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Situations to Consider When Variable Air Volume Is an Option

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ABSTRACT

Variable-air-volume systems utilize some of the latest technology available to control zone temperatures and save fan energy. In fact, the energy savings can be quite substantial. Then why do engineers and building managers have reservations about using this type of system? Probably the memory of past experiences.

The chain of design, equipment selection, installation, and air balancing must be tailored to a building's needs or conflicts will arise. There are many disciplines to consider when creating a VAV system, and if one link is weak, there can be trouble. Are more complicated systems the price we have to pay for saving energy?

EVOLUTION OF VAV

Variable-air-volume systems have come a long way since their inception. This has been driven by the advancements in the pneumatic and DDC control industry. Pressure-independent VAV boxes that automatically compensate for changes in duct static pressure have made pressure-dependent boxes virtually obsolete. Lower duct static pressure is needed for the modern VAV box. More sophisticated transducers and computer software have achieved a more precise control of air volumes.

Above all, falling prices for variable-frequency drives (VFDs) have unleashed a premier energy-saving technology. What used to be a luxury is now the norm. Fan volume control is much more precise with a VFD. The fan runs quieter than with a vortex or system damper. Static regain design of ductwork has also reduced fluctuating duct pressure and noise.

Proper testing and balancing is now specified more often. This is the final link that can either make or break the system. VAV systems are by no means "self-balancing." In fact, they are quite the opposite. There is more to go awry and numerous components that must work together in harmony. Even the factory settings are not dependable and usually must be reset in the field. Just setting the proper flow at the VAV box does not mean that the diffusers are balanced (or even hooked up). Testing and balancing of all diffusers is needed.

WHEN IS VAV THE PROPER APPLICATION?

Room volume in conjunction with the required air changes per hour determine minimum airflow needed for the space. If this number is close to the maximum airflow needed at full load, then VAV is not prudent. The same holds true if loads are fairly constant. If installed under either condition, the VAV box would never modulate to a reduced airflow.

The lower the minimum airflow, the greater the savings. But how low can you go? Many designers go all the way to zero. This is a real saving but controversial from an indoor air quality standpoint. Is enough of a load created when occupants are present? After all, proper air changes are usually only needed when space is occupied.

If electric reheat is necessary, VAV might not be practical unless the coil is offset from the primary airstream, as in a fan-powered VAV box. This is because electric coils usually need at least 500 fpm face velocity (2.54 m/s) to prevent overheating.

If precise room pressurization control is necessary, it gets more complicated. VAV return or exhaust is needed to track the supply. In critical spaces such as laboratories, the controls and air balancing must be very precise to prevent room pressure swings.

If precise humidity control is required, VAV makes controlling humidity more difficult due to the dynamics of continual airflow variations. Best results occur when special modulating humidity controls are used. Duct modulating-type humidity sensors along with an integrating device that resets the output of the humidifier are recommended. This allows the duct sensor to quickly respond to a quick rise in duct humidity caused by reduced air volume. This arrangement, commonly

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referred to as "anticipating control," allows the duct sensor to override the space humidistat and provide uniform control.

To benefit from the energy savings of variable-frequency drives, the air-handling system needs to be of moderate capacity. The larger the fan motor, the lower the minimum energy draw percentage. Motors in the range of 20 to 100 hp generally can go down to 35%-40% of full-load amps. Motors from 5 to 20 hp can generally reduce to 40%-60% of FLA and from 1 to 5 hp to around 60%-80%. Slowing down a small motor does not save as much energy as slowing down a large one.

There is no doubt that VAV systems save energy when compared to constant-volume systems. All zones of a building generally do not reach their peak loads simultaneously and, therefore, will never need a fan running at total capacity. Constant-volume systems run continuously at these excessively high air volumes and waste a great amount of energy. On average, a VAV system runs at 60% of full load during occupancy operation. This can translate to generous energy savings when variable-frequency drives are installed because the fan electrical energy decreases with the fan volume according to the cube fan law.

Since the total of all peak loads will never occur at the same time, the sum of all the peaks will never be needed and, therefore, the equipment does not need to be sized that large. There is a diversity factor that permits the size of the cooling, heating, and air-distribution equipment to be selected on lower actual maximum occupied simultaneous loads rather than a higher design load. The diversity factor can be 70% to 80% in many situations.

Existing constant-volume systems can be retrofitted to variable air volume and be added to without increasing the size of the central equipment. The diversity of VAV makes this possible (see Figures 1 and 2).

SYSTEM STATIC PRESSURE CONTROL

Static pressure control is needed to prevent overpressurizing the duct system and is the key to energy savings. The sensor should be located about 75% of the distance from the first to the most remote terminal. It must be adjusted to account for the pressure loss between the sensor and the farthest terminal. Locating it at the end of the ductwork or too close to an isolated terminal with local pressure swings will cause a ripple effect throughout the system as the VAV damper modulates.

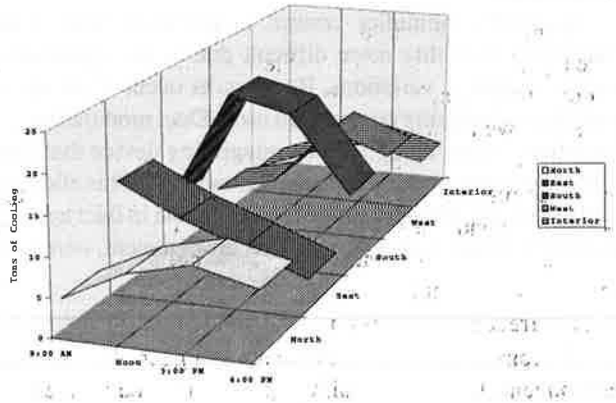

Figure 1 *Zone loads for different times of day.*

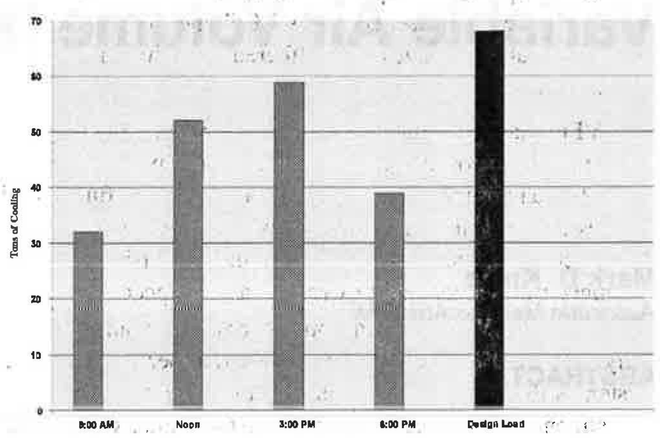

Figure 2 *Actual maximum occupied simultaneous load vs. design load.*

There are a handful of methods for controlling system static pressure. Some work better than others.

1. **System Bypass**—a relief damper opens and dumps excess air into the return duct or plenum. With this type of control, fan motor energy savings are nonexistent. This low-budget system will control space temperatures properly, but the relief damper is usually a source of air leakage and noise. This type of control is still popular for small office systems and DX coil units where constant coil velocities must be maintained in the air-handling unit.

2. **Discharge Damper**—an automatic damper at fan discharge. Only used on forward-curved fans. They are not as efficient as a vortex damper and are a source of noise, increased pressure drop, and system effect. Discharge dampers are rarely used anymore.

3. **Vortex Damper**—an automatic damper on the inlet of the fan. System losses due to air inlet conditions are a drawback. Once very popular, vortex dampers are now being overshadowed by the superior variable-frequency drive.

4. **Variable-Pitch Vaneaxial Fan**—volume of air changes with the angle of the blades. Good for larger applications up to 60,000 cfm (28,302 L/s) where higher percentage throttling is needed. Initial costs are high, and they must be properly maintained.

5. **Two-speed Motor**—volume of air is cut in half when motor is switched to low speed. Used for fume hood exhaust in occupied/unoccupied modes, but not a recommended option. The lab occupant might use the fume hood with the fan on low speed, which could be a dangerous condition due to the lack of face velocity.

6. **Variable-Frequency Drive**—electrical signal is altered and modulates motor speed. This is the most efficient

method of all. Inverter maintains motor efficiency regardless of rpm or horsepower. The motors do not lose their power factor and stay at about 95%. Some VFDs may cause electrical noise that can be filtered out with an isolation transformer.

VFDs have become more reliable in recent years and are less sensitive to power surges. They still can trip off, so it is not a good idea to use them for critical systems such as fume hood exhaust, unless an alarm system is included. In situations where constant stack velocity is required, outside air inlet dampers are used instead of varying the fan speed.

Prices for VFDs have dropped dramatically and are now only about 20% more than a vortex damper system. The system still must be large enough to make the additional investment worthwhile. Figure 3 shows annual energy use with different flow-throttling techniques.

CONTROL EQUIPMENT

DDC Takes Over

Direct digital control (DDC) products are much more advanced, cost-effective, and reliable than just a few years ago. Building managers soon learn to love facility-wide integration and data accessing from a single location. Event scheduling, data logging, and alarm reporting are easy once they figure out how to use the software.

New products can be exciting, with many possibilities and more flexibility. Control technology is evolving quickly, so quickly that it does not always seem to have been field tested.

Amid the dust and wide temperature swings of a construction site, VAV boxes are installed with the micro-electronic controls already mounted. But what worked fine in the laboratory often has a short life at the job site.

Control technicians certainly have their work cut out for them with these new products. They are often left trying to figure out how the system works under an aggressive schedule, with people ready to move in and an air balancer breathing down their necks.

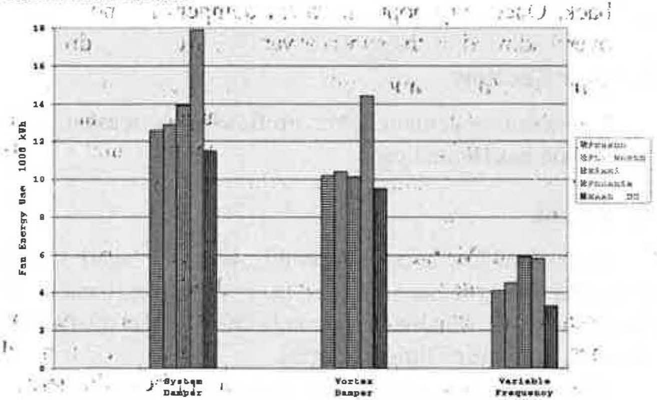

Figure 3 Annual energy use with different flow throttling techniques.

This can lead to job delays, animosity between the balancing and control contractors, and to a system that has multiple shortcomings or just does not work. New products can be a headache. Generally, the DDC hardware and software that have not been radically changed in a while prove to be the most reliable.

There are many different VAV control vendors, and their products are continually being updated, so the balancing technician often needs assistance to start the job. The necessary hardware and software also need to be provided. This should be reflected in the control contractor's job specification. Some balancing contractors now own laptop computers that can interface with a growing number of systems, but control contractors are reluctant to loan out proprietary software.

DDC VAVs have not changed the need for air balancing. Even though the computer screen may read 1262.5 cfm (595.5 L/s), the actual airflow could be several hundred cfm higher or lower. This happens quite frequently because of the duct configuration, transducer accuracy, or program writers who just ballpark the flow coefficient or make errors. There are literally hundreds of lines of text, and one tiny mistake can have a large impact.

Control technicians are expected to be experts at HVAC systems, electrical wiring, pneumatics, computer programming, customer relations, and all their company's latest products. This is a lot for anyone to master. Also consider the time they are given to do a proper check on what was just installed. Whether the construction is behind schedule and the people are ready to move in or the control technician has too many other places to be, the DDC VAV controls are, more often than not, working improperly when the balancer is told "everything is ready." By cooperating with each other, the balancer and the control technician can calibrate the DDC VAVs to produce accurate readings.

Pneumatic VAV

Pneumatic VAV is simpler and more user-friendly. Everyone is not at the mercy of the control contractor. The balancing technician is usually able to troubleshoot the limited number of problems without assistance of the control technician.

A manometer can be hooked up to the differential pressure taps. This is good for troubleshooting but is not accurate enough for balancing. Often the inlet duct configuration will give a skewed reading.

The pneumatic controllers contain a separate minimum and maximum adjustment knob to make overcoming these poor inlet conditions easier. DDC VAV boxes typically have only one flow adjustment. They are balanced at maximum and then set to minimum to be checked. Minimum flow is hopefully correct because no further adjustment is available.

Pneumatic VAV systems are more rugged and have fewer components that can fail, although they do need frequent calibration. Their major drawback is that they cannot easily or accurately obtain the degree of energy savings that come from night setback, multiple minimum and maximum airflows, and history logging.

Probably one of the biggest limitations, when it comes time to sell a pneumatic control system, is that maintenance personnel are not able to troubleshoot problems from an office computer. Pneumatic VAV boxes are not capable of sending data through a local area network for systemwide sharing of information. Sophisticated building control strategies cannot be performed. The pneumatic VAVs cannot be accessed through a computer or via a modem over telephone lines.

Analog Electronic VAV

Analog electronic VAV systems are an improvement over the old pressure-dependent electric units. An analog VAV system has a velocity sensor and controller that will maintain proper air volume after balancing has been completed.

One advantage an analog system has over a pneumatic one is that it can be designed to sense upstream duct temperature and make a decision whether this air is needed in the space. This is next to impossible to do with a pneumatic system, which requires a heating coil at each terminal box if heat is necessary. With an analog system, only a heating coil in the air-handling unit is required. Of course, the building must be zoned properly because heating and cooling are not available at the same time.

Beside that one bright spot, analog electronic VAV systems have many of the disadvantages that pneumatic and DDC systems have. Like pneumatic systems, analog systems are limited in their ability to communicate to the building's energy management system. They also contain sensitive electronic components that are more likely to fail, similar to DDC.

TYPES OF VAV TERMINAL BOXES

Cooling Only, Single Duct

Great for interior spaces of multiple-story buildings, but subcooling can be a problem if the minimum is not zero and IAQ can be a concern if the minimum is zero.

Reheat, Single Duct

Usually used for exterior and under-roof areas of buildings that require heating as well as cooling. The trouble is that reheat water is often needed all year long to prevent subcooling from the minimum airflow.

Fan Powered

Installed in ceiling plenums and used for spaces that require heating as well as cooling, they are excellent for maintaining room air circulation.

Parallel—Appropriate where the ratio of heating to cooling hours is low. There are energy savings because cold air does not have to be reheated. The fan draws in ceiling plenum heat generated by lights. If this is not sufficient, an offset reheat coil can be added.

Drawbacks include the additional cost and the maintenance required for added motors in the system. Wide airflow swings can be noticeable when the terminal is switching from heating to cooling, especially if the fan terminal is oversized. There is a new product that controls the flow by monitoring the duct pressure on the discharge side of the terminal box to avoid this.

Series—Not often used because of the high energy penalty from fans running for long periods. In the occupied mode, the internal fans must run continuously.

Induction

Made to increase room circulation by mixing plenum air with primary duct air. Induction is created by primary air nozzles with small orifices that create jet streams that draw plenum air into the terminal box. Induction ratios can vary from 25% to 65%.

One limitation of this box is that full shut-off is not usually an option, and this can lead to subcooling of the space, especially since colder discharge air temperatures from the air-handling unit are usually necessary. A slightly higher static pressure in the duct must also be maintained compared to a conventional VAV.

VAV Diffuser

Works well for a partial VAV system in areas such as a conference room or corner office. They are self-contained and require no pneumatic or electric connections. They even have their own built-in thermostat but do not sense airflow.

The next generation of VAV diffusers do sense airflow but cannot measure it, so they are still pressure dependent. A low voltage tie-in is required. Temperature setpoints are more precise and can be adjusted via a hand-held remote control.

Bypass Terminal

Unwanted air is dumped into the return plenum, which can sometimes still drop back down into the occupied space.

This approach does not reduce the fan airflow demand. In turn, there are no fan motor energy savings, and diversity can not be taken advantage of.

Damper Section

Two-position actuation with no flow measurement. This application has limited use.

Air Valves

The valve has a cone assembly with a staged spring inside. As static pressures change, the cone moves to maintain the set airflow. The valve is accurately calibrated at the factory and usually requires little balancing.

The valves are popular on laboratory fume hoods for their corrosion-resistant design and quick response time.

Due to their cost, they are usually limited to laboratories, isolation rooms, and process air.

Even though variable-frequency drives are not usually used on fume hood exhaust fans, the energy saved by not exhausting large amounts of conditioned air out of a building is an even greater benefit. One to three dollars per cfm ($0.47 to $1.42 per L/s) annual savings can be expected.

Dual Duct

With a hot and cold duct, unwanted mixing can waste energy as well as cause discomfort in the space. This is caused by a leaky damper or downstream air sensors. Inlet air sensors are favored instead of a downstream one because low duct pressure can cause the unwanted deck to open trying to maintain proper volume.

In certain parts of the country humidity control can be a problem. During the summer months, the humid outside air passes through the hot deck with nothing to drop out the moisture. This causes the building to be a little on the humid side.

INLET AIRFLOW SENSORS

Air moving through a VAV box is not easy to measure. The airflow sensor, usually located at the inlet, must be designed to contend with the turbulent movement of air found in most duct systems. Reliable flow measurement and control ensures that the VAV terminal will operate properly years down the road, just as on the day it was balanced. The most common inlet sensors are as follows:

Multiple-Point Velocity Pressure Grid

This velocity pressure grid works on the same principal as a pitot tube, which has been universally accepted and is approved as the standard method of air velocity testing by ASHRAE. The grid is not a true averaging sensor, but the center-weighted ones tend to work just fine.

The grid is the most common inlet sensor and is used with all types of control systems. It is the most rugged, rarely ever getting damaged or plugged. Their greatest attribute is their ability to overcome poor inlet conditions. Elbows and curvy flex at VAV inlets do diminish the accuracy of the reading, but the controllers can usually be reset to balance the box properly.

A very sensitive controller or transducer is needed to read this type of sensor because of the nature of the exponentially based velocity pressures. The pressures tend to be very low, especially at minimum airflow. This high turndown ratio hurts the sensor's accuracy at the low end of the scale.

Thermal

This "hot wire" type of sensor is very good at reading low velocities accurately. The high end of the scale is where it is not as true. It is also vulnerable to failure from system dust, but a new style that has a protective coating has supposedly solved this shortcoming. These sensors are usually found on analog VAVs and are often called "thermistors" or "heated RTDs."

Vortex Shedding

This mass flow sensor is very accurate even at low velocities. It is expensive and only seen on high end systems such as those designed for laboratories. The sensor sends out digital pulse outputs at a frequency that is linear to the airflow. The pulse is created by vortices of the air created as air moves through the sensor.

Substantial straight duct upstream is highly recommended because resetting calibration to match actual airflow is very cumbersome and time consuming. The vortex shedding sensor cannot be located, upstream or downstream, near any source of excessive turbulence. For example, a VAV damper at minimum can cause enough turbulence to make this sensor unreliable.

Fluidic

Similar to the vortex shedding sensor, the fluidic type is a mass flow sensor that is accurate even at low velocities. In contrast to vortex shedding, it is used only with pneumatic systems and is very quick and easy to balance. It consumes small amounts of pneumatic air in its measurement process. The pneumatic air must be clean and dry at all times or the matched controller will fail.

The fluidic sensor, even though it works very well, is being pushed aside by DDC compatible and multipoint sensors. The fluidic type is limited to single-point sensing.

CONTROLLING OUTSIDE AIR

Providing constant ventilation in a variable-air-volume system is usually overlooked. There is often no provision for maintaining the necessary minimum outside air. As the supply fan volume is reduced, so is the outside air volume. As a result, design minimum outside air is only achieved at maximum cooling load or in the economizer mode.

There are several methods for maintaining proper ventilation in a VAV system.

Outside Air Injection Fan

A separate duct and fan are installed in parallel with the economizer duct. Of course, the minimum outside air duct can be sized much smaller than the economizer duct.

The injection fan supplies a constant volume of outside air to the mixed air plenum at all times. The fan can be controlled by a velocity sensor in the outside air duct.

This appears to be the up and coming method, and engineers have had success with it. It is simple and reliable.

CO_2 Sensors

Two methods use carbon dioxide detectors to control ventilation. The first method uses CO_2 as a surrogate for rate of ventilation. Whether or not carbon dioxide is a true method of tracking ventilation effectiveness is debatable. Contaminants from other sources are essentially ignored using this occupancy driven strategy. In addition, it can take hours for carbon dioxide to reach a level at which the control system will act upon it. To avoid potential IAQ problems, the CO_2 concentration should not be used to drop the ventilation rate below the quantity that is required to satisfy the scheduled occupancy profile (Janu et al. 1995). At the present time, a sensor that reads carbon dioxide and volatile organic compounds is being developed.

The carbon dioxide concentration method, in contrast, is a practical method of instituting continuous measurement and closed-loop control of outside airflow (Janu et al. 1995). The method is established on a tracer gas concentration balance that uses carbon dioxide as the tracer gas.

The outdoor airflow rate (in cfm or L/s) is determined as follows:

$$\text{CFM oa} = \frac{CO_2\ \text{ra} - CO_2\ \text{sa}}{CO_2\ \text{ra} - CO_2\ \text{oa}}\ \text{X CFM sa} \qquad (1)$$

A single CO_2 sensor is used for reasons of accuracy. Samples of supply, return, and outside air are pumped to the sensor alternately via a three-way valve. CO_2 is measured in parts per million. These data are sent to the control system, which uses this information to determine the position of the outside air damper. This method's success is heavily dependent on the long-term reliability of the CO_2 sensor. Periodic calibration of the sensor needs to be part of the maintenance program.

Flow Stations

This method of continuous airflow measurement in the system uses pitot flow stations, pressure drops across orifices, heated thermistor grids, or vortex shedding devices to monitor the supply, return, and/or outside air. It is difficult to measure outside air directly, due to low velocities, wide temperature swings, and limited space. The best arrangement calls for flow stations in the supply and in the return back to the AHU. Relief air is not included. The difference between these two readings should give the actual outdoor airflow volume. Or does it?

TABLE 1
Compounded Errors with Flow Stations

	Design	*Actual
Supply CFM	10,000	9,500
Return CFM	8,000	8,400
Outside Air CFM	2,000	1100
% Error OA	0	45

* Assuming a − 5% error for supply measurement and a + 5% error for return measurement.
To convert cfm to L/s, multiply cfm by 0.472.

As you can see from Table 1, an error of only 5% in the flow readings causes a 45% error in outside air calculations. Flow stations can be a lot more than 5% off. This is due to the lack of proper straight duct, which is usually a factor.

The flow station strategy also cannot take into consideration the fact that most air-handling units leak air. It is not usually apparent because of the negative pressure they are under. In this scenario, mechanical room air would be assumed to be outside air.

Mixed Air Plenum Static Pressure Control

In a typical system, outside air is drawn in because of the negative air pressure produced by the mixed air plenum. If this pressure is reduced, so is the outside air. This is exactly what happens when a VAV system is not at full load.

If the control system is designed to maintain a constant static pressure in the mixed air plenum, this would guarantee a constant volume of outside air. A static pressure sensor located in the mixed air plenum would reposition the return air automatic damper to maintain the proportions of return air and outdoor intake that adequate air quality requires (Cohen 1994). Throttling the return air automatic damper maintains a constant outside air intake.

As long as the mixed air dampers are properly sized, this type of OA control can be added to an existing HVAC system. It could even be installed on packaged HVAC equipment without modifications to the ductwork or ceilings.

Constant Space Pressure

This direct approach measures building static pressure and compares it to outdoors. The return fan capacity or the return and relief dampers are adjusted by the control system in response to the static pressure signal. The problem is that wind can have an adverse effect on the sensor that is located outdoors. Windows and doors that are left open would also challenge the system. This method of outside air control is more for maintaining the building pressure than providing adequate ventilation. It should only be used in facilities that have a generous amount of exhaust, such as laboratory buildings.

With all these methods of controlling outside air, it is important that ASHRAE Standard 62 be followed. Proper ventilation is very important from health and energy standpoints. People spend large portions of their lives in buildings, and they should be provided a healthy environment. On the other hand, building owners spend large amounts of cash on conditioning outside air, so it is a delicate balance.

CONCLUSION

It appears that there are numerous situations that need to be considered when creating a VAV system. They cannot be viewed like a constant-volume system. VAV systems are not constant but a dynamic, ever-changing assemblage of components that must be custom equipped to satisfy the needs of the occupants and owners.

The complex technology to do this is now here. All we have to do is manage it properly. Most of the past VAV problems have now been solved, but there is still a long way to go in implementing a successful strategy, consistently. More complicated systems are indeed the price we have to pay for saving energy.

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