Centrifugal vs Rotary Screw Air Compressor Performance: Full Load and Part Load Efficiency

Mike Lenti
Compressed Air Consultants
Keynote Speaker

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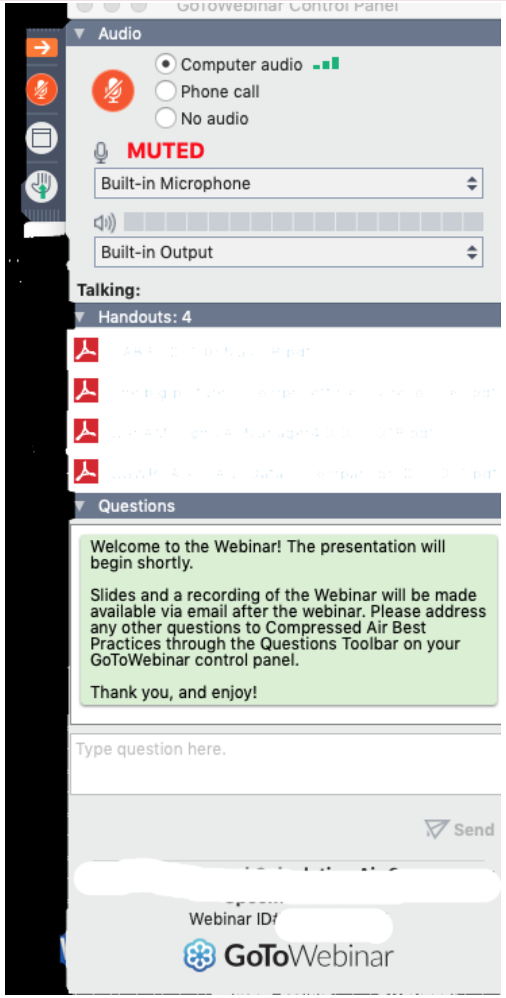

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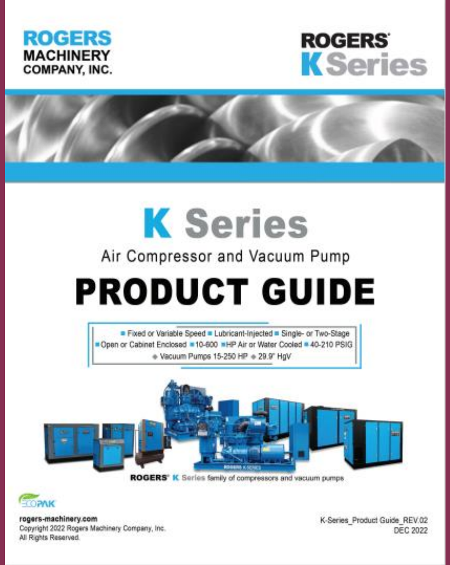

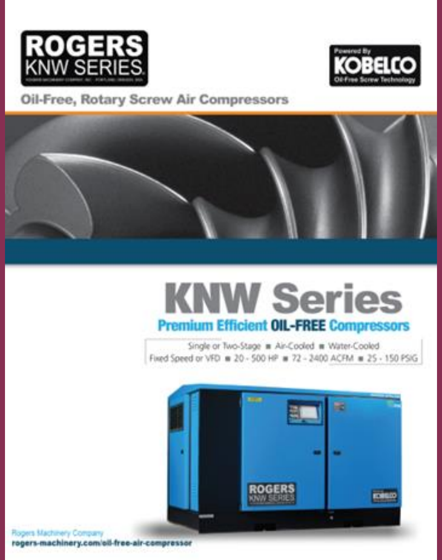

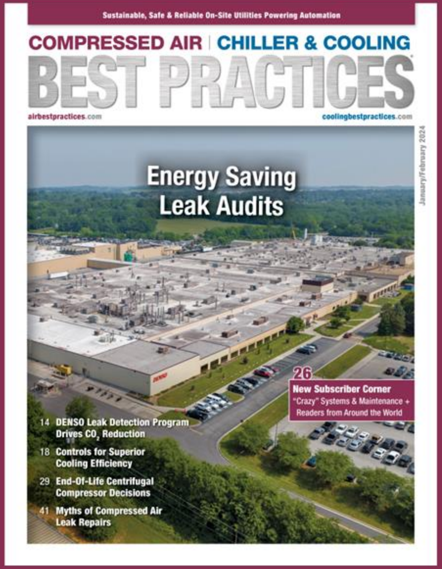

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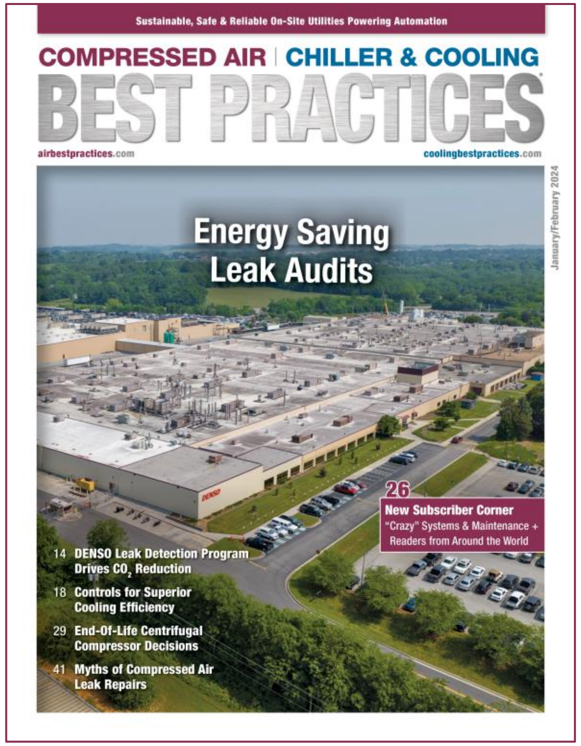
Centrifugal vs Rotary Screw Air Compressor Performance: Full Load and Part Load Efficiency

Introduction by

Compressed Air Best Practices® Magazine



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About the Speaker

Mike Lenti
Compressed Air Consultants

- Senior Auditor, Compressed Air Consultants
- Evaluated over 400 compressed air systems globally over the past 27 years
- Redesigned and assisted in the installation (both retrofit and new) of compressed air systems for optimization and reliability

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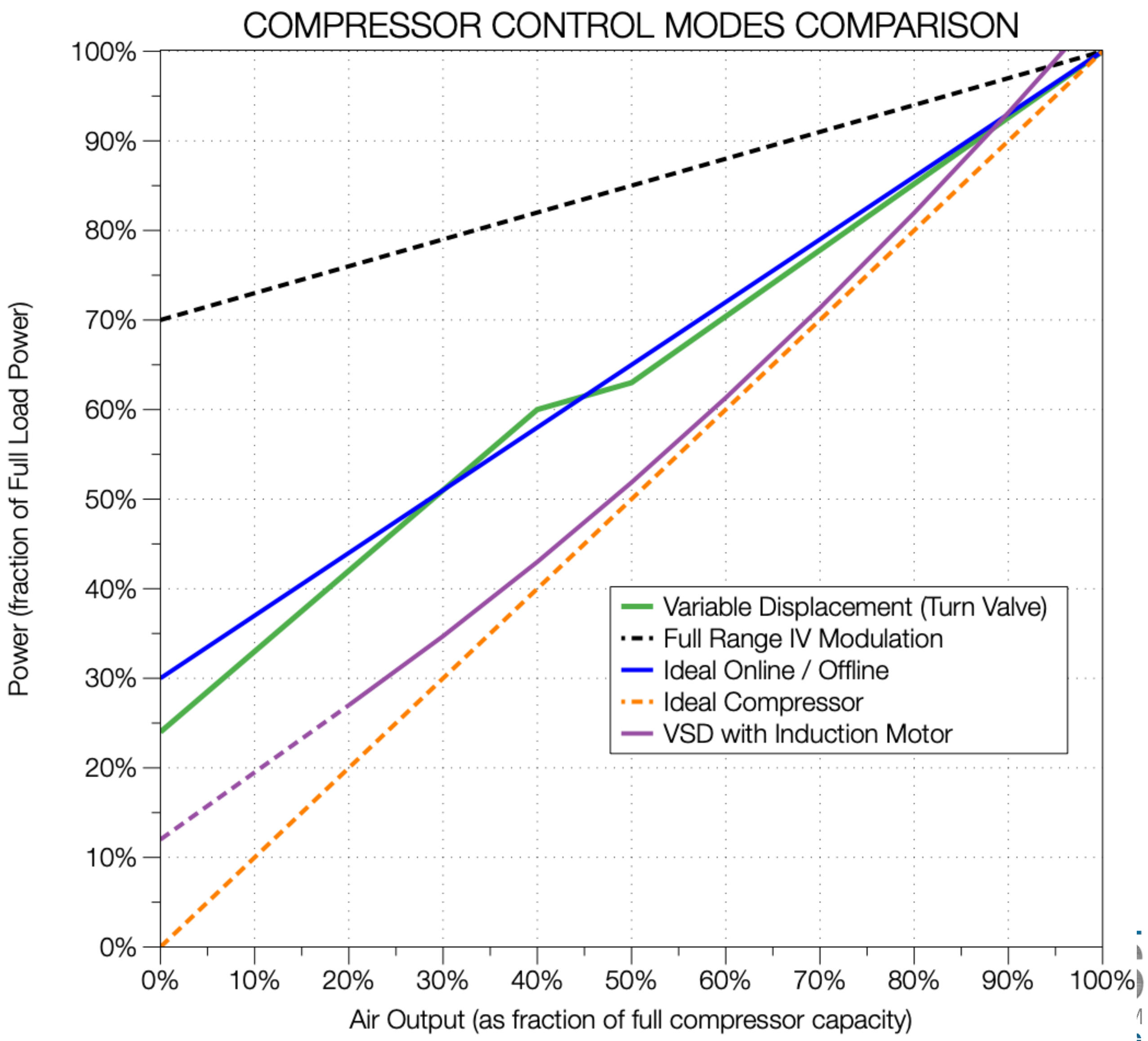
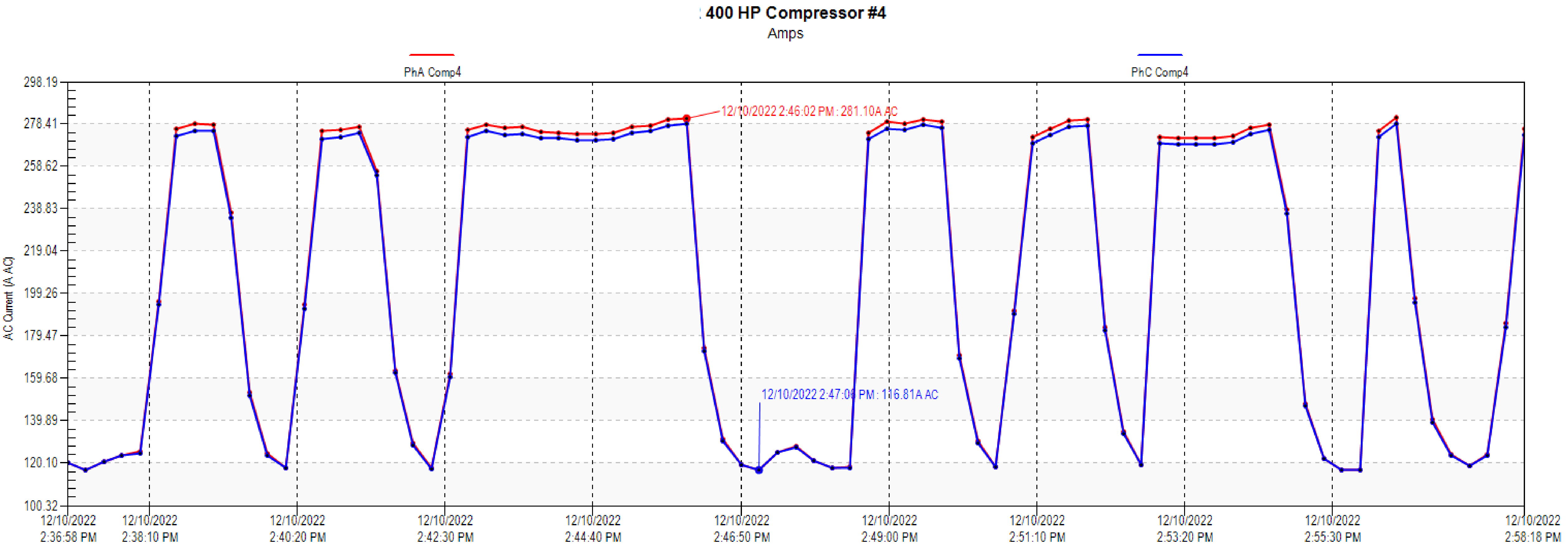
Individual Compressor Modes of Control

- On / Offline
- Modulation
  - Inlet Valve
  - Turn / Geometric Valve / Poppet
- Variable Speed Drive

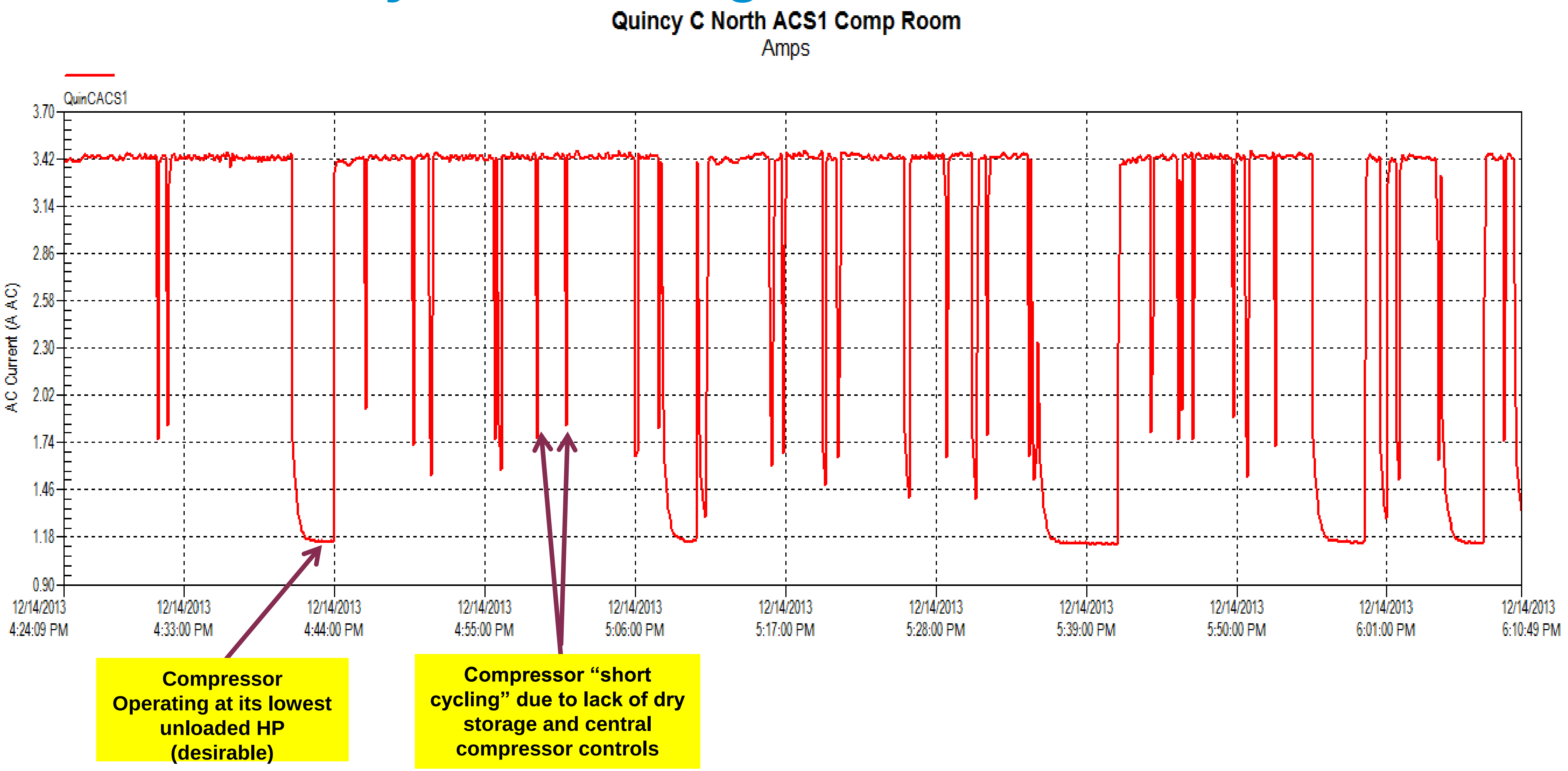


Online / Offline – Lubricated Compressors



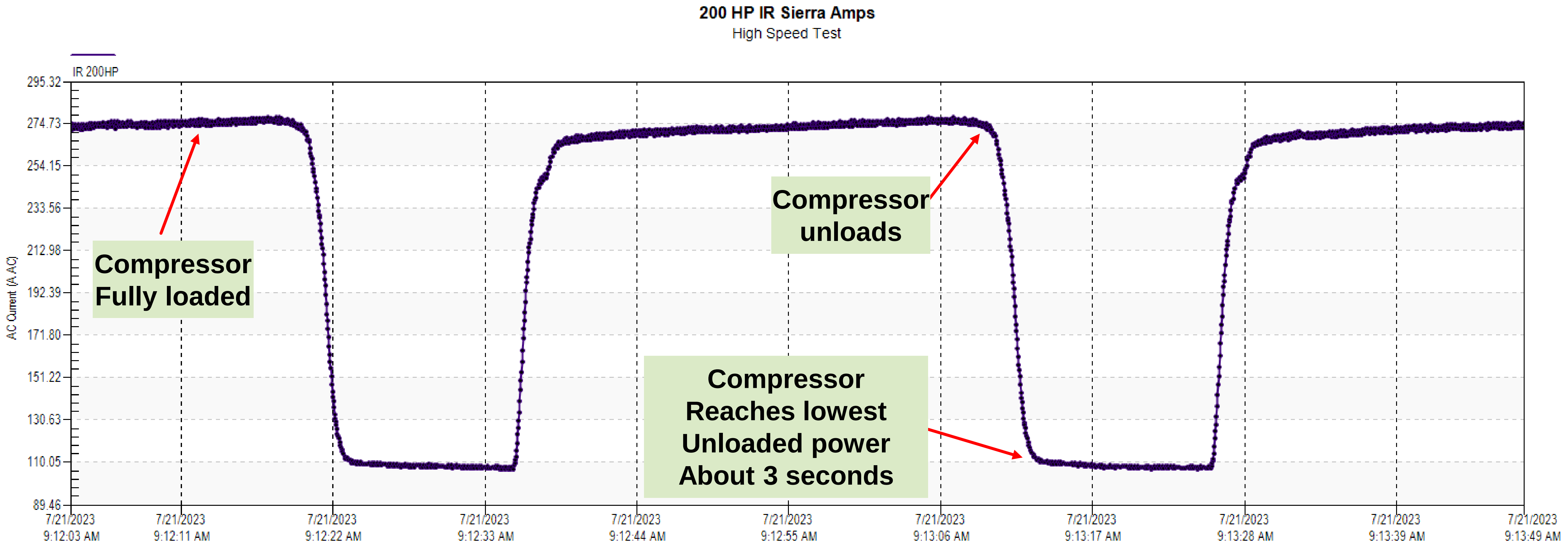
This compressor takes about 45 seconds to reach its lowest unloaded power level. Typically takes 30 seconds to 2 minutes. For lubricated compressor to unload to its lowest unloaded power level.

System Storage Considerations



Optimization of the compressor supply includes adding dry storage (after dryers) and Central compressor controls to coordinate loading of compressors

Online / Offline – Oil-Free Compressors



Compressor reaches its lowest unloaded power level in 3 to 4 seconds. Inter-stage has little volume to evacuate to reach lowest power level.

Oil Free Rotary Screw Compressors – Fixed Speed

Advantages

- Efficient part load efficiency due to low unloaded BHP – Short time to achieve lowest unloaded power
- Equipment does not require filtration for lubricant removal
- Low maintenance requirements and costs for annual maintenance
- Excellent option as trim service compressor for systems requiring oil-free air

Disadvantages

- Higher initial cost compared to other compressors (fixed speed / geometry controls)
- High rebuild costs relative to lubricated rotary screw units
- Sometimes less efficient operating at 100% load compared to a centrifugal
- Frequent cycling can shorten its life expectancy due to thrust loads on air end / element bearings

Annual Cost to Operate A Comp Air System - Energy

Financial Analysis - Annual Cost of Operation
Gold Producer and Processor

	Existing			Proposed			Financials			
Component - Electricity	**Annual Hours**	**KWD**	**Cost**	**Annual Hours**	**KWD**	**Cost**	**Annual Savings**	**Existing Kwh's**	**Proposed Kwh's**	**Annual Kwh Reduction**
Profile #1 - Normal Production										
Air Compressor / Dryer Power / Pumps / Fans	**8,700**	1,478	$ 578,563	**8,700**	1,146	$448,578	$129,986	12,856,962	9,968,394	2,888,569
Total Hours of Operation	**8,700**			**8,700**						
Sub Total			**$578,563**		**Totals**	**$448,578**	**$129,986**	**12,856,962**	**9,968,394**	**2,888,569**
Average Cost / KWH			**$0.0450**							
Annual Kwh Reduction			**2,888,569**							
Financial Analysis - Annual Cost of Operation										
Portable / Rental Equipment			**Existing**			**Proposed**	**Annual**			
Rental Compressors (Average 1.25 units)			$ 95,250			$ 23,813	$ 71,438			
Rental Air Dryers / Other Equipment			$ -			$ -	$ -			
Annual Diesel Fuel Portable Comps. Based on $2.20/Gal			$ 192,720			$ 48,180	$ 144,540			
Sub Total Portable Equipment			**$ 287,970**			**$ 71,993**	**$ 215,978**			

Annual Cost to Operate A Compressed Air System

Annual Maintenance			Cost			Cost	Savings
Outside Maintenance & Repair			$ 75,000			$ 75,000	$ -
Internal Maintance Labor			$ 30,000			$ 30,000	$ -
Major repairs			$ 40,000			$ 40,000	
Lubricant			$ 34,250			$ 20,550	$ 13,700
Desiccant Dryers			$ 20,000			$ 20,000	$ -
Waste Disposal			$ 7,808			$ 4,500	$ 3,308
Production Loss due to compressed air issues			$ 1,534,500			$ 383,625	$ 1,150,875
Other Uses							
Sub Total			**$ 1,741,558**			**$ 573,675**	**$ 1,167,883**
Grand Total Energy / Portables / Maintenance			**$ 2,608,091**			**$ 1,094,245**	**$ 1,513,846**
% Annual Operational Savings							**58%**
Energy Savings Analysis							
Average Air Generated by Air Compressors			**6,067**		**Scfm**	**5,119**	**948**
Annual Cost to Generate 1 SCFM All Cost			**$ 430**			**$ 214**	**$ 216**

Supply Side Optimization Techniques – High Production Losses Due to Compressed Air

Industries

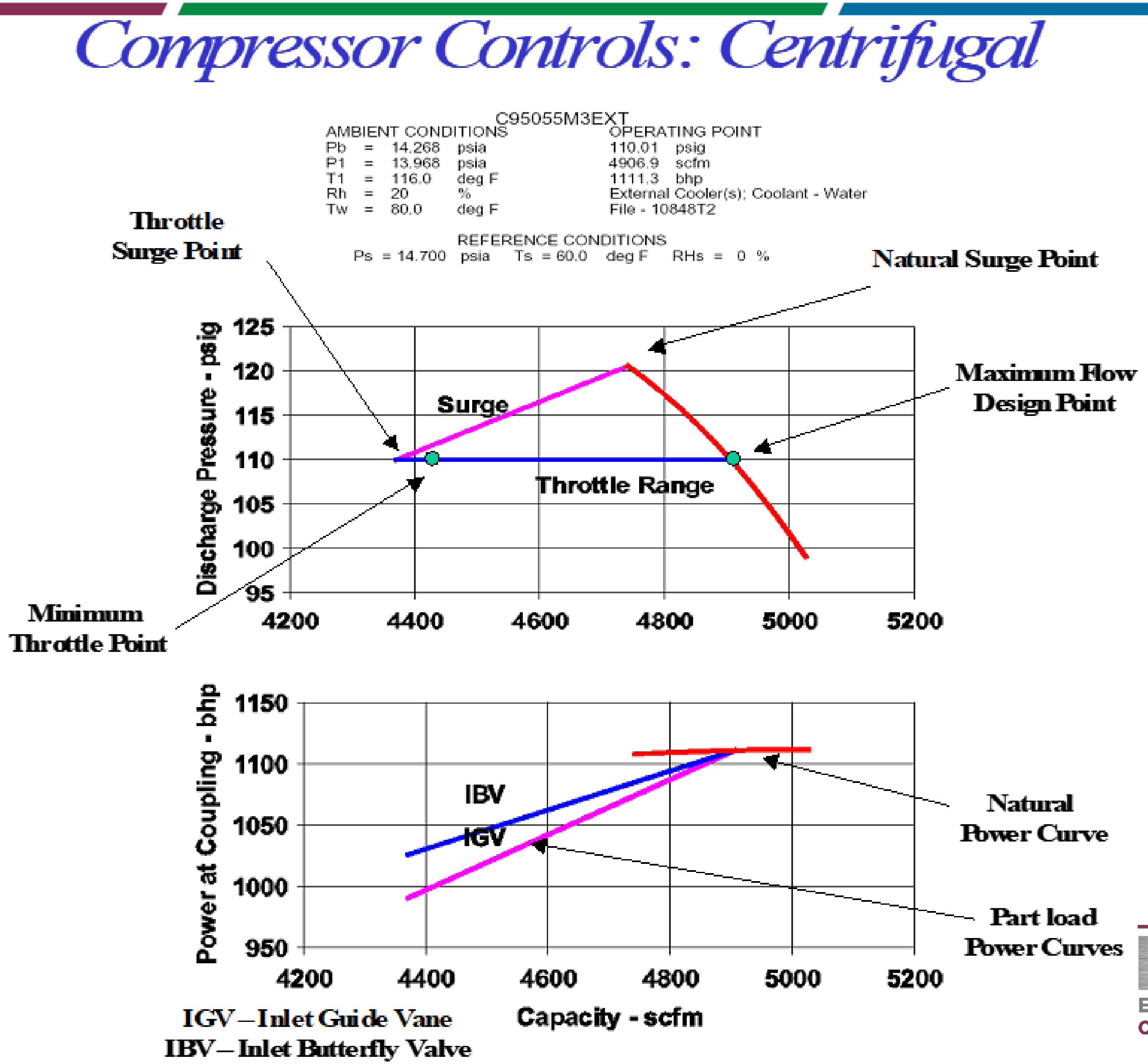
- Oil Refineries / Petrochemical
- Chemical / Plastic Plants
- Pharmaceutical
- Power Plants
- Railyards
- Textile Plant (Air Jet Spinning and Weaving)

Optimization requires a process approach as compared to strictly an energy approach

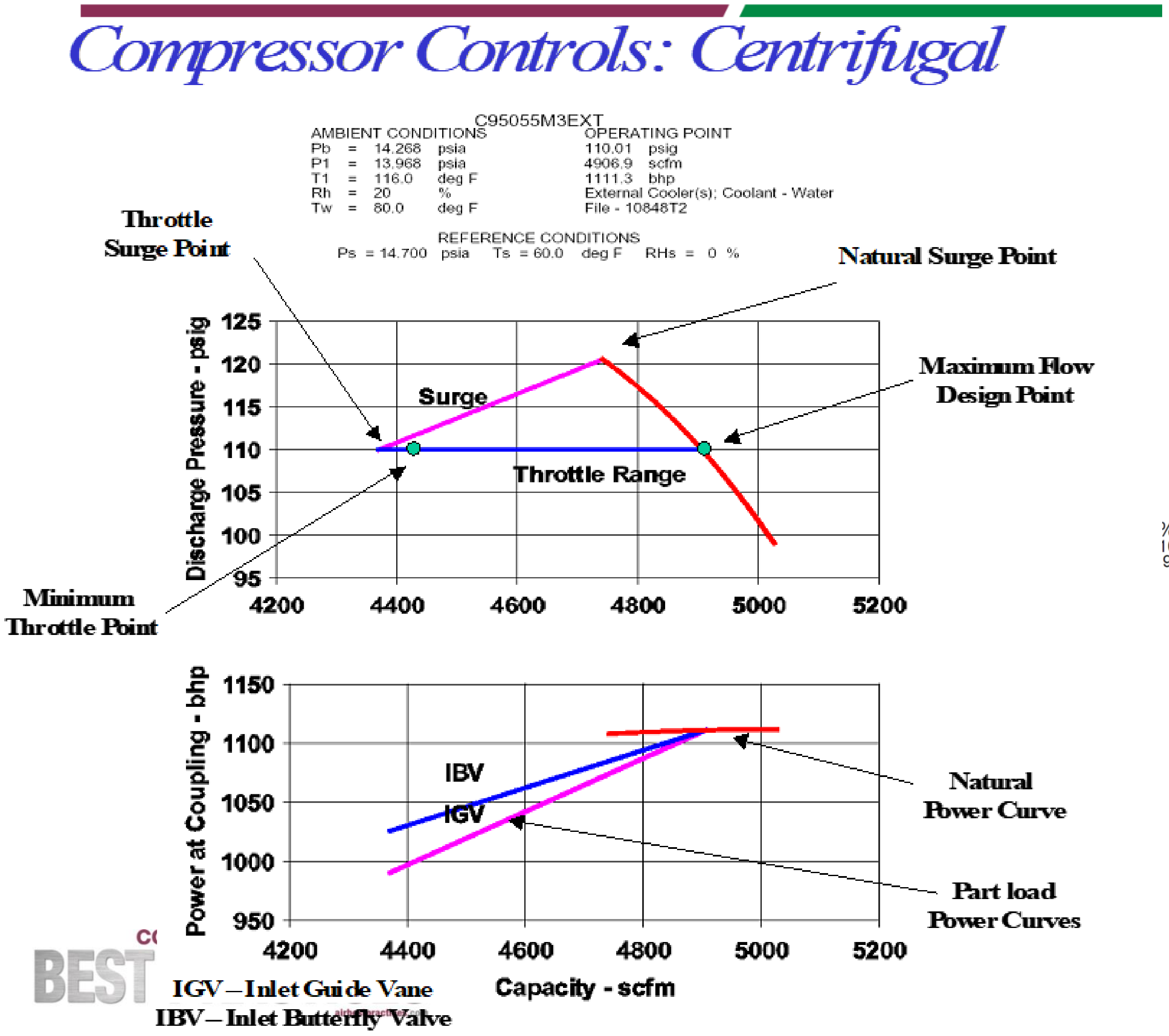
Centrifugal Compressors – Varying Capacity and Surge Line

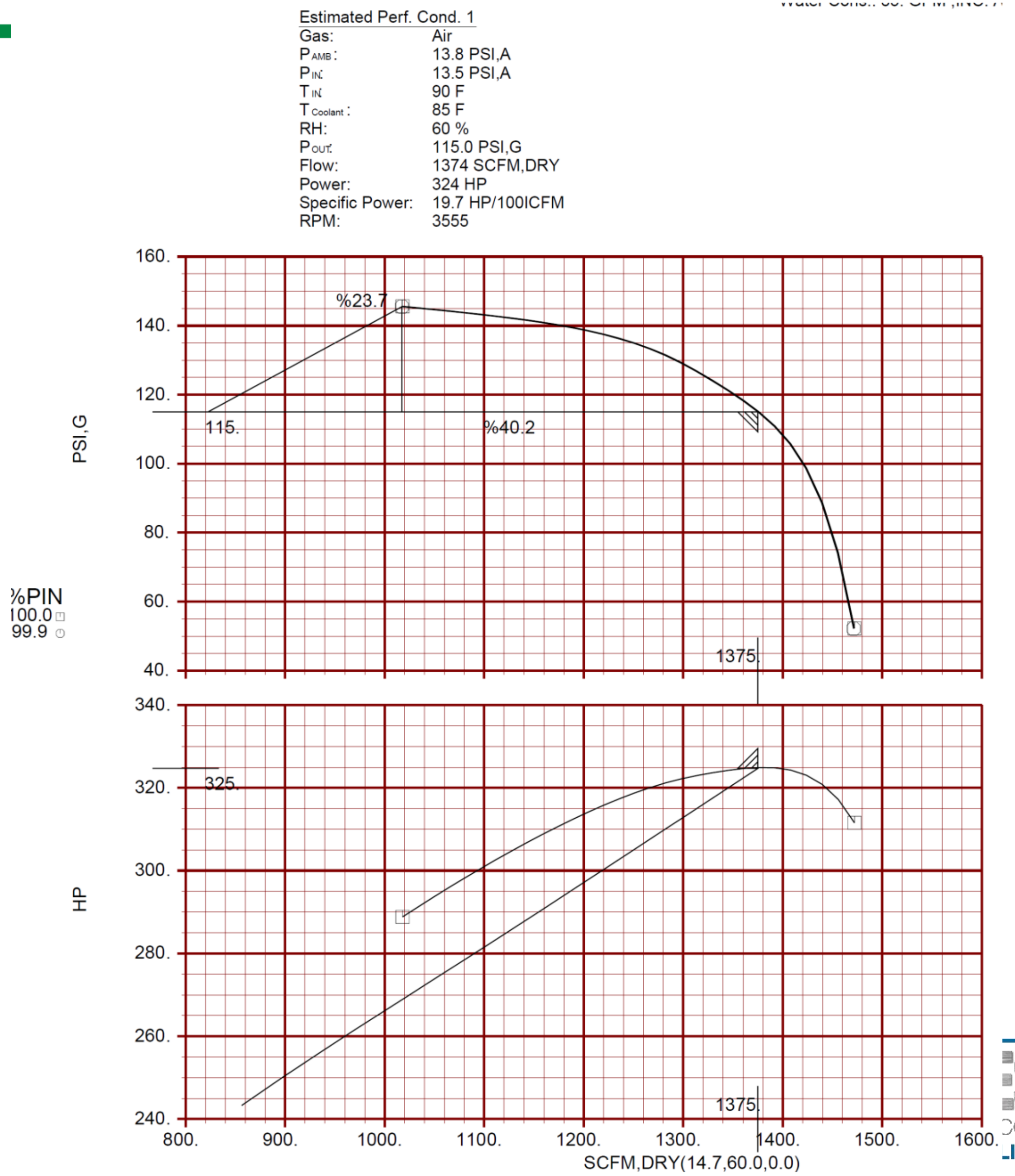
Centrifugal Controls
- Constant Pressure
- Auto Dual

Inlet Valves Option
- Inlet Butterfly Valve
- Inlet Guide Vanes
- VSD



Controls - Backward Leaning Versus Axial Type Impeller





Improve Centrifugal Compressor Reliability

- Operate Centrifugals at 100% loaded on natural curve for efficient and reliable operation.

- Load sharing compressors may increase possibility of surging but allows more capacity online to handle a loss of a machine.

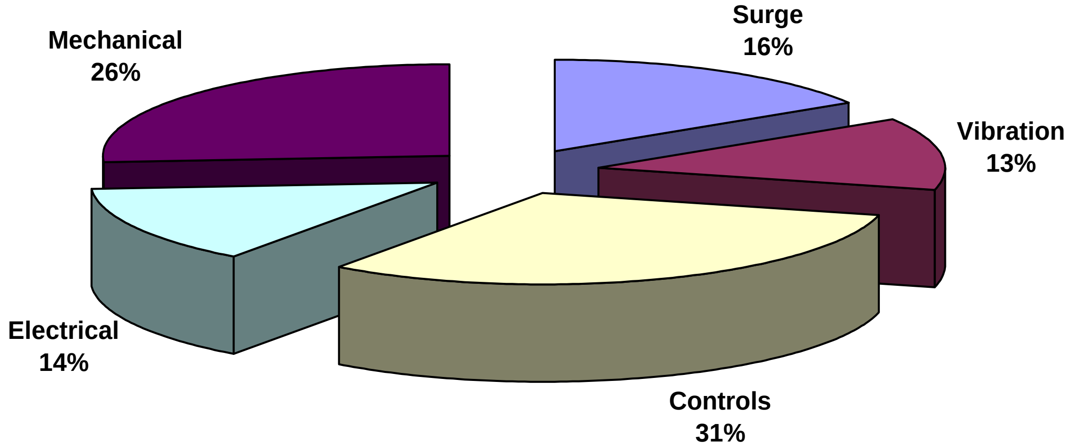
- Operate Centrifugals at lower discharge air pressure if possible, moving operating point of the machine away from throttle line and natural surge point

- Minimizing compressors on-line translates into possibly fewer failures if other machines can be used for trim operation (rotary screws).

- Increase storage to dampen pressure pulsations caused by intermittent peak events. Storage extends the time it takes for a centrifugal compressor to reach a throttle or natural surge.

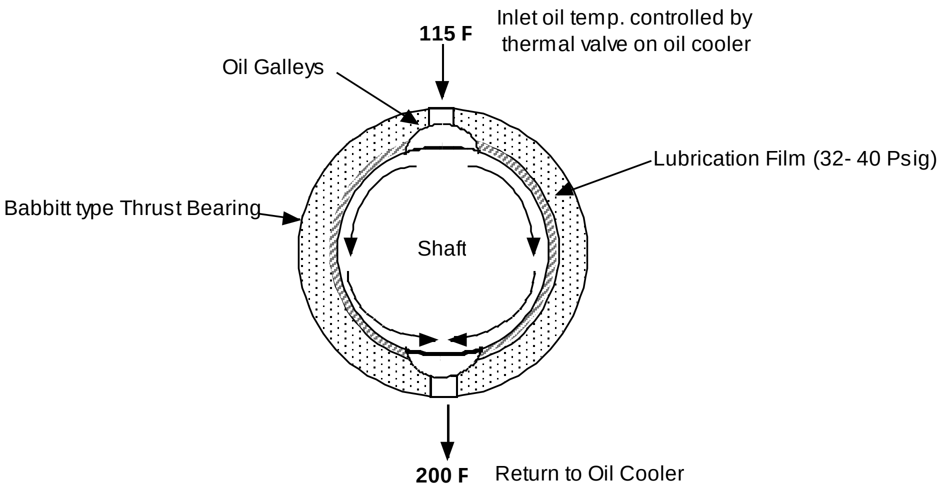
Centrifugal Compressors – Failure Rates by Percentage

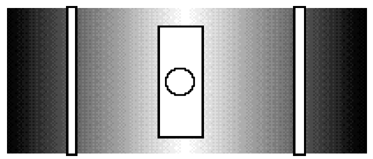
Failure Rates on Centrifugal Compressors



* Based on a sample of 60 (operating 8,400 hours a year

Centac Compressor
Thrust Bearing Bearing Configuration





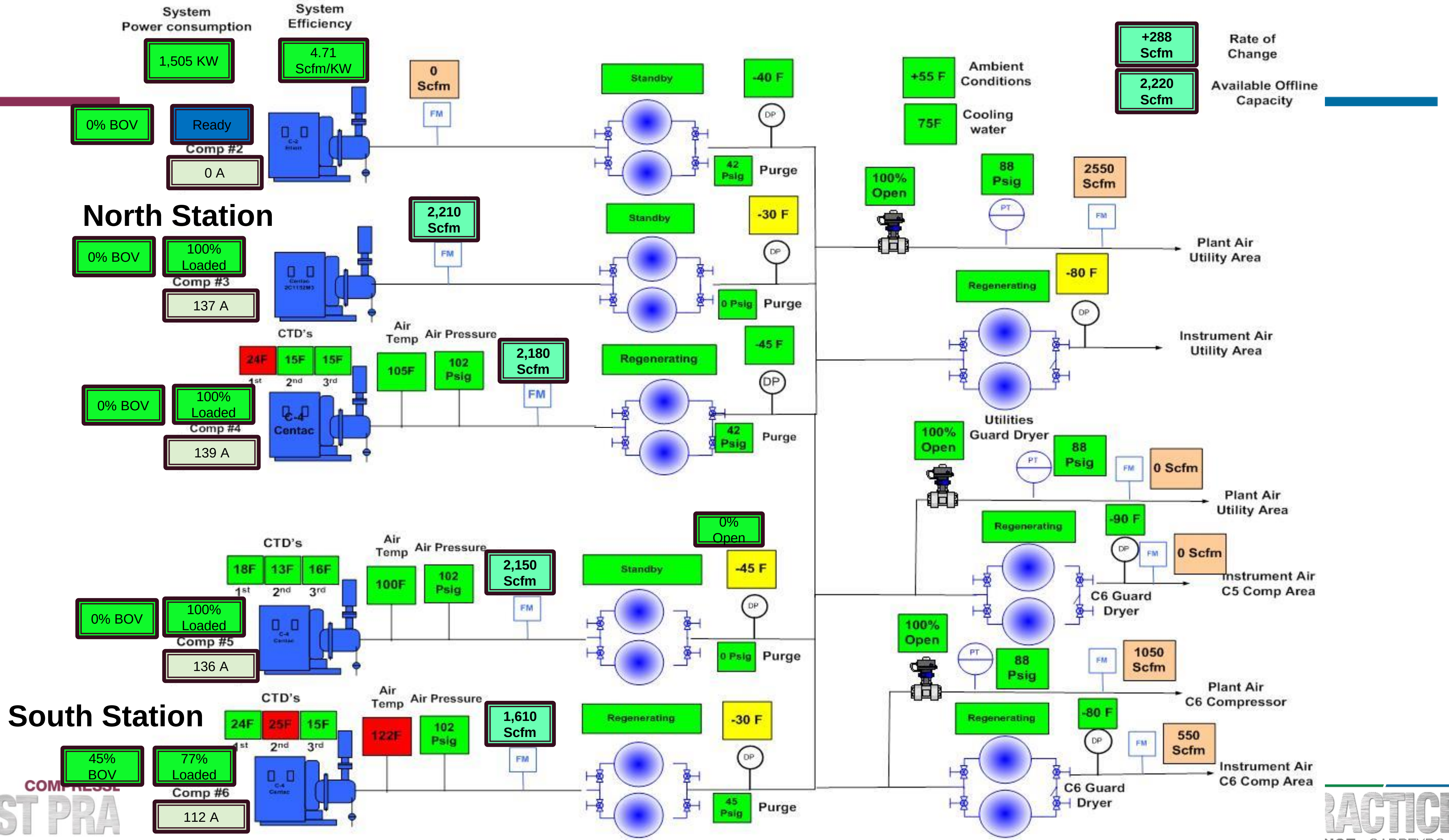
Top View

Both low and high oil temperatures can lead to premature bearing and air end failures. The shaft rotates on a lubrication film. If the oil temperature is too low (65-90 F), the high viscosity of the oil can cause the "lubrication film" to be interrupted causing hot spots at various points on the bearing. The hot spots can lead to "frosting" and deformation of the bearing. The low oil temperature set point should not be set below 100F.

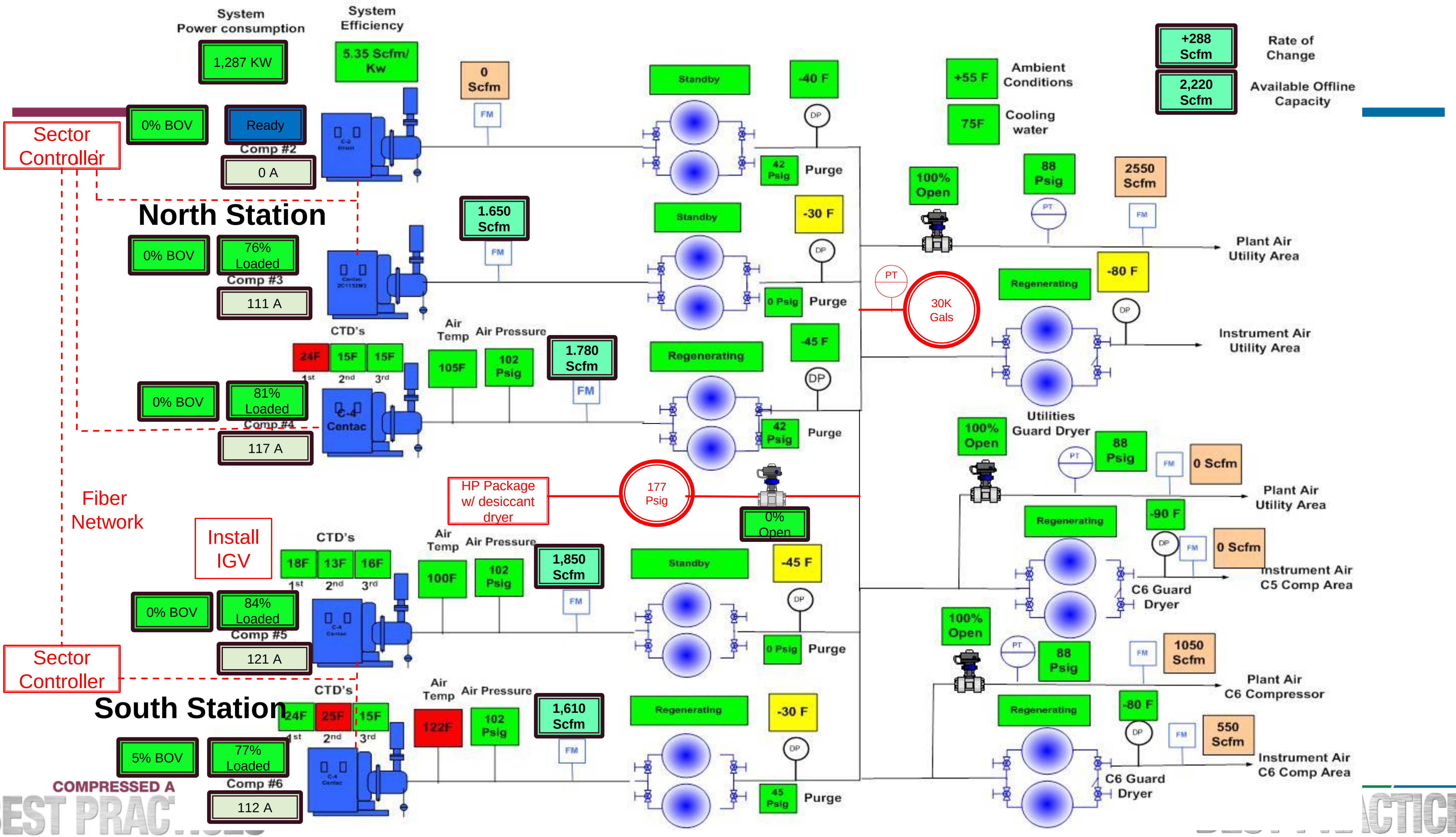
Oil temperatures exceeding 300F can lead to varnishing or oil failure. Oil varnishing leaves a residue that reduce path of the lubrication. The varnishing will eventually interrupt the lubrication path causing the shaft to "grab" the bearing. Again, the failure of the bearing can lead to the air end damage. Since each stage is connected through a bull gear, damage can occur in multiple stages. The high oil temperature should not be set higher than 125F. Using these parameter, the typical operating temperature of the bearing will be below 200F.

Existing Compressed Air System – Centrifugal Compressors

- Two (2) compressor stations (North & South) located on opposite sides of the facility and are interconnected.
- All centrifugal system with machines from the same manufacturer – backward leaning impeller technology
- Most compressors are equipped with Inlet Guide Vanes (IGV) except for one unit (inlet butterfly valve)
- Average demand equivalent to 3.2 compressors. Three comps fully loaded. One compressor in significant blowoff
- Low pressure conditions results in some batch processes aborting, resulting in production losses in the $100,000's
- Backup compressor has a staggered set point to load if pressure drops by 15 Psig.
- Most cases backup compressor does not load in time to protect some processes from aborting batch process
- Backup compressor takes about 45 seconds to go through permissives, start, ramp up, and load onto the system.



System Power consumption
1,505 KW
System Efficiency
4.71 Scfm/KW
0 Scfm
FM
Standby
-40 F
DP
+55 F
Ambient Conditions
75F
Cooling water
+288 Scfm
Rate of Change
2,220 Scfm
Available Offline Capacity
0% BOV
Ready
Comp #2
0 A
42 Psig
Purge
100% Open
88 Psig
2550 Scfm
PT
North Station
2,210 Scfm
Standby
-30 F
0% BOV
100% Loaded
Comp #3
137 A
0 Psig
Purge
Plant Air Utility Area
-80 F
Regenerating
Instrument Air Utility Area
CTD's
24F
15F
15F
1st
2nd
3rd
Air Temp
105F
Air Pressure
102 Psig
2,180 Scfm
Regenerating
-45 F
0% BOV
100% Loaded
Comp #4
C-4 Centac
139 A
42 Psig
Purge
Utilities Guard Dryer
100% Open
88 Psig
0 Scfm
Plant Air Utility Area
Regenerating
-90 F
0 Scfm
Instrument Air C5 Comp Area
C6 Guard Dryer
0% Open
CTD's
18F
13F
16F
1st
2nd
3rd
Air Temp
100F
Air Pressure
102 Psig
2,150 Scfm
Standby
-45 F
0% BOV
100% Loaded
Comp #5
136 A
0 Psig
Purge
100% Open
88 Psig
1050 Scfm
Plant Air C6 Compressor
South Station
CTD's
24F
25F
15F
1st
2nd
3rd
Air Temp
122F
Air Pressure
102 Psig
1,610 Scfm
Regenerating
-30 F
-80 F
Regenerating
550 Scfm
Instrument Air C6 Comp Area
C6 Guard Dryer
45% BOV
77% Loaded
Comp #6
112 A
45 Psig
Purge


System Power consumption
1,287 KW
System Efficiency
5.35 Scfm/ Kw
0 Scfm
Standby
-40 F
+55 F
Ambient Conditions
75F
Cooling water
+288 Scfm
Rate of Change
2,220 Scfm
Available Offline Capacity
Sector Controller
0% BOV
Ready
Comp #2
0 A
42 Psig
Purge
100% Open
88 Psig
2550 Scfm
North Station
1.650 Scfm
Standby
-30 F
Plant Air Utility Area
0% BOV
76% Loaded
Comp #3
111 A
PT
30K Gals
0 Psig
Purge
Regenerating
-80 F
CTD's
24F
15F
15F
Air Temp
105F
Air Pressure
102 Psig
1.780 Scfm
Regenerating
-45 F
Instrument Air Utility Area
0% BOV
81% Loaded
Comp #4
117 A
C-4 Centac
42 Psig
Purge
Utilities Guard Dryer
100% Open
88 Psig
0 Scfm
Fiber Network
HP Package w/ desiccant dryer
177 Psig
0% Open
Plant Air Utility Area
Regenerating
-90 F
0 Scfm
Install IGV
CTD's
18F
13F
16F
Air Temp
100F
Air Pressure
102 Psig
1,850 Scfm
Standby
-45 F
Instrument Air C5 Comp Area
C6 Guard Dryer
0% BOV
84% Loaded
Comp #5
121 A
0 Psig
Purge
100% Open
88 Psig
1050 Scfm
Sector Controller
Plant Air C6 Compressor
South Station
CTD's
24F
25F
15F
Air Temp
122F
Air Pressure
102 Psig
1,610 Scfm
Regenerating
-30 F
Regenerating
-80 F
550 Scfm
Instrument Air C6 Comp Area
C6 Guard Dryer
5% BOV
77% Loaded
Comp #6
112 A
45 Psig
Purge

Centrifugal Compressors – System Modifications

- Install central controls in each area to prevent individual compressors from blowing off to atmosphere
- Install IGV's on one of the South compressors to provide more stable modulation reducing likelihood of a throttle surge
- Use load sharing strategy to distribute output based on throttling capability of each machine
- Communicate with controllers using plants existing fiber network to coordinate compressor loading
- Add 30K of general storage to dampen pressure fluctuations & allow backup compressor to load during failure
- Install HP 180 Psig tank and dryer to slow pressure rate of decay for low pressure conditions / failure of compressor
- Upgrade a controller on a North compressor dryer so that is communicates with dedicated air compressor to prevent damage or fire

Long Term Replacement Strategy:

- Replace centrifugal reaching the end of its life cycle w/ an oil-free rotary screw, centrifugal w/ auto dual capabilities
- Modify controls strategy to operate the centrifugal comps fully loaded, a trim with oil-free screw or new centrifugal
- Minimizes starting of centrifugal compressors which is associated with high failure rates

Intermediate Controls

Intermediate Controllers

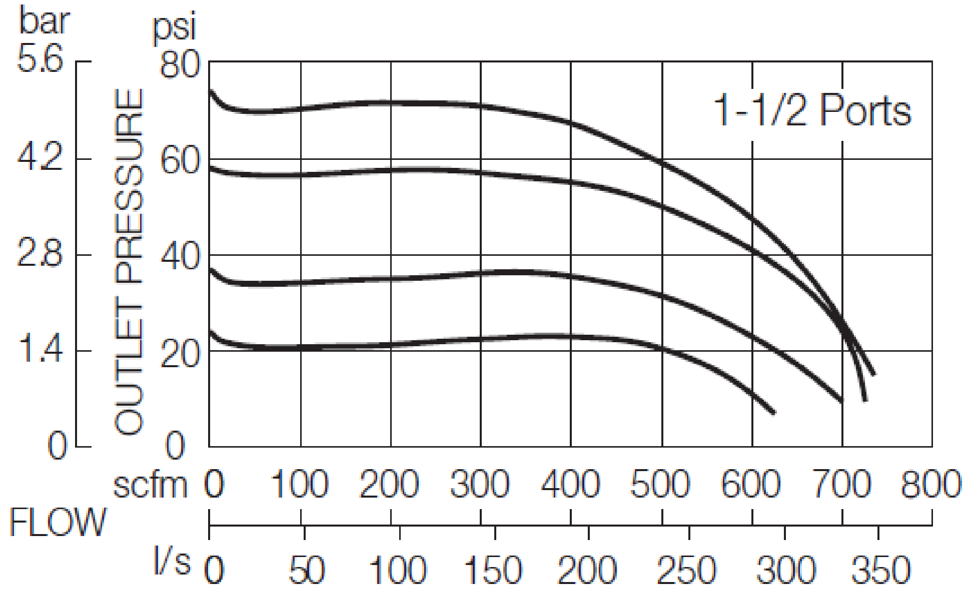
Pressure Control Stations

Intermediate Controls - Attributes

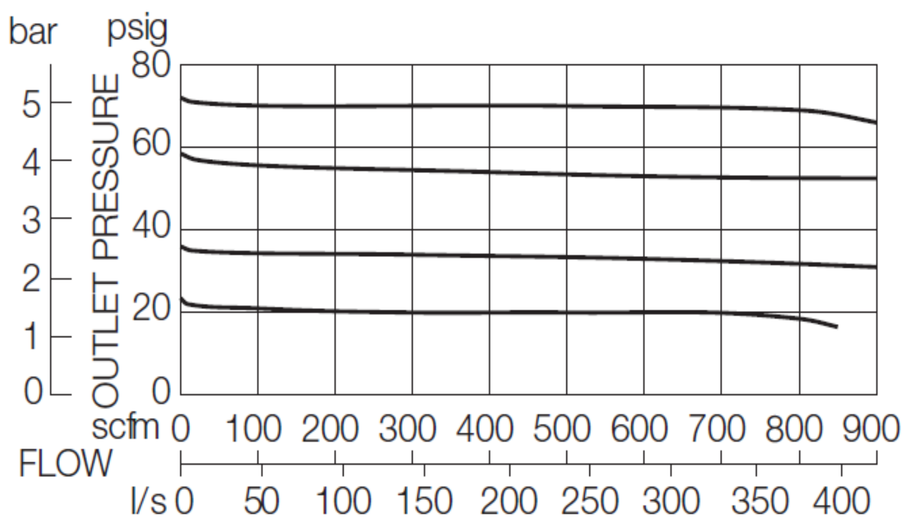
Storing compressed air at a higher pressure (useful storage) using an intermediate controller has the following benefits:

1. **Quick Availability of Comp Air –** Can quickly supply air to the system to serve intermittent peak demands in lieu of starting the next available compressor.
2. **Improved Supply Side Efficiency -** High pressure or “control” storage slows the rate of pressure change which enables a central compressor automation system to more effectively optimize the supply. **Often the supply side efficiency in terms of Scfm/Kw increases but is offset by productivity gains.**
3. **Protect Production Pressure During Failure -** Control storage (upstream of intermediate controller) can be designed to supply offline air that acts like a compressor during a failure mode. Control storage slows the rate of pressure decay during a compressor failure allowing time for the automation or local compressor controls to respond and start an offline compressor. This arrangement ensures that the site does not suffer from a low-pressure condition when an online unit fails. **Preventing production interruptions may be the greatest benefit of an intermediate controller.**
4. **Stable “Target Pressure” Control** – Provide tight pressure control that can allow average distribution pressure to be lowered. Lower average distribution pressures result in the reduction of artificial demand. **Stable pressure can improve productivity of pneumatic equipment in production.**

Pressure Regulator Performance Curves

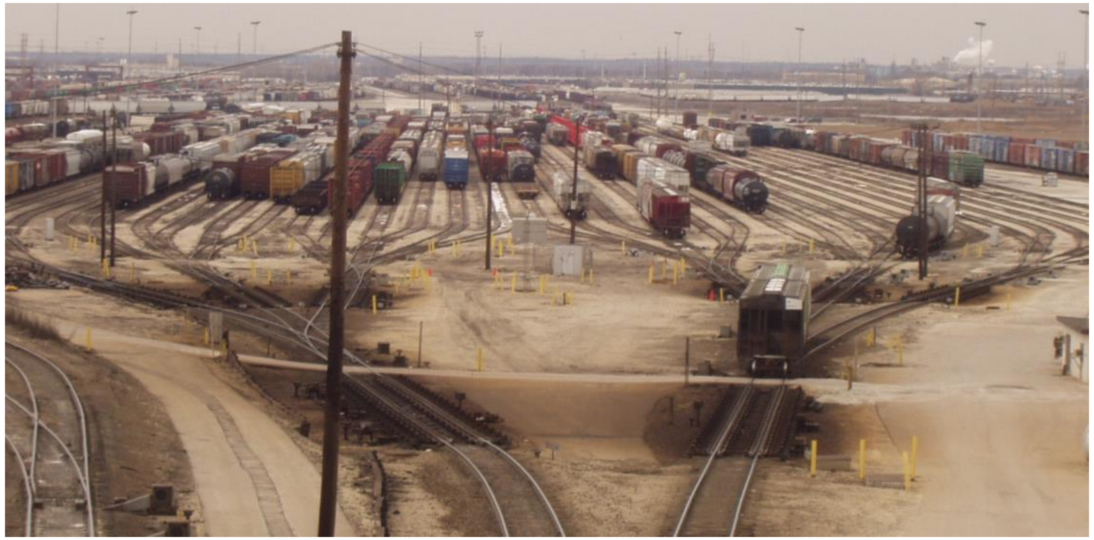


Internally Piloted Regulator

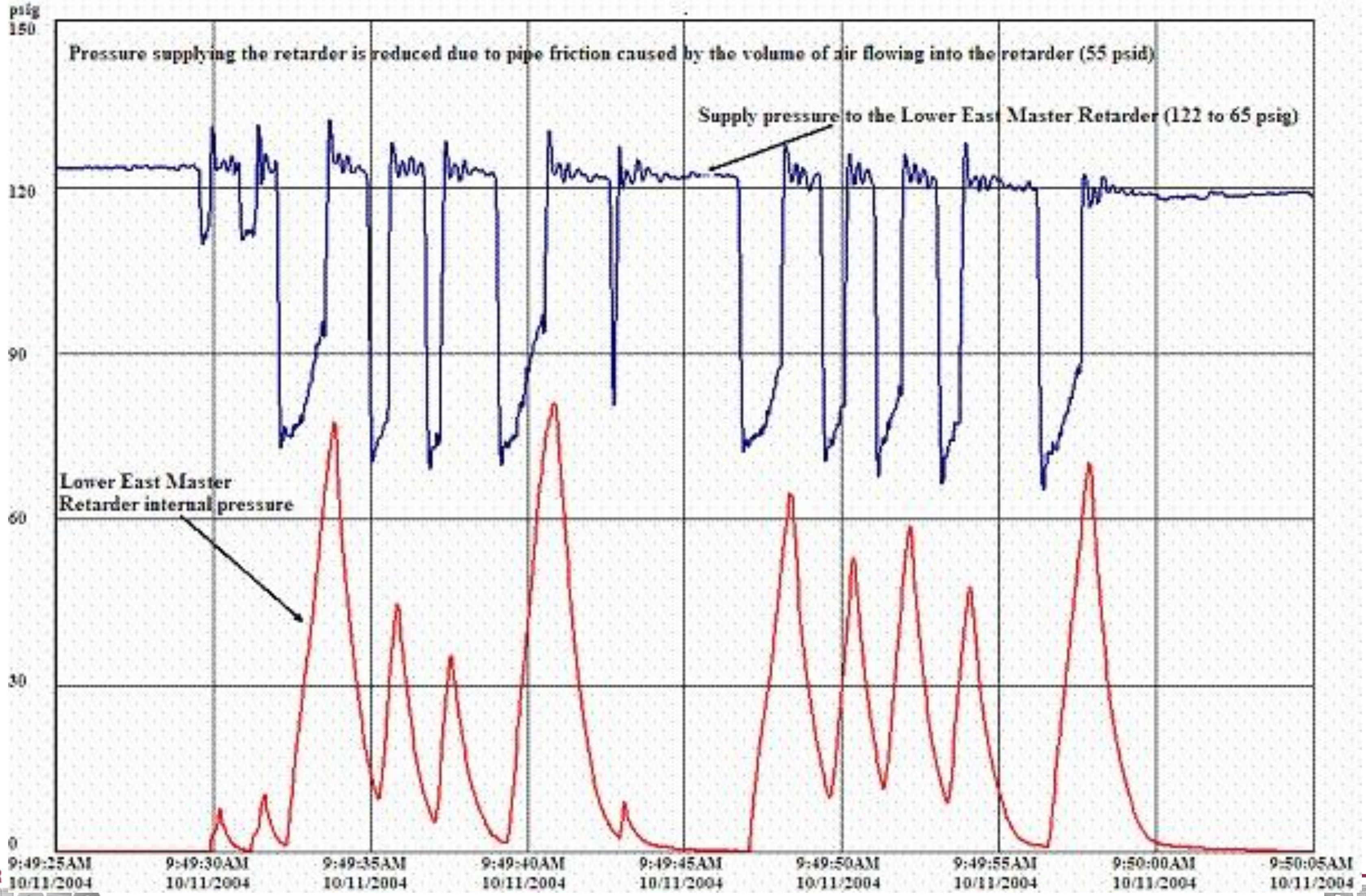


Externally Piloted Pneumatic Regulator

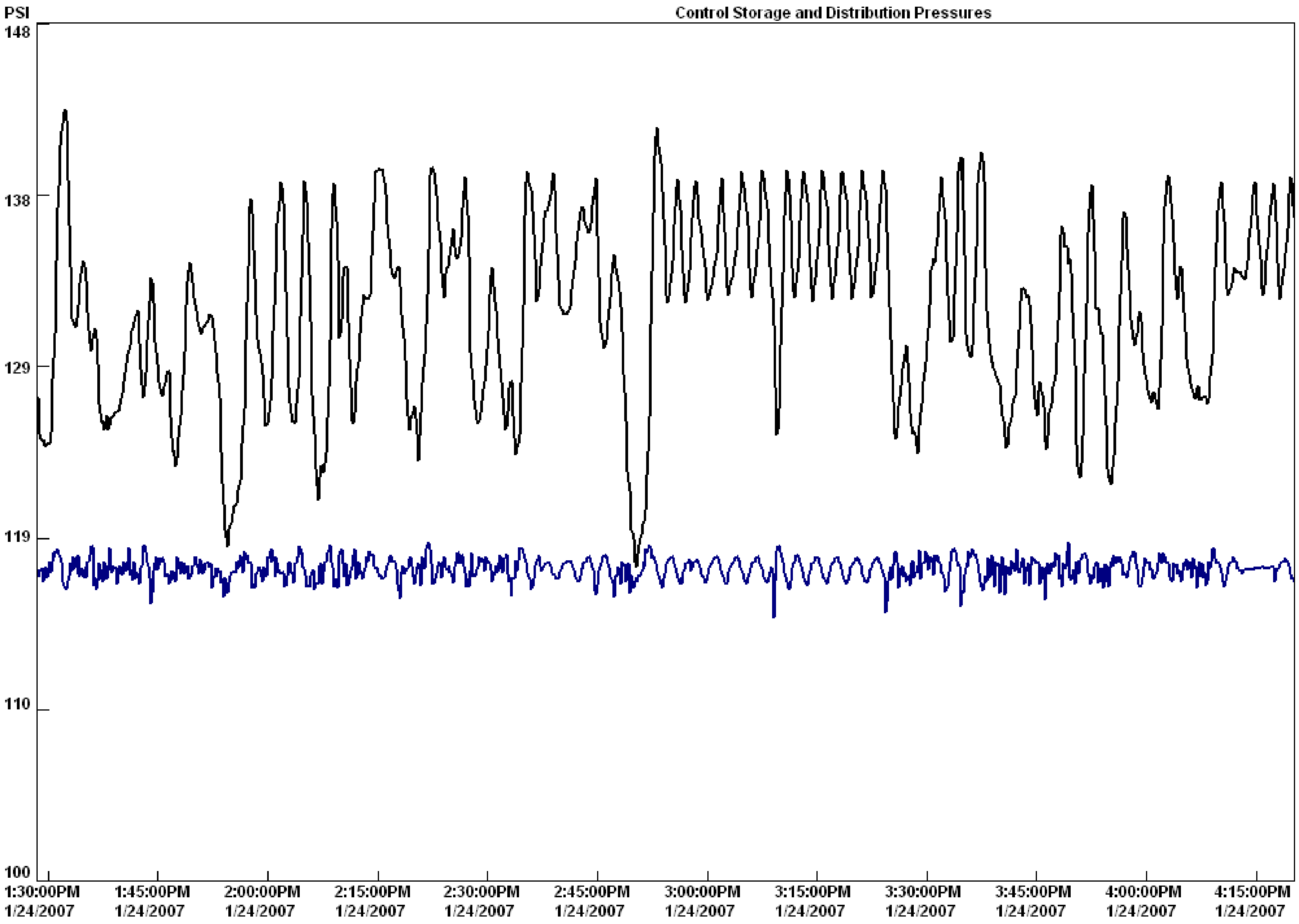
Handling Large Intermittent Peak Demand – Accurate Control



Railyard Supply Side Improvements – Intermediate Controllers



Intermediate Controls – Utilizing Electronic PID Loop Controls

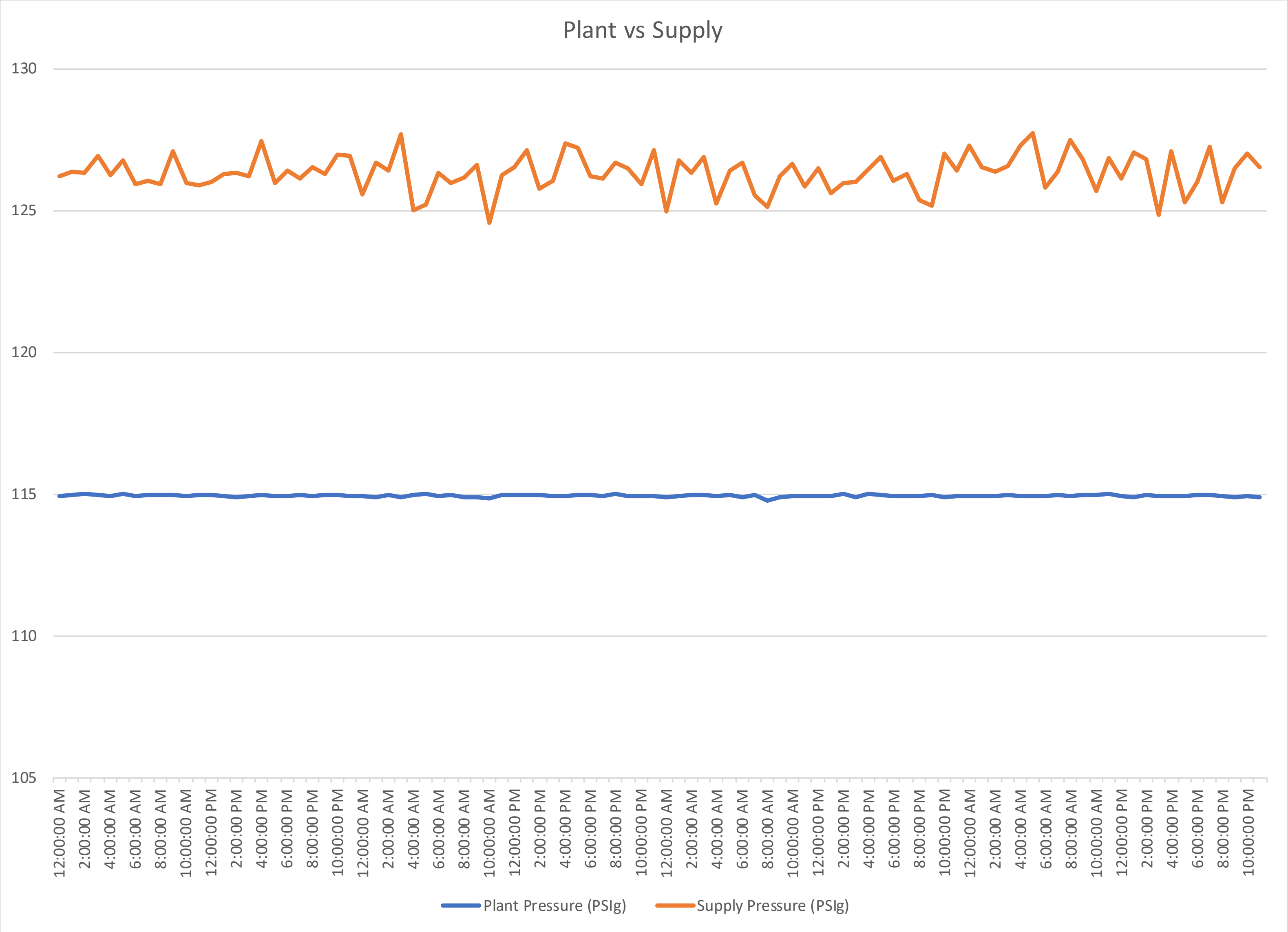


Two (2) 350 HP 2-stage lubricated screws (base). Operating below SF.

Two (2) 200 HP single stage lubricated screws (trim). Below SF.

15K Control Storage in Comp Room
15K General storage @ retarders

Intermediate Controls – Retrofit using Electronic PID Loop Controls



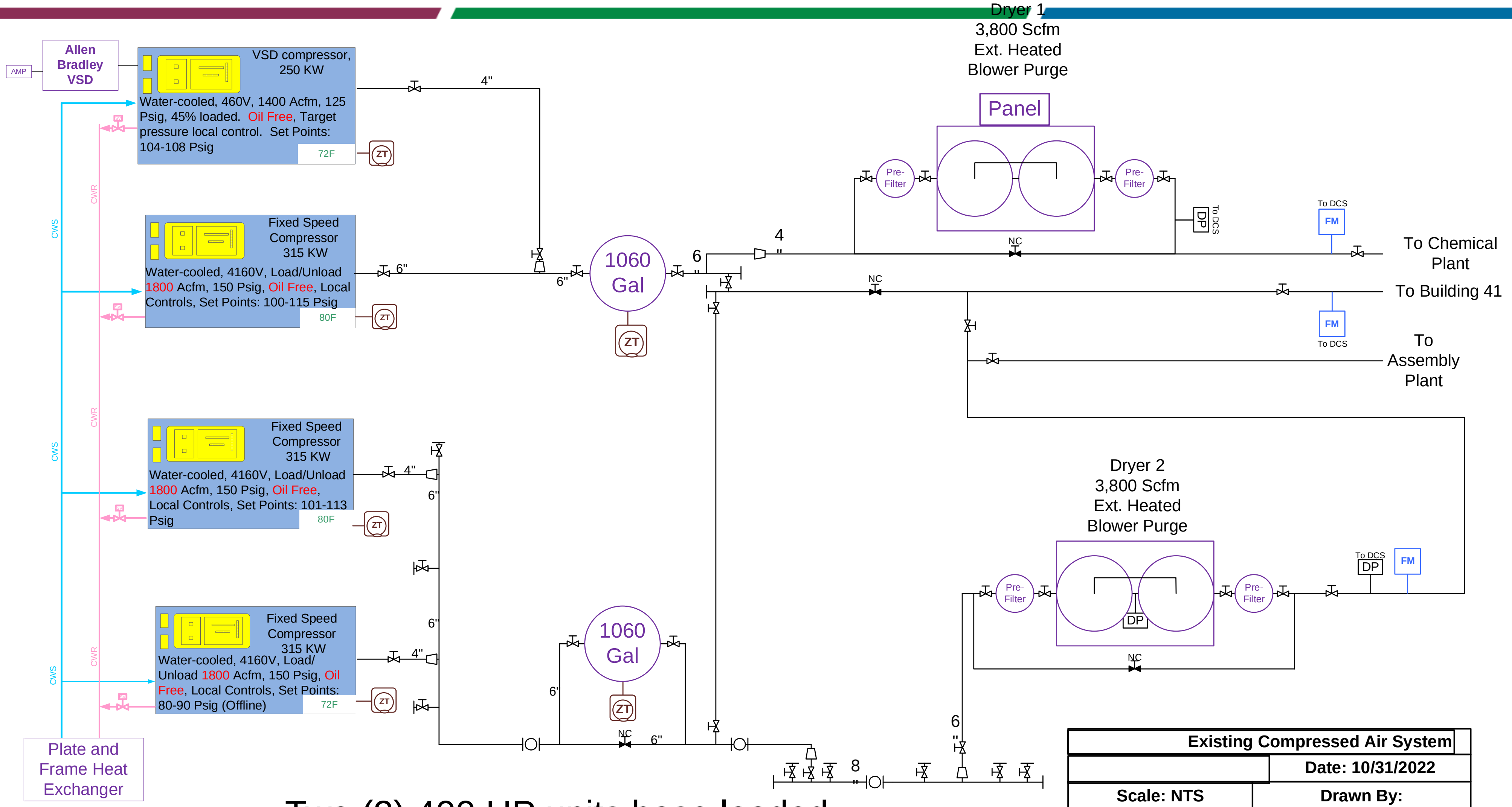
Base / Trim Control Strategy with redundancy

- Must take a systemic approach instead of focusing on the most efficient compressor in the market
- Use centrifugal & large rotary screw compressors as base load units running at 100% capacity
- Relegate smaller rotary screw compressors for incremental trim service
- Distribution network pressure drop MUST be minimal for system to be repeatable
- Determine the impact of starting and stopping an air compressor. Any negative impacts?
- Develop a controls strategy that also accounts for the required storage in the overall system
- Monitor system for supply side efficiency (and other KPI's) so any degradation can be detected
- Make sure there is redundancy (N+1, N+2) if loss of compressor results in high production losses

Design Considerations

- Rating of compressors should be higher than their actual operating pressure. Avoid motor service factor
- Centrifugal compressor power increases at a slower rate as the pressure is increased
- Design will not work if intermediate controls are not properly selected (response rate / pressure drop)

Base trim strategy using VSD compressor - Existing

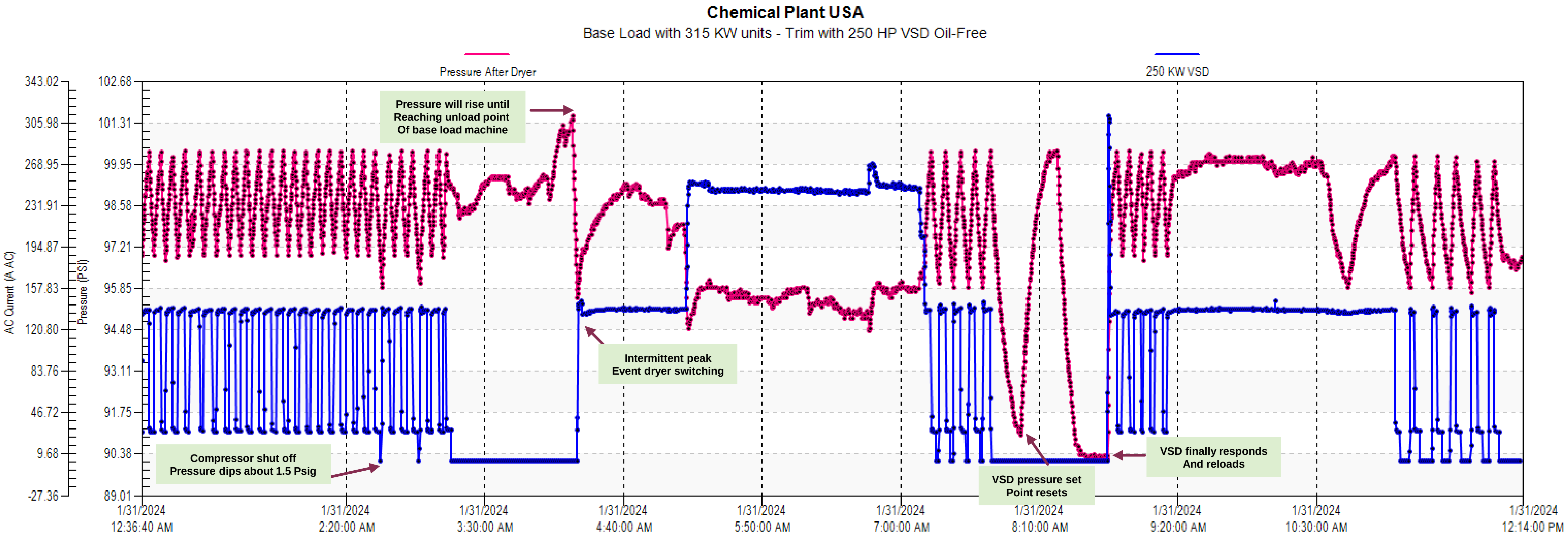


Existing Compressed Air System	
	Date: 10/31/2022
Scale: NTS	Drawn By:
Drawing:CAC-M001	

Two (2) 400 HP units base loaded.
One (1) 350 HP VSD for trim
One (1) 400 HP unit as backup at lower pressure

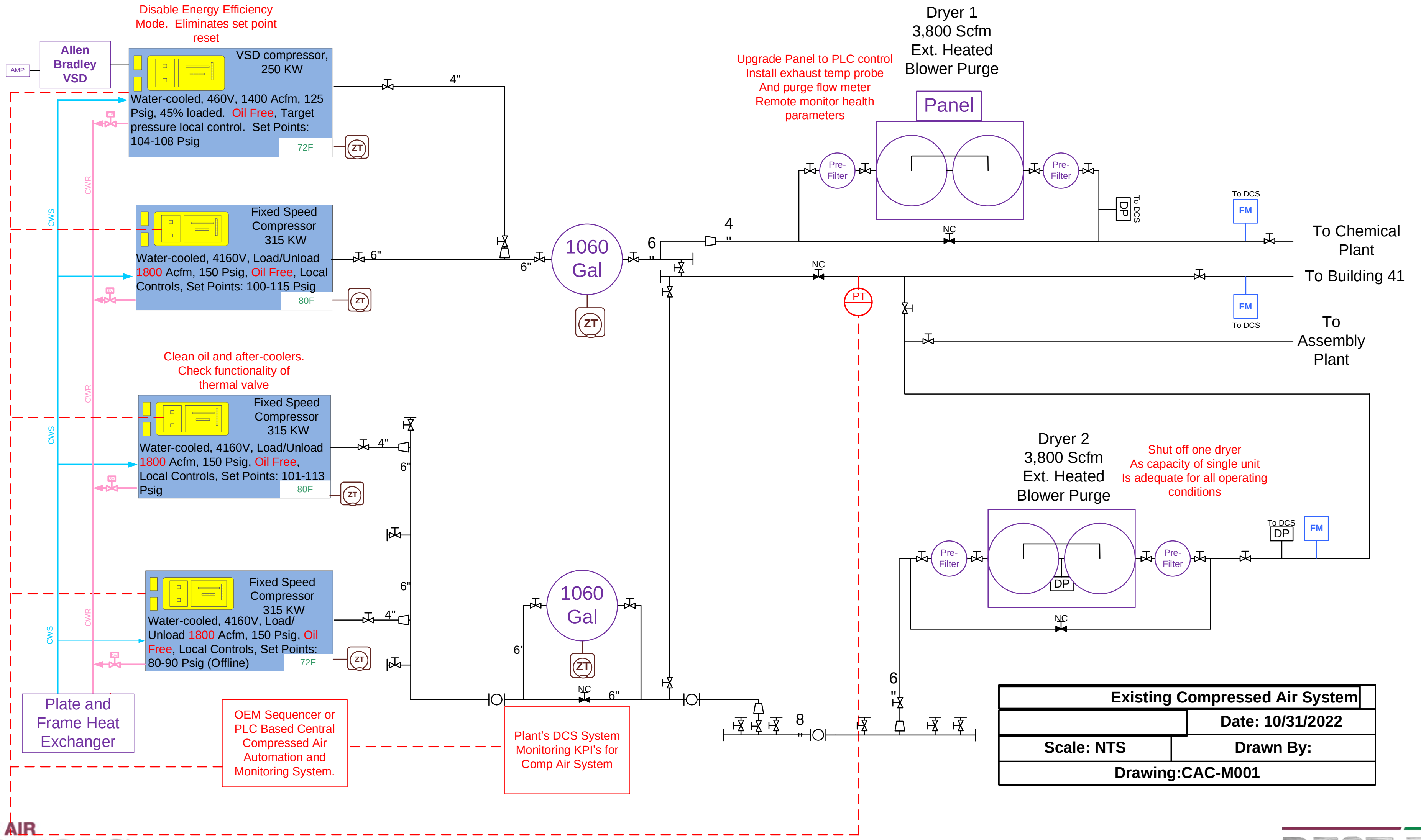
Base Trim Strategy with VSD compressor – Pressure Instability

Two (2) 400 HP Base load compressors
One (1) 300 HP VSD trim compressor (amps shown below)



VSD control with 12 Psig pressure variation in distribution header in 12-hour period.
Pressure variation up to 19 Psig over a 4-day period

Base trim strategy using VSD compressor - Upgrades



Existing Compressed Air System	
	Date: 10/31/2022
Scale: NTS	Drawn By:
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Results of implementing a Base Trim Strategy w/ a VSD compressor

- Production complained of intermittent low-pressure conditions
- Air operated booster pumps were installed on critical production equipment that often failed due to low pressure
- Increase in system demand due to compensating for low pressure forced utilities to run an additional compressor
- Supply side efficiency is reasonable at the expense of unstable distribution pressure and repeatability

What went wrong?

- Compressor had an “energy efficiency” mode that resets the set points based on compressor loading and other criteria
- Compressor operated in this mode for close to 10 years as operators were either not effectively trained during installation or the knowledge of the system was not passed down over time
- Control strategy was not well though out resulting in controls conflicts
- Storage considerations were not accounted for. Large demand swings affected the resetting of pressure set points on the VSD

Summary – Optimization of Compressed Air Systems

- Determine the total cost annually to operate the compressed air system. Include all costs
- Design system to reduce costs that impact the site the most (portables, production losses, energy, waste)
- Develop control strategy that minimizes the overall cost of operation
- Implement control strategy for proof of concept and modify as necessary
- Develop specifications for new equipment that align with the site's strategy
- Monitor key performance indicators (KPI's) for continual feedback on the health of the system
- New equipment should be purchased with specific intent to fulfill a need that aligns with your control strategy

About the Speaker

Jackson Redline
Rogers Machinery

- Engineered System Solutions Project Manager, Rogers Machinery
- Mechanical Engineer in the Engineered Systems Solutions team
- Joined Rogers Machinery post-college

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Variable Speed Drives for Rotary Screw & Centrifugal Compressors

Jackson Redline

1 What is a variable speed drive (VSD)?

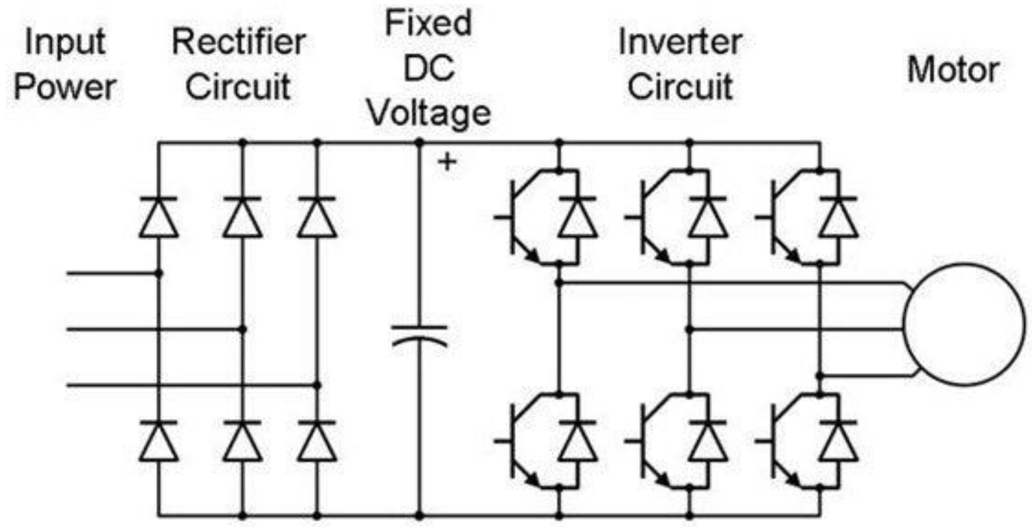
2 How does a VSD affect a rotary screw compressor?

3 How does a VSD affect a centrifugal compressor?

4 Summary

WHAT IS A VARIABLE SPEED DRIVE?

- Control device that regulates the energy from the supply side to the process side
- Converts/regulates incoming to the specific voltage and current output to provide the power needed by the process
- VSD will increase/decrease the power to the motor to increase/decrease the motor speed (more power = more torque = more speed)
- Process control logic will dictate to the VSD how much power is needed to match equipment output to system demand continuously



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PROS & CONS FOR VSD's

PROS

- Matching system output to demand can lead to more energy efficient system by generating less excess air
- Reduced starting current is easier on some equipment and system facilities (ramped start vs. full speed start)
- Reduced speeds can result in less thermal energy produced
- Reduced speeds can result in less noise generated

CONS

- VSD's are expensive adding to more cost up front and expensive to replace
- Require more complex controls and more system instrumentation for control scheme
- Increase power requirements by 5-7% due to losses internal to the VSD
- If system demands don't fluctuate enough, then potential energy savings might not be justified over equipment lifecycle
- Not good to use in dirty or hot environments

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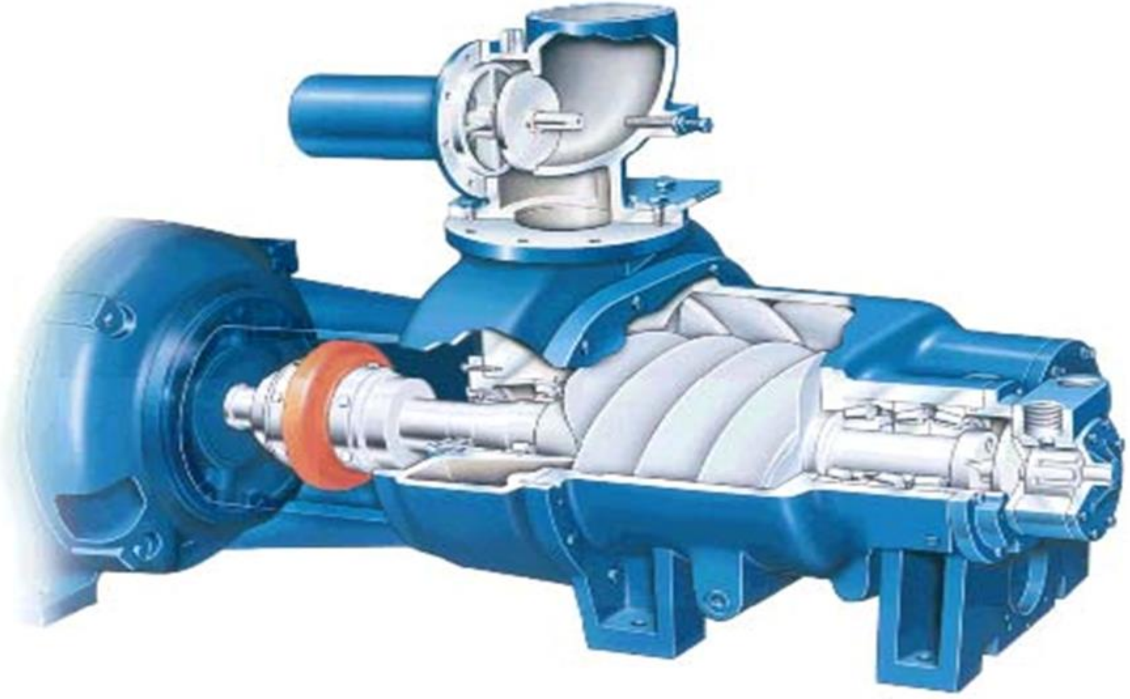
ROTARY SCREW
POSITIVE DISPLACEMENT COMPRESSORS

- Every rotation of the compression element (screw, piston, scrolls, lobe, etc.) captures a fixed volume of gas and compresses out the discharge
- Designed for constant volume at variable pressure
- Increasing/decreasing the speed of rotation increases/decreases the output volumetric flow
- Increasing/decreasing the speed of rotation increases/decreases power requirements



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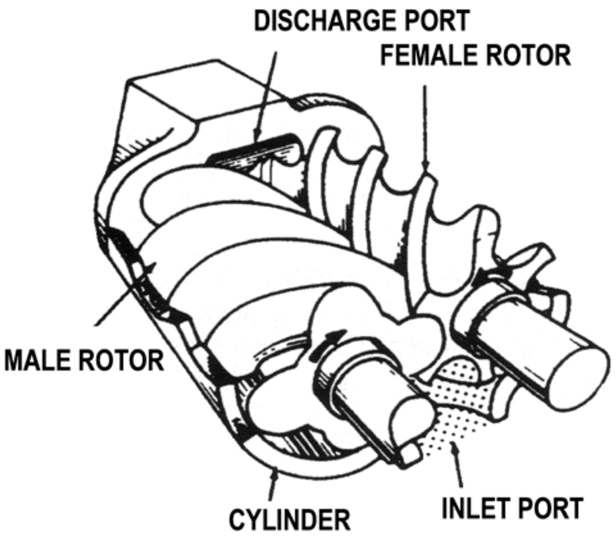
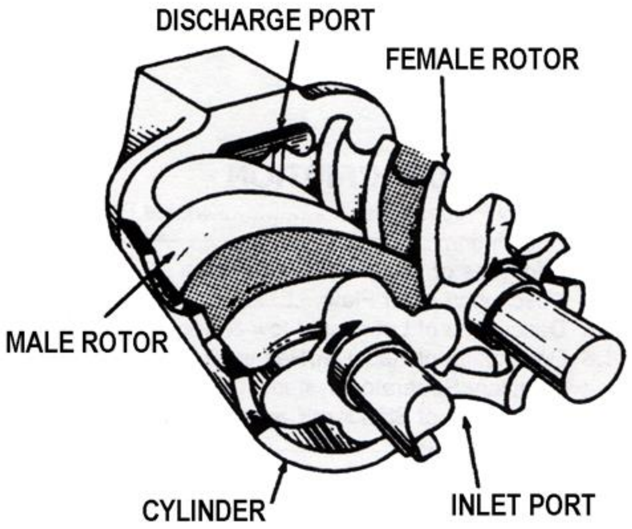
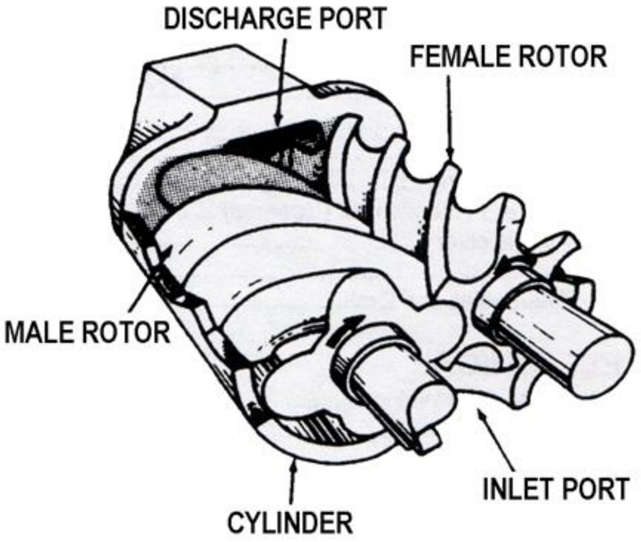
COMPRESSION CYCLE ROTARY SCREW



INTAKE



COMPRESSION



DISCHARGE

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ROTARY SCREW POSITIVE DISPLACEMENT COMPRESSORS

- Two main types – fixed speed vs. variable speed
- Fixed Speed
  - Operate at motor speed (i.e. 1800 RPM, 3600 RPM for 60Hz regions) or other speeds if using gearing
  - No change in speed during operation
  - Output controlled by either load/unload (allowing or blocking air at inlet) or modulation of inlet valve (proportionally restricting the inlet to reduce output)
- Variable Speed
  - Operate at a range of speeds (~20-60Hz depending on compressor design)
  - Output controlled by modulating the speed of the motor/screws to match output

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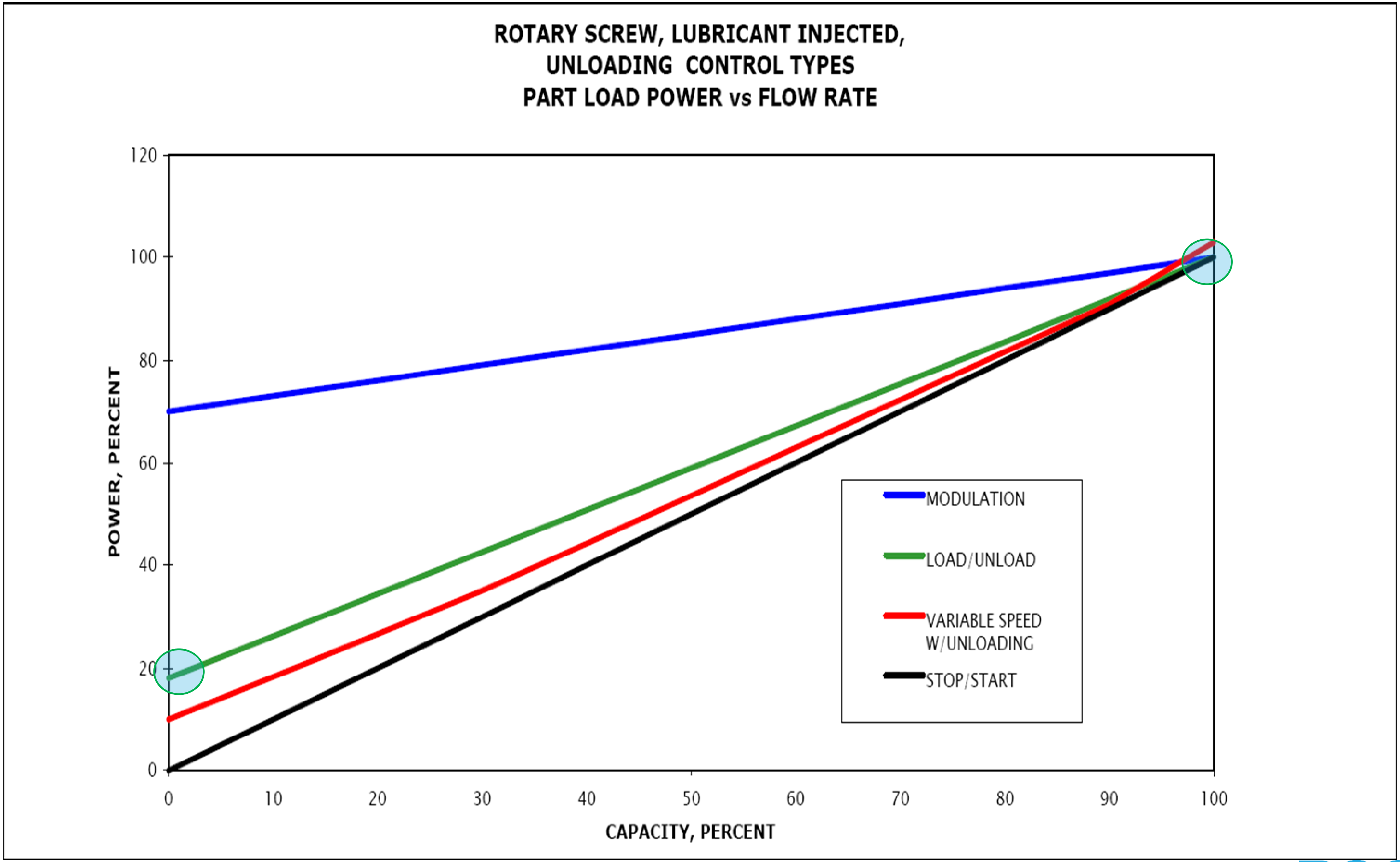
ROTARY SCREW, LUBRICANT INJECTED,
UNLOADING CONTROL TYPES
PART LOAD POWER vs FLOW RATE
POWER, PERCENT
CAPACITY, PERCENT
0
20
40
60
80
100
120
0
10
20
30
40
50
60
70
80
90
100
MODULATION
LOAD/UNLOAD
VARIABLE SPEED W/UNLOADING
STOP/START

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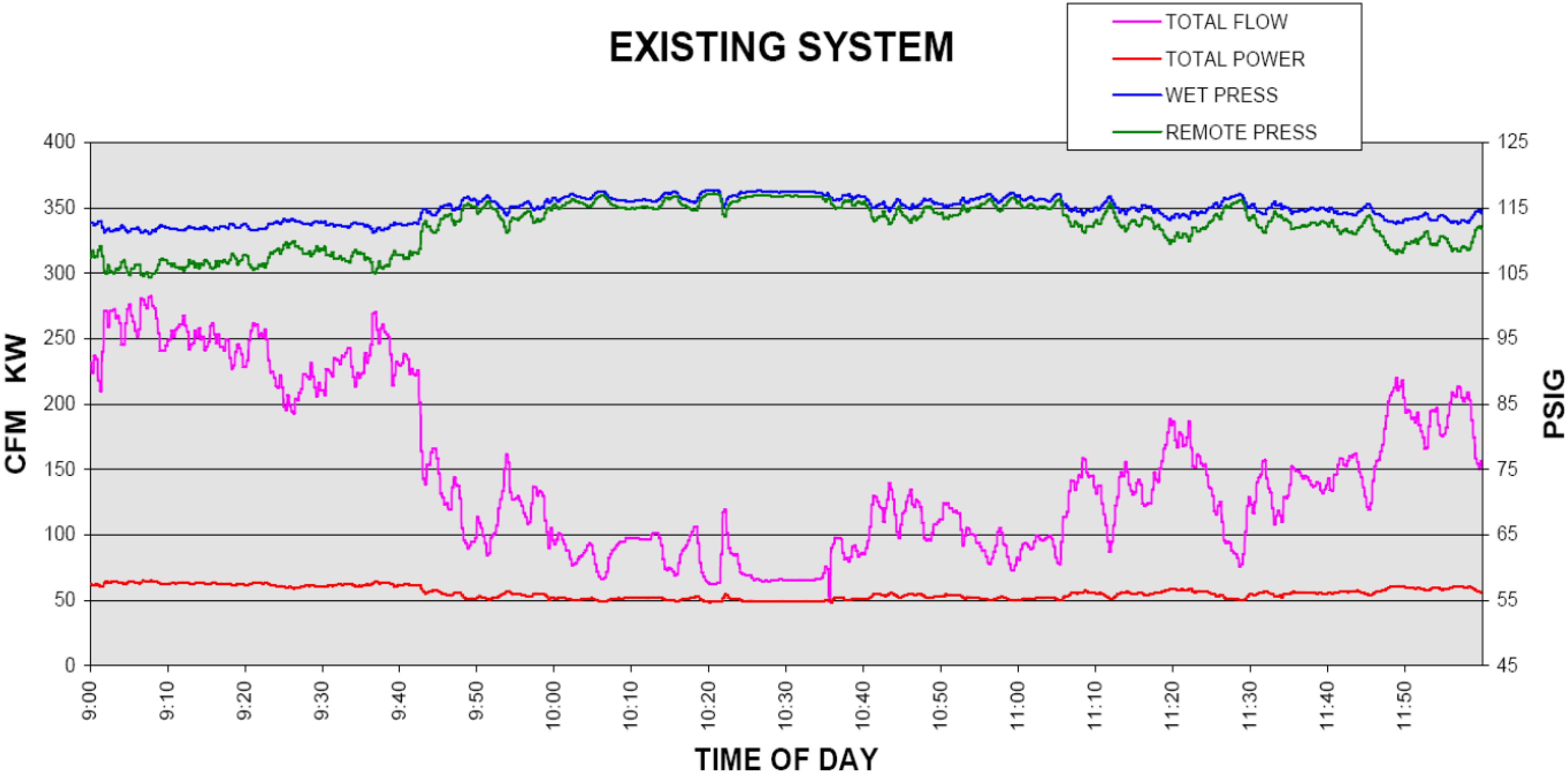
AIR PRESSURE FLOW CHART
FIXED SPEED COMPRESSOR



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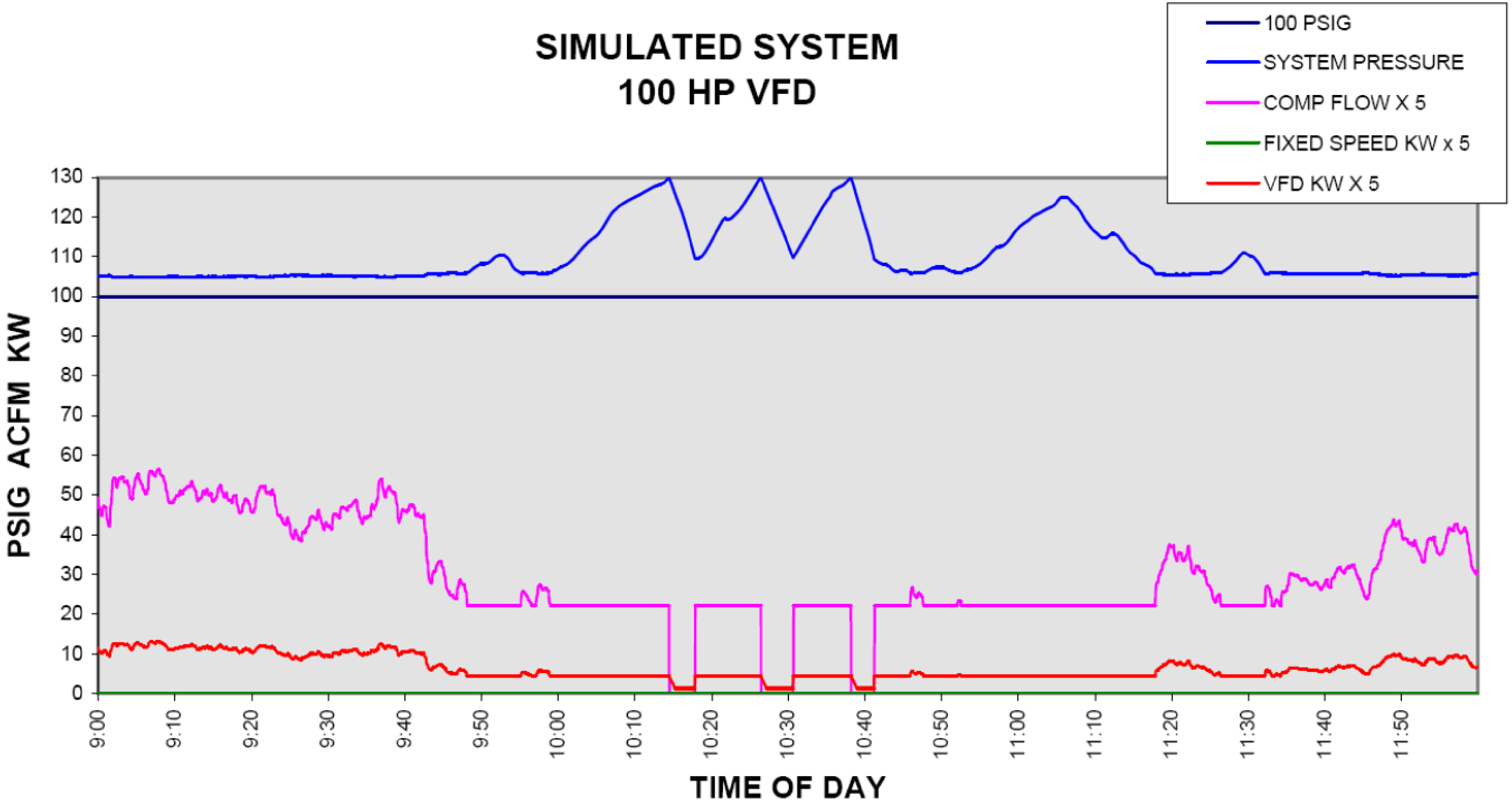
VFD COMPRESSOR



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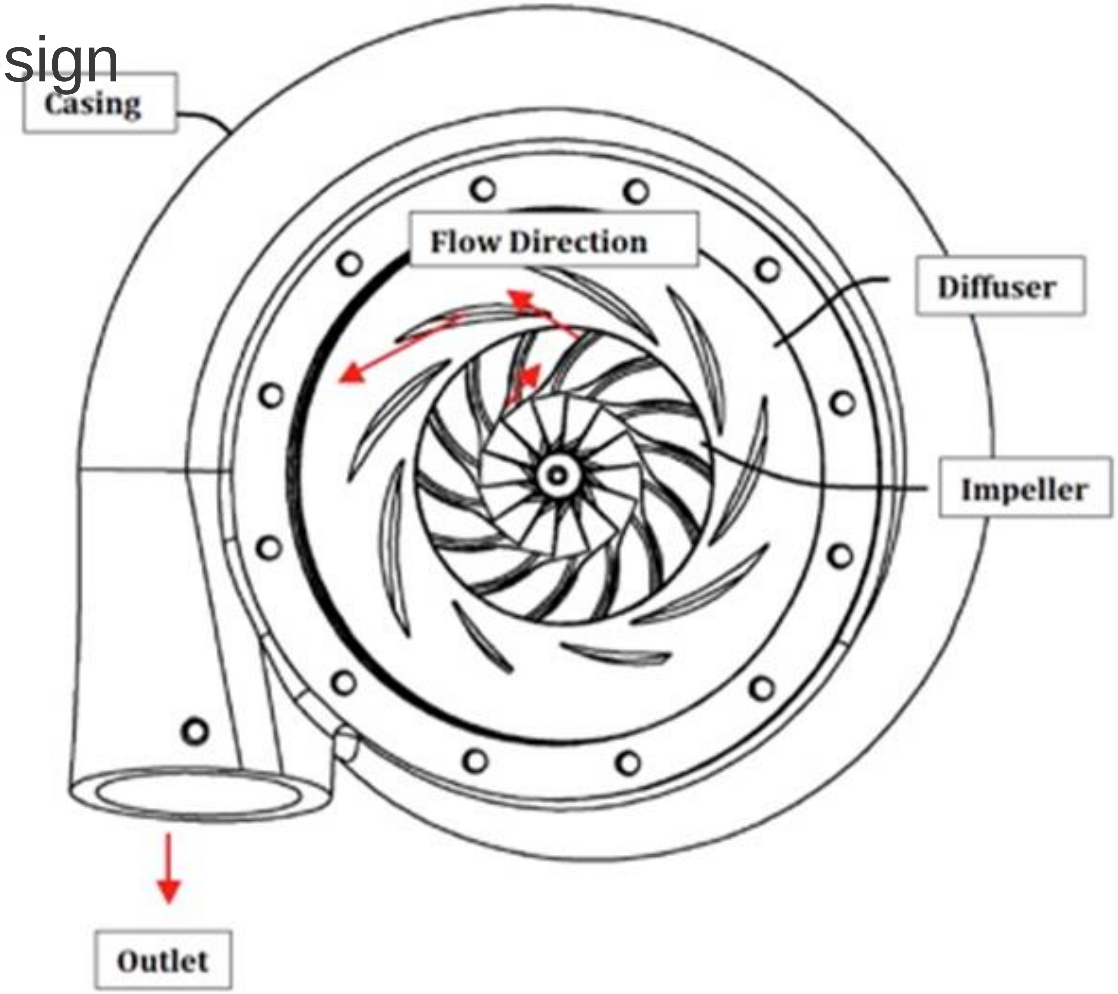
OIL-FREE CENTRIFUGAL COMPRESSORS

- Dynamic compressors = constant pressure design
- Impellers designed to accelerate gas to high speeds afterward it is then slowed down converting the speed into pressure
- Designed around specific range of conditions:
  - Temperature
  - Inlet & discharge pressure
  - Molecular weight (gas type) for each stage inlet
  - Motor / driver speed
- Very efficient compressor, +5.2 cfm / kW depending on discharge pressure and inlet conditions and running at full load

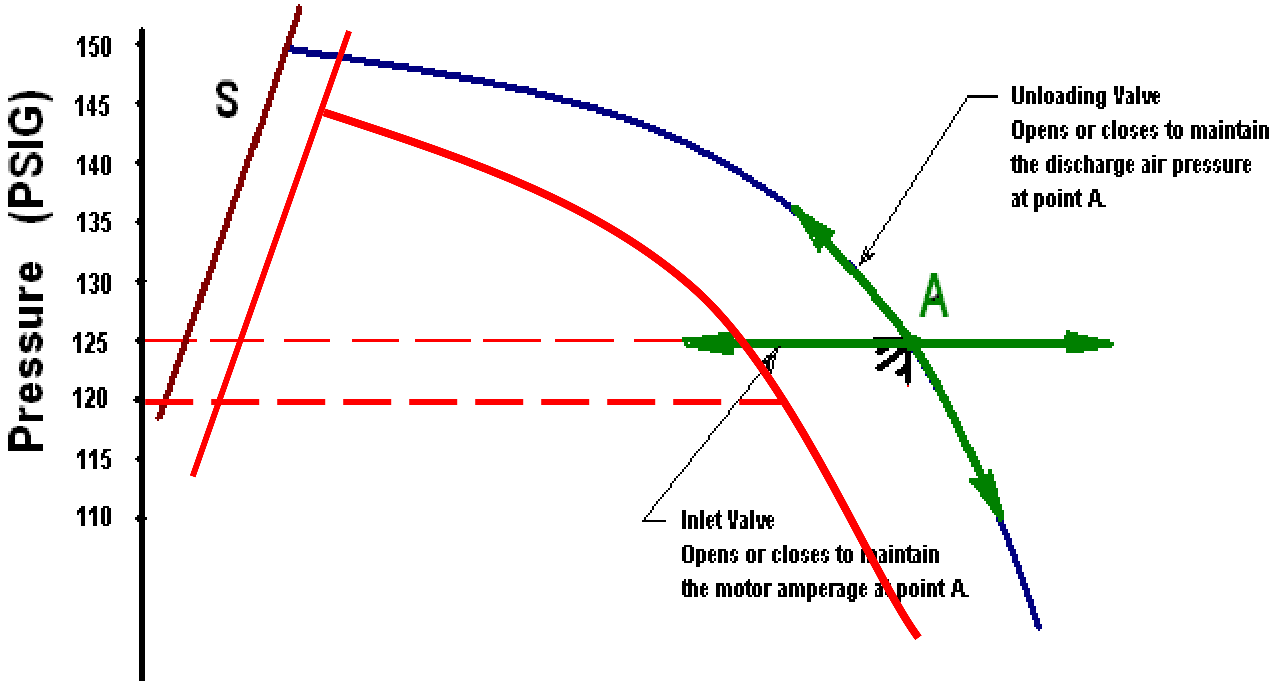


TYPICAL CENTRIFUGAL COMPRESSOR CONTROLS

- Control schemes are to prevent surge
- Two methods to control:
    - Inlet guide vanes or unloading valve modulate inlet air control restricting air ingested by compressor
    - Unloading control valve at discharge vents extra air to atmosphere (amounts to losing expensive compressed air)

CENTRIFUGAL COMPRESSORS AND VARIABLE SPEED DRIVES

- Decreasing the speed of a centrifugal compressor slows the speed of the air coming off the impellers
- Changes the dynamics of operation
  - Less speed = less pressure generated
  - Less flow = less air drawn into the system (less mass flow)
  - Less stable range of operation = more likely to surge



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SHOULD YOU USE A VARIABLE SPEED DRIVE?

VSD + Rotary Screw Compressor = Good OR Bad/Not so Good*

**Depends on system air usage – please consult a compressed air specialist to help determine if a VSD is right for your system*

VSD + Centrifugal Compressor = Bad Combo

Cost vs. potential savings are rarely viable

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THANK YOU!

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Centrifugal vs Rotary Screw Air Compressor Performance: Full Load and Part Load Efficiency

Q&A

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Thank you for attending!

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