POTATO FAN VFDs

PHASE 1 GENERAL REPORT - HANDOUT

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1.1 INTRODUCTION

Potato storage ventilation systems are designed to move air through stored potatoes in order to remove the heat of respiration and control product temperature. During holding periods, most storage site managers reduce ventilation rates. This can be done by reducing fan run hours, or reducing the number of operating fans.

Another way to control the ventilation rate is by adjusting fan speeds with Variable Frequency Drives (VFDs). This method has the advantage of dramatically reducing energy consumption at reduced fan speeds. At 50% speed, a fan will produce 50% flow but consume only 15% power. VFDs are continuously adjustable between 0% and 100% speed, whereas fans can only be shut off in whole numbers.

VFD owners report decreased mass loss, pressure bruising, utility bills, and condensation, as well as increased operational flexibility. None have reported any adverse product quality effects. VFD control of fans is becoming a common technology in controlled atmosphere (CA) apple storage as well as cold storage warehouses.

1.2 ENERGY ECONOMICS FACTORS

The economic incentive to install VFDs to reduce electrical costs will be stronger as more of the following factors are present:

1. Long storage season
2. High energy cost
3. Lots of hours when outside air (OSA) is available for cooling (OSA cooling hours increase with colder weather and/or higher storage temperatures.)
4. Building designed for high ventilation rates
5. Utility incentives will pay part of VFD cost

1.3 SAMPLE ENERGY ECONOMICS

Three sample economic cases are shown below. Each case assumes 80 hp of fans serving 10,000 tons of potatoes which are held for 200 days. Each case assumes that the VFDs are a retrofit, the VFD installation cost is $200 per fan horsepower, and that no utility incentives are available. Actual installation costs could vary from $100 to $300 per horsepower.

Case 1 represents storing Russet Burbank tubers 46°F in Moses Lake WA. The non-VFD practice is to operate 3 of 4 fans during 120 days of winter holding for 23 hours per day. Case 1 VFD practice is to operate all fans at 50% speed for the same run hours.

Case 2 represents storing Russet Norkotah tubers at 38°F in Boardman OR. The non-VFD practice is to operate 3 of 4 fans during 120 days of winter holding for 17 hours per day. Case 2 VFD practice is to operate all fans at 60% speed for the same run hours.

Case 3 represents storing Russet Burbank tubers at 46°F in Burley ID. The non-VFD practice is to operate all fans 50% of the time during 120 days of winter holding. This is commonly done using 12 hrs on/12 hrs off or 6 hrs on/6 hrs off type practices. Case 3 VFD practice is to operate all fans at 50% speed 24 hours per day. Cultivars held at cooler temperatures will be similar to this in the colder Idaho climates.

Table 1: Sample Economic Cases

	Case 1	Case 2	Case 3
Location	Moses Lake WA	Boardman OR	Burley ID
Cultivar	Russet Burbank	Russet Norkotah	Russet Burbank
Holding Temperature	46°F	38°F	46°F
Storage Days	200	200	200
Project Cost	$ 16,000	$ 16,000	$ 16,000
Energy Savings, kWh	115,033	80,871	96,924
Utility	Grant Co. PUD	PacifiCorp	Idaho Power
Rate Schedule	2	27	9
Energy Cost/kWh	$ 0.02250	$ 0.03831	$ 0.04339
Energy Cost Savings	$ 2,588	$ 3,098	$ 4,206
Demand Savings at 5% of Energy	$ 129	$ 155	$ 210
Total Electrical Cost Savings	$ 2,718	$ 3,253	$ 4,416
Simple Payback, years	5.9	4.9	3.6

1.4 Impact on Product Quality

1.4.1 Ventilation Rates

Most control methods using VFDs result in decreased total air movement.

Table 2: Total Ventilation

	Case 1	Case 2	Case 3
Non-VFD Season Avg. CFM/ton	7.8	6.8	6.3
VFD Season Avg. CFM/ton	6.1	5.8	6.1

This reduction should improve product quality. Once holding temperatures are reached, any extra ventilation air beyond what is necessary to remove the heat of respiration and building loads will cause unnecessary shrinkage. A shrinkage loss of 1% costs $10,000 at $5.00/cwt for the sample storage of 10,000 tons (cwt = 100 lbs). The product quality benefits through the use of VFDs could outweigh the energy benefits.

Even in cases where the total ventilation is essentially unchanged, as in case 3, there may be significant product quality benefits through shortening or eliminating periods where the fans are off. Control of the environment is lost when the fans are off. Natural convective air flows are created, air temperature stratifies, and relative humidity changes.

Some schools of thought believe that a large fraction of shrink loss occurs during fan off periods. With VFDs, the fans can operate even when OSA is lost (not available for cooling), consuming little energy and adding little heat, but preventing uncontrolled convection, stratification, and variations in relative humidity. This can also reduce condensation problems encountered when the fans are off.

1.4.2 Full Scale Field Trials

Field trials conducted in Maine in 1991-1992 indicated reduced mass loss of 0.71% and large reductions in pressure flattening through the use of VFDs. No adverse product quality effects were discovered. (Ashby, R., Hunter, J., and S. Belyea. 1992. Use of Electronic Speed Controllers for Potato Storage Fans. Proceedings of Maine Public Service Company Conference. pg. 97-106.)

Dr. Gale Kleinkopf and Ph.D. Candidate Nathan Oberg at the University of Idaho are conducting full scale field trials and research into the product quality impacts of using VFDs. Preliminary results show no harmful product quality effects due to VFD use, and also show a reduction in mass loss.

2.0 FACTORS AFFECTING VFD SUITABILITY

2.1 POTENTIAL OBSTACLES TO VFDS

The following obstacles may reduce the benefits of VFDs.

2.1.1 Storage Season Length

The majority of energy savings and product quality benefits occur during winter holding, after suberizing (curing) and cool down. A storage site should spend at least 30 days in winter holding before VFDs are considered. Typically a site is loaded in late September, and could start reducing fan speeds as early as Nov 15^{th} or Dec 1^{st}.

Some growers have multiple buildings, and unload the buildings at a steady rate from November through June. Ideally the grower would outfit the medium and long term buildings with VFDs, but this is not always possible to predict.

2.1.2 Building Air Flow Rate

If the building is older and was designed at 10 or 12 cfm/ton, it may not be possible to reduce fan speeds very far during winter holding periods without raising the temperature difference between return air and plenum air (ΔT). Once the tubers are at their holding temperature, the air temperature is close to the potato temperature. ΔT is often used to indicate the difference in temperature between return and plenum air, as well as the difference between pulp temperatures at the top and bottom of the pile.

If an evaporative cell or refrigeration coil is fouled, the building may never achieve the design air flow rates, which would limit the potential fan speed reduction. A 20 CFM/ton building with fouled equipment may only operate at 17 CFM/ton. On the other hand, many buildings operate at lower pressure drops and higher flows than design ratings. This would allow for additional reductions in fan speeds.

2.1.3 Poor Air Distribution

Buildings with booster fans in the plenum or return air may suffer from poor air distribution at full load conditions. Such sites would similarly suffer from poor air distribution with VFDs. It is generally believed that if a site has good air distribution at design conditions, that it will have good distribution at reduced flows.

2.1.4 Cold Variety-Warm Location

If a low temperature variety, such as Russet Norkotah is being held at 38°F in a warm location, the available OSA hours will be limited. If all fans must operate whenever OSA is available to maintain the desired ΔT, then benefit of VFDs will be reduced.

2.1.5 Tight ΔT Requirements

Very tight ΔT requirements force the ventilation rates and fan speeds to be higher. VFD installation sites with .8°F and .5°F ΔT requirements are able to reduce fan speeds to 63%-75% during winter holding. VFD sites with 1.5°F or 1.0°F ΔT requirements can commonly operate at 35%-60% speed during winter holding.

2.1.6 Aggressive Fan Reduction Practice

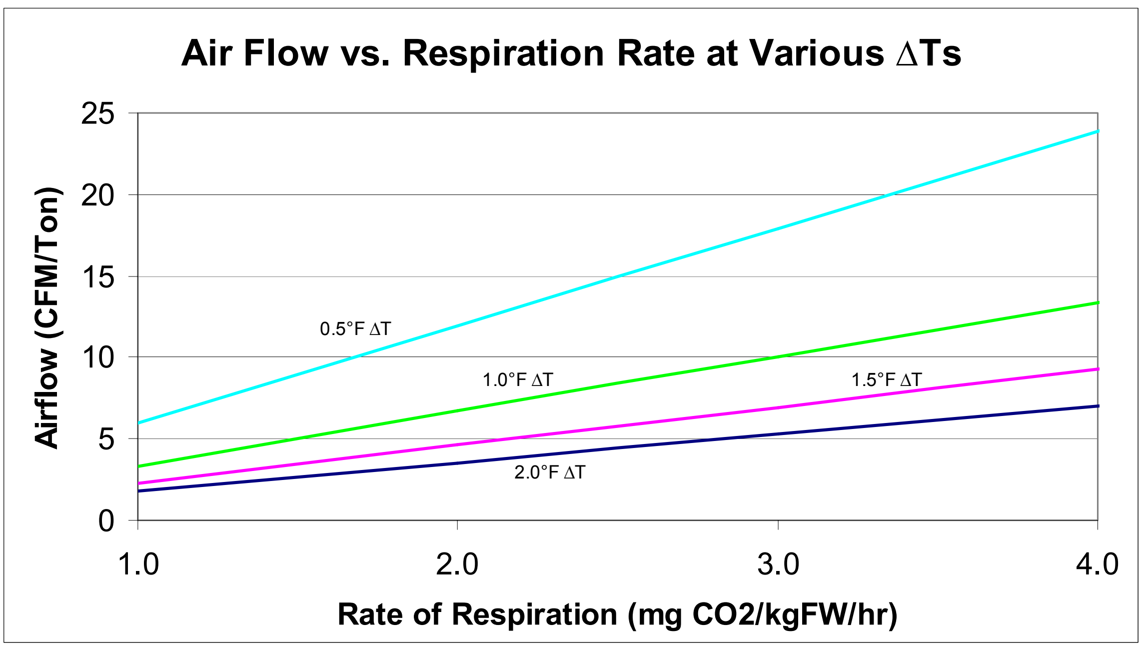
Occasionally a grower will have an aggressive fan reduction practice, where during winter holding 2 out of 4 fans (or similar) are shut off and run times are extended. This grower is capturing part of the energy savings and product quality benefits that could be had through VFDs. The economic difference between the two operations may not be enough to justify VFD installation.

Most fan reduction practices only shut off 1 out of 4 or 5 fans. There is a significant difference between this practice and a VFD practice. VFDs may be justified.

2.2 MAINTAINING ΔT

During winter storage, a healthy crop would be expected to have a rate of respiration of about 3 mg CO_2/kgFW/hr. As the figure below shows, a ventilation rate of 18 CFM/ton is required to maintain 0.5°F ΔT. If 1.5°F ΔT is acceptable, the ventilation rate can be reduced to about 7 CFM/ton. With VFDs this reduction can be accomplished by slowing the fans down, reducing electrical costs, and improving product quality without prolonged fan off periods.

Figure 1: Air Flow vs. Respiration Rate for ΔT



The ventilation rates in this figure account only for the respiration heat load. Increased building loads in the spring would require additional ventilation. Respiration rate varies with variety, crop condition, and storage length.

2.3 Non Energy or Quality Benefits

2.3.1 Increased Flexibility

Storage sites with one fan have no choice but to control ΔT by adjusting run times. Sites with 4 fans can't operate 2 ½ fans. This forces the operation to over-ventilate to the next whole fan. With VFDs, the fan speeds can be adjusted in 1% or smaller increments.

2.3.2 Increased OSA Hours

With slower air velocities through the evaporative cooler, the air has more time to approach the saturated wet bulb temperature, resulting in cooler air. Reducing fan speeds also reduces the heat load and temperature gain by the air. Both of these effects will slightly increase the available OSA hours.

2.3.3 Reduced Condensation

Condensation can be a significant problem during fan off periods in cold weather. With VFDs the fan off periods can be significantly reduced or eliminated without over ventilating the crop.

2.4 VFD Costs

The cost to retrofit an existing storage building to VFDs can range from $100 per fan horsepower to $300 or more depending on contractor, motor protection devices, electrical modifications, VFD brand, etc. This report uses $200/hp for retrofit situations. Anyone curious about project costs is strongly encouraged to obtain a bid from a local electrical contractor.

For new construction, the incremental cost of VFDs can be as low as $100/hp. Motor starters are eliminated, VFD rated motors can be specified, re-work is eliminated, and the design will accommodate VFDs from the outset. Anyone considering new construction should thoroughly evaluate VFDs.

3.0 STORAGE PRACTICES

3.1 Practices

There is a wide range of building design and storage practice. It would be impossible to discuss every situation. The following discussion is intended to represent the majority of practices encountered.

3.1.1 Observed Non-VFD Storage Practices

In Grant County Washington and Northern Oregon, most sites ventilated whenever OSA was available during winter holding. Some shut a fan down during the cool winter months, but usually didn't go below 75% horsepower.

Near Twin Falls Idaho, the most common practice was timed run ventilation with all fans operating between 10 and 16 hours per day. Some times these were broken into shorter periods such as 6 hrs on 6 hrs off to reduce condensation problems.

3.1.2 VFD Storage Practices

Several VFD sites limited their maximum fan speed to 55 Hz, or 92%. This provides a 20% fan energy reduction during suberizing and pulls down periods, but reduces air flow by 8%.

All VFD sites ventilated whenever OSA was available during winter holding. None used forced air circulation when OSA was lost. Design ventilation rates varied from 17 to 20 CFM/ton. Winter holding fan speeds varied from 35% to 75%. Holding temperature and ΔT requirements were significant factors on fan speeds. Sites holding at 38°F or with ΔT requirements at .8°F or below tended to operate with fan speeds between 55% and 75% when using OSA. Sites holding at 46°F with ΔT requirements near 1.5°F tended to operate between 35% and 55% speed when using OSA. Building design had an impact, with the 17 CFM/ton building operating with fan speeds about 15% higher than nearby 20 CFM/ton buildings holding at the same temperature and ΔT.

During refrigeration, most VFD sites increased their fan speeds to between 70% and 100%. This was to avoid coil icing. None of the VFD sites had experienced coil icing with VFDs, but increased the fan speeds as a precaution.

3.2 MANUAL AND AUTOMATIC VFD CONTROLS

Roughly half of the VFD sites manually adjusted the fan speed. Operators would evaluate crop condition, run times, and ΔTs about once per day and adjust fan speed. The rest of the VFD sites used automatic fan speed controls. Automatic fan speed control should best prevent over or under ventilating the crop and save the most energy. Automatic controls are now offered by a variety of ventilation contractors, probably some not listed below. The ventilation contractors listed below can supply and install VFDs and automatic controls.

- The Gellert Company, www.gellert.com (208) 736-7000, Twin Falls ID
- Industrial Ventilation Inc., www.ivi-air.com (800) 444-7152, Nampa ID
- JMC Ventilation & Refrigeration, www.jmcvr.com (877) 586-9893, Kennewick WA

All of the VFD controllers adjust fan speed to maintain the pile ΔT that the user enters. All controllers have a minimum fan speed setting.

Additional features that are available with some control panels include:

- The ability to reference different temperature sensors. For example, when the building is full, the controller would calculate ΔT based on the return air temperature sensor. But when the building is part full, it could be set to reference a pile sensor, which may more accurately report the pile temperature.
- Low speed operation when OSA is lost. This feature operates the fans at low speed (about 10%) when OSA is lost, using very little energy. This should prevent temperature, humidity, and CO_2 stratification in the pile by keeping a small amount of air moving. This also keeps humidity up as the air continues to pass through the evaporative cooling cell.
- Automatic fan speed control during refrigeration. This would allow the fans to vary between 65% and 100% speed (depending on the refrigeration system). This should save additional fan energy during moderate weather in winter and early spring when OSA is not available, but 100% refrigeration capacity isn't required.

Features are constantly changing, so contact a dealer to find out what their controller offers.

4.0 FAN SYSTEMS

4.1 AFFINITY LAWS

In theory, fan power equals fan speed cubed. At 50% speed, the fan power would be 50% x 50% x 50%, or 12.5%. Air flow is proportional to fan speed. At 50% speed a fan would produce 50% flow while only consuming 12.5% power. In reality, 50% speed operation consumes about 15% power due to VFD losses. A 20 CFM/ton building can operate at 10 CFM/ton using about 15% power.

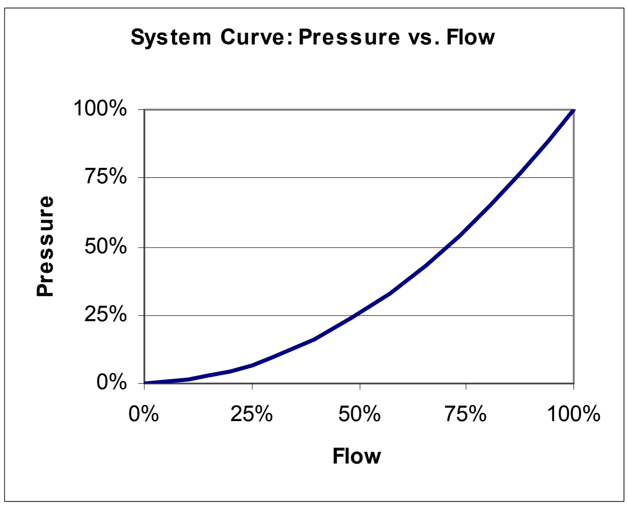
Accounting for VFD losses, fan power can be modeled as %Fan Power = %Fan Speed ^ 2.7 / VFD Efficiency. Modern VFDs are 95% efficient or better.

4.2 FAN CURVES AND SYSTEM MODELING

4.2.1 System Curves

Each building has a unique relationship between pressure and flow. The relationship is % pressure = % flow squared. Many potato storage buildings are designed at 1.25" water column static pressure.

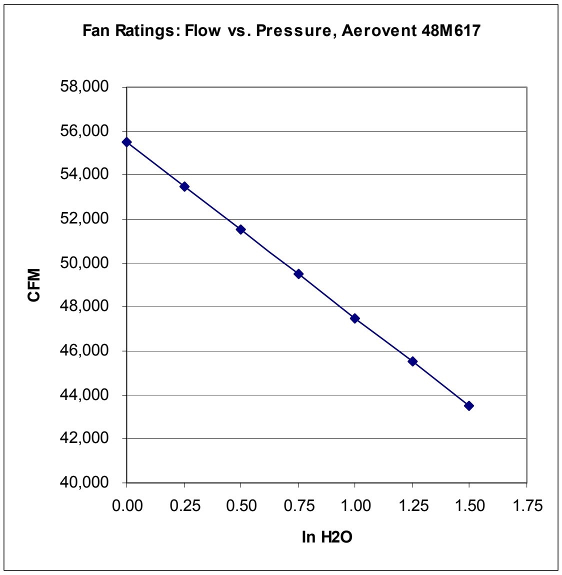
Figure 2: System Curve

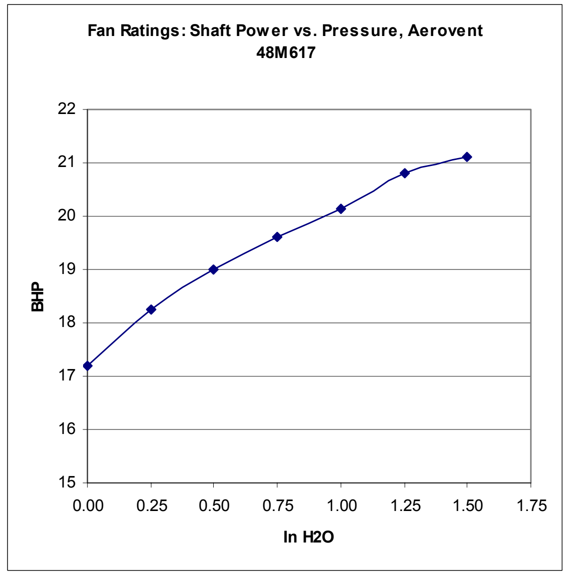


4.2.2 Fan Curves

The following fan curves are for a common 20 hp fan. Note that flow increases and shaft power decreases as pressure falls.

Figure 3: Fan Curves

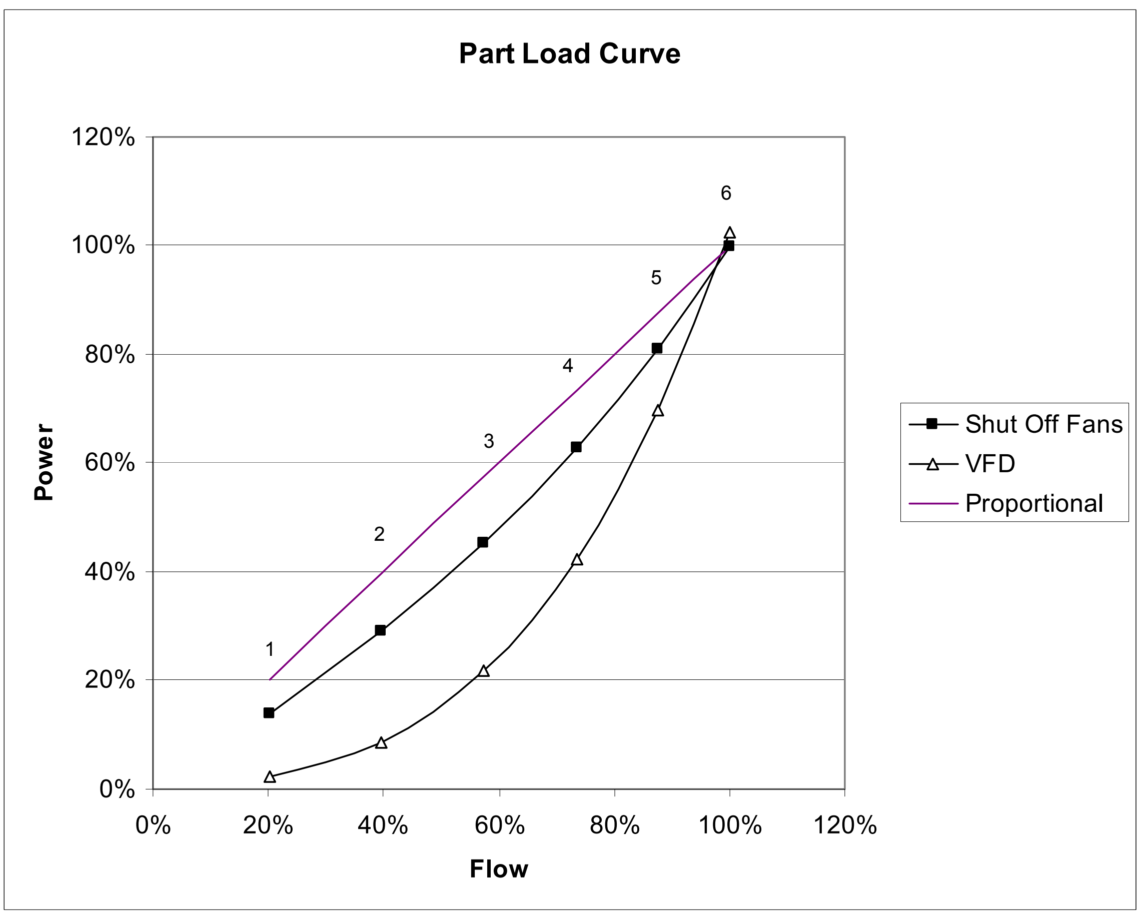




4.2.3 Shutting Fans Off vs. VFDs

The following discussion and figures are for a ventilation system with six identical fans.

Figure 4: Power vs. Flow, Part Load Curves

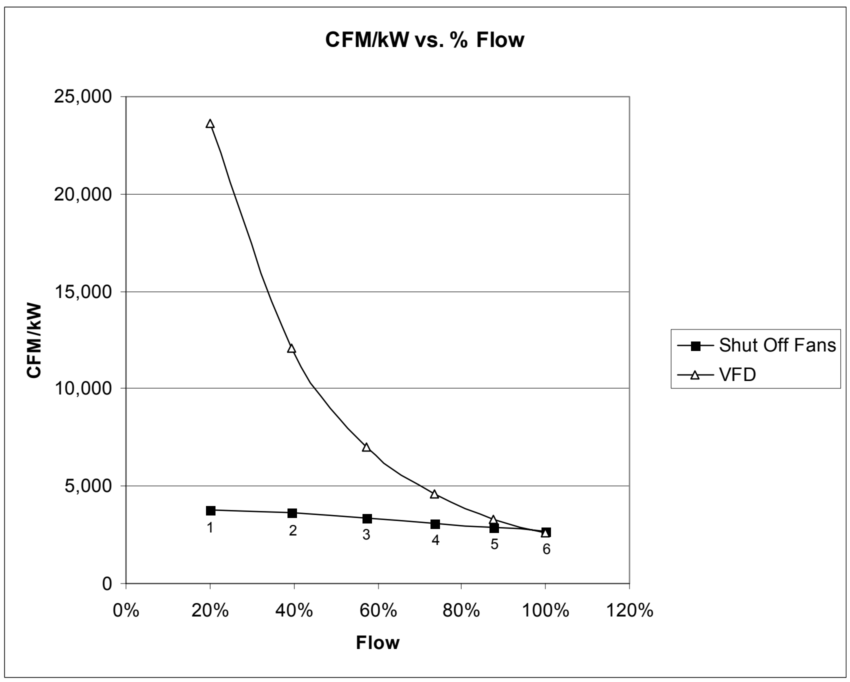


When a fan is shut off, the pressure falls, and the remaining fans produce slightly more flow and use slightly less energy. This is indicated by the black squares in the figure above. Note that this building can not operate between the squares, only at them. If the building had 4 fans, the location of the black squares would move, but would be on this same line.

With VFD control of the fan speed, the part load curve follows the line marked by the triangles. The system can operate anywhere on the line. The energy savings between the two operations is indicated by the vertical distance between the Shut Off Fans squares and the VFD triangles. For instance, with 3 fans shut off, the remaining 3 fans produce 57% flow and use 45% power. To produce 57% flow with VFDs, they would operate at 57% speed and consume 22% power. Note also that at 100% flow, the VFD power is slightly higher due to VFD losses.

Another way to look at the issue is to compare flow per unit power across the operating range. As shown in the figure below.

Figure 5: CFM/kW vs. Flow



4.3 AIR HEATING

Air heating can be a concern in warmer climates with limited OSA availability. With VFDs at reduced speed, the air is heated less than it would be by reducing the fan count as shown in the figure below. This would have the effect of extending OSA time slightly.

Table 3: Air Heating

Fans On Line, or Equivalent VFD Flow	6	5	4	3	2	1
Shut Off Fans Air Temp Rise, °F	1.2	1.1	1.0	0.9	0.9	0.8
VFD Air Temp Rise°F	1.2	0.9	0.7	0.4	0.3	0.1

5.0 VARIABLE FREQUENCY DRIVES

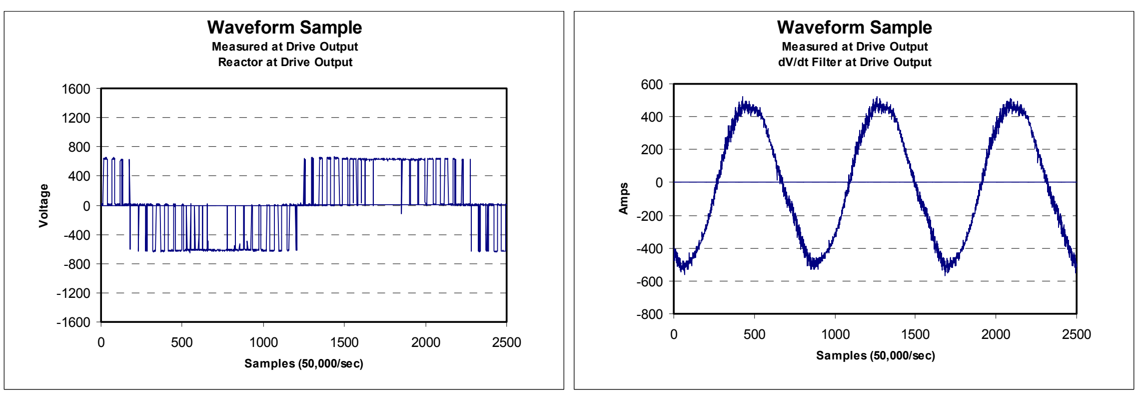
5.1 HOW A VFD WORKS

The VFDs pictured below serve (3) 15 hp fans and (3) 20 hp fans at Lamb Weston's Warden 1 storage facility.

Figure 6: VFDs at Lamb Weston 1, Warden WA

VFDs work by taking the 60 Hz AC power, converting it temporarily to DC, then converting it back to Pulse Width Modulated (PWM) AC power. The drive's input voltage is a smooth sinusoidal wave, but the output will look something like the figure below.

Figure 7: VFD Output Voltage and Current

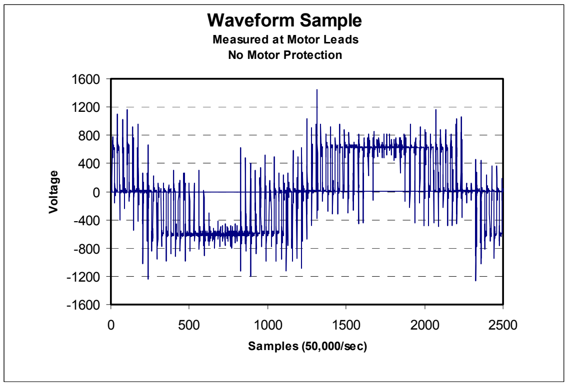


By varying the duration of the voltage pulses, the VFD can produce a nearly sinusoidal current output at any frequency desired.

5.2 MOTOR PROTECTION

If the lead lengths between the VFD and the motor are long, or multiple motors are controlled by the same VFD, damaging reflected voltage waves can form. These standing voltage waves can break down the motor winding insulation. An example of this is shown below.

Figure 8: VFD Output Voltage, Reflected Waves



5.2.1 VFD Rated Motors

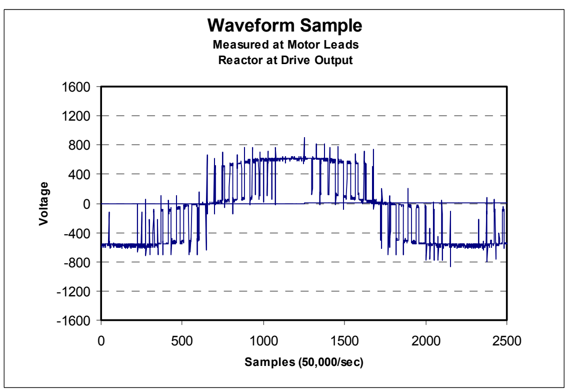
All motor manufacturers make a line of "VFD Rated" or "Inverter Rated" motors. They are built to withstand these voltage spikes. Other motors may or may not withstand them, and some additional form of motor protection is usually recommended.

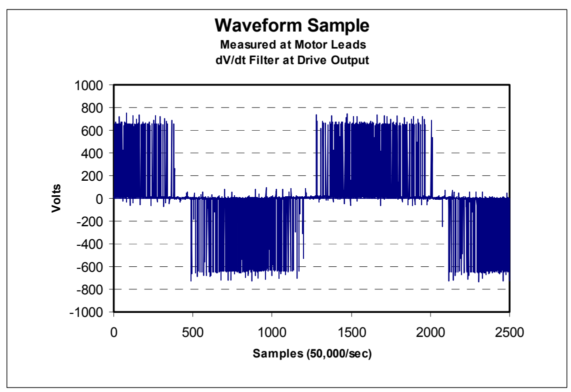
For new construction, it is best to install VFD rated motors. Load reactors may also be advised. When retrofitting existing buildings, the existing non-VFD rated motors can generally be used, but some level of motor protection may be necessary.

5.2.2 Load Reactors and Output Filters

The first level of motor protection is a load reactor. These act like a simple buffer, moderating the worst voltage spikes.

The next level of motor protection is the dV/dT output filter. This filter stops the voltage signal from exceeding a certain level, providing extra assurance that voltage spikes do not harm the motor.





5.3 LINE REACTORS AND NUISANCE TRIPS

A line reactor can be installed just before the VFD. It serves two functions:

1. Buffers incoming power which helps protect the VFD and reduces nuisance trips
2. Buffers harmonics created by the VFD, reducing disturbances fed back to the power grid. This can also have the benefit of reducing interference with other on site equipment. Some utilities require a line reactor for each VFD.

Nuisance trips occur when the VFD senses a fluctuation of the incoming power quality and shuts down to protect itself. Some brands of drives are more prone to nuisance trips than others. Sometimes the VFD settings can be adjusted to reduce nuisance trips. This is not a frequent problem, but does reinforce the need to monitor storage sites even, if automatic controls are in use.

5.4 VFD BYPASS CONTACTORS

The VFDs shown below each serve a 15 hp fan. The VFDs are contained in cabinets that contain bypass contactors.

Figure 9: VFDs with Bypass Contactors, Thaemert Farms

A bypass contactor allows the operator to bypass the VFD should it fail. By turning one of the switches in the lower left corner of the picture shown above, the VFD is removed from the circuit and the motor can operate at full speed. The ventilation system is then operated with non-VFD practices.

Most air systems with multiple fans don't have bypass contactors. The reasoning is that if one of 4 VFDs fail, the system could get by with 3 fans for a day or two until a new VFD is installed. In 1990, when VFDs were relatively new technology, it could take a week or more to get a replacement VFD. This becomes less of an issue every year, as VFDs are standard technology in many applications and dealers keep them in stock.

This report is available on the web in PDF format at cascadeenergy.com.