimary).AxisTitle.Characters.Text = "Press. (Psi)"
```

```
    Set sc1 = .SeriesCollection
    Set Ser1 = sc1.NewSeries
    With Ser1
        .XValues = Pressure_DataT
        .Values = Current_DataT
        .ChartType = xlXYScatter
    End With

    .SeriesCollection(1).MarkerSize = 2
    .Axes(xlValue, xlPrimary).MinimumScale = 0
    .Axes(xlValue, xlPrimary).MaximumScale = Current_98 * 10 / 9
    .Axes(xlCategory, xlPrimary).MinimumScale = 0
    .Axes(xlCategory, xlPrimary).MaximumScale = Pressure_98 * 10 / 9
End With

'Chart 2 is a normalized plot scaled of the corrected current and pressure
'data, scaled so that the 98 and 2 percetials for both current and pressure
'lie on the 10 and 90 percentials of the graph
Dim co2 As ChartObject
Dim ct2 As Chart
Dim sc2 As SeriesCollection
Dim Ser2 As Series
```

```
Set co2 = Sheets("Output Data").ChartObjects.Add(Range("K9").Left, Range("K9").Top,
470, 280)
    co2.Name = "Full Chart"
    Set ct2 = co2.Chart
With ct2
    .HasTitle = True
    .ChartTitle.Text = "Normalized Preformance Curve"
    .HasLegend = False
    .Axes(xlValue, xlPrimary).HasTitle = True
    .Axes(xlValue, xlPrimary).AxisTitle.Characters.Text = "Cur (Norm)"
    .Axes(xlCategory, xlPrimary).HasTitle = True
    .Axes(xlCategory, xlPrimary).AxisTitle.Characters.Text = "Press. (Atm)"

    Set sc2 = .SeriesCollection
    Set Ser2 = sc2.NewSeries
    With Ser2
        .XValues = Pressure_DataCT
        .Values = Current_DataCT
        .ChartType = xlXYScatter
    End With

    .SeriesCollection(1).MarkerSize = 2
    .Axes(xlValue, xlPrimary).MinimumScale = 0
```

```
    .Axes(xlValue, xlPrimary).MaximumScale = 1
    .Axes(xlCategory, xlPrimary).MinimumScale = (Pressure_02C - ((Pressure_98C -
Pressure_02C) / 8)) / 14.7
    .Axes(xlCategory, xlPrimary).MaximumScale = (Pressure_98C + ((Pressure_98C -
Pressure_02C) / 8)) / 14.7
End With

End Sub
```

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VITA

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