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VAV FOR LABORATORY HOODS—DESIGN AND COSTS

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ABSTRACT

Laboratories with chemical fume hoods can have HVAC systems designed for variable air volume (VAV) for the optimum in safety and cost savings. Various VAV designs are discussed with their associated advantages and disadvantages. Controls for providing VAV operation of fume hoods are outlined. A computer simulation of the energy usage for constant vs. variable volume hood operation is performed. The energy and cost savings are discussed along with a construction cost comparison of constant volume with variable volume. An economic analysis for retrofitting VAV in laboratories is performed with the VAV system in this example having a simple payback of three years and a 35% rate of return on the differential investment.

INTRODUCTION

Laboratory buildings are found in many industrial and institutional settings. Every branch of research and development requires associated lab facilities. Buildings of this highly technical nature are being built at an ever increasing rate as the requirements of technology grow more demanding. This paper will concentrate on laboratories equipped with chemical fume hoods and with other specialty exhaust devices. HVAC designs for new laboratory construction may be variable air volume (VAV) in order to realize the tremendous energy and cost savings that the operation of VAV systems offer owners in comparison to constant volume systems. The general requirements of laboratory HVAC are set out in ASHRAE Applications (1982).

The use of VAV designs has become feasible for almost every type of facility. The laboratory building is one of the last to start using VAV air-conditioning because of the difficulty of applying variable air volume to fume hoods while still maintaining room pressurization and temperature control. In most research laboratories, conditioned air is used once through with no recirculation. The design supply air volume is most often determined by the exhaust required rather than by the heating and cooling load. In most designs described in this paper, the thermostat controls the amount of reheat. Devices are now available that make it possible to run the fume hood as a variable volume device while still maintaining room pressurization levels. Previous work on variable fume hood testing has been reported by Farho, et al. (1984) and by Wiggin and Morris (1985).

The laboratory fume hood is one of the keys to successful VAV designs in laboratory buildings. The HVAC design must guarantee that the fume hood will be able to operate in a safe manner. The effectiveness of fume hoods is generally measured by ASHRAE 110P (1982). The development of this method to test fume hoods as reported by Caplan and Knutson (1978) now makes it possible to compare the safety of hoods during variable volume operation as opposed to constant volume operation. The current test results show that safe conditions are maintained in fume hoods during variable volume operation as long as sash face air velocities are maintained at appropriate constant design levels. However, the safety of fume hoods is affected by many factors. The authors feel that additional tests should be developed to supplement ASHRAE 110P. A battery of tests could then be performed on hoods already installed to verify that they are operating safely.

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When designing HVAC systems for hoods, one of the most important factors for safe hood operation is the manner in which supply air is brought into the laboratory room. Supply air should be introduced at a point as far away as possible from the hood face with terminal velocities adjacent to the hood kept to a fraction of hood face velocity. This topic is discussed further in ASHRAE Applications (1982) as well as Peterson et al. (1983) and Caplan and Knutson (1978) Part 2.

LABORATORY PRESSURIZATION REQUIREMENTS

Laboratories should be provided with HVAC systems that provide safe conditions. Cost-effective and energy-efficient operation and providing an environment conducive to the comfort and productivity of those people in the laboratory are also important.

The laboratory room for purposes of this discussion is a space in which exact pressurization control must be maintained as well as temperature control. Adherence to the National Fire Code (NFPA 45 (1984) usually results in the use of 100% outside air ventilation systems. HVAC systems for laboratories must be able to maintain room pressurization control. Most laboratory rooms require that the lab be negative with respect to corridors or nonlab areas. When the lab has a negative pressure with respect to the corridor, air will be drawn in from adjacent areas into the lab. This negative pressurization in the lab helps to prevent any flow of contaminated air out of the lab. Additional supply air must be supplied to the corridor so that this extra air can be drawn into the lab.

For clean laboratories, where the product or process is not hazardous and must be kept free from contamination, positive lab pressurization is frequently used. In the case of positive pressurization, more air is supplied to the lab than is exhausted. The extra air supplied increases lab pressure and makes it difficult for contaminants to enter.

Pressurization control requires a higher sophistication in designing and controlling an HVAC system than is the norm. Therefore, more attention must be paid to this feature of the design during design and construction. Constant volume systems can provide negative or positive pressurization in labs. Pressurization with a constant volume system usually requires rebalancing when chemical fume hoods are added or deleted from the system. Variable volume systems can be designed so that changes can be made without rebalancing. Variable volume pressurization is achieved through active control and monitoring. Constant volume systems can be equipped with the same kinds of controls to achieve tracking and pressurization control to overcome changes in filter pressure drops, coil losses, etc.

This discussion of pressurization control and variable air volume systems has suggested some of the tremendous flexibility possible with variable volume systems. Rooms can be changed from positive to negative pressurization with the turn of a screw. Exhaust devices can be added or removed without the need for rebalancing the fan and other components of the system. Systems can be oversized for future expansion without any operating cost penalties.

Direct pressurization control uses a sensor measuring pressure difference or air velocity between the lab and the corridor. A sensor is placed in the wall to maintain a set pressure differential or air velocity, for example, 0.05 inches of water (0.0125 kPa). This requires a very sensitive sensor, accurate to 0.005 inches of water (0.00125kPa). This sensor is often fooled by local disturbances. Overrides may be needed for such things as door openings that can momentarily disturb the static pressure balance. However, it is not economically feasible to design a system that will maintain pressurization control at every moment. The more precise and sensitive the control, the more likely it will be out of balance and provide the reverse result to what is desired.

Facilities people prefer reliable pressurization systems based on volumetric tracking where controls maintain a constant relationship between the exhaust and supply air volumes. This does not require as accurate a sensor as the direct pressurization control. Therefore, sensor error is less likely to be a problem with tracking controls.

Two tracking schemes currently in use are constant offset and ratio tracking. In constant offset, the difference between supply and exhaust air is always a constant amount, such as 400 cfm (189 L/s). With ratio tracking, the supply air is a constant percentage of the exhaust air, such as 90%. Ratio tracking is usually more cost-effective, but constant offset is more effective in maintaining the desired in or out flow relationship. For minimum air amounts, the pressure differential becomes very small with ratio tracking.

VAV DESIGN CONSIDERATIONS FOR LABORATORIES

Temperature control requirements for laboratories are sometimes very precise. Accurate control of temperature with no large temperature swings is desirable. For this reason, terminal reheat systems are recommended for close temperature control. Terminal reheat creates false loads in order to control air temperatures and therefore requires large amounts of energy to operate. However, the many special considerations in operating a lab make the energy expenditure in terminal reheat systems worthwhile in order to maintain close control of room ambient conditions. As stated earlier, in most laboratories the amount of supply air is determined by the exhaust requirements rather than by the loads. Except in perimeter zones, laboratories are characterized by small heating loads and large cooling loads with cooling loads largely from sensible heat from equipment. Consequently, the room thermostat controls the amount of reheat at the VAV box rather than controlling the amount of supply air.

One VAV design scheme uses constant face velocity sensors to control the variation in hood exhaust volume (see Figure 1). All of the exhaust from the laboratory space is through the fume hood exhaust. The supply box tracks the exhaust flow to provide the same amount of air needed by the exhaust less a constant amount to keep the lab at a negative pressure. The supply and exhaust systems have preset minimums that meet the maximum room load. The reheat coil in the supply box can meet the maximum demand for heating even when the supply and exhaust systems are providing the maximum amount of conditioned air. The room thermostat only controls the amount of reheat in order to meet the temperature needs of the space. The air quantity is set by the exhaust requirement. This scheme is straightforward and easy to control. It provides both good pressurization control and good temperature control but requires large amounts of reheat depending on the total exhaust air. Closing the hood sash reduces the exhaust air and thus reduces energy use while maintaining pressurization.

A second VAV scheme, frequently used in clean labs and labs with no special or toxic exhaust, is one similar to standard commercial air-conditioning except that the tracking of supply and exhaust for pressurization control is necessary (see Figure 2). The amount of supply air is set by the temperature requirement as sensed by the room thermostat. At maximum cooling load, the supply air is at a maximum. As the cooling load decreases, the supply air decreases until the supply air reaches the present minimum to be provided from the VAV box. If the room temperature is too cool, the thermostat activates the reheat coil until the thermostat setpoint is satisfied. The exhaust air tracks the supply air and maintains a close and constant relationship.

A third scheme, and probably the most flexible and energy-efficient discussed here, is one where the fume hood exhaust is combined with a ceiling exhaust (see Figure 3). The supply air tracks the combined exhaust through a duct velocity transmitter to maintain negative pressurization. The exhaust amount through the fume hood duct is controlled by the constant face velocity sensor. The ceiling exhaust is controlled by the room thermostat and comes on when the room cooling load is not satisfied due to inadequate supply air that matches the fume hood exhaust. The supply air tracks the total of the ceiling exhaust and the fume hood exhaust minus a constant offset to maintain negative lab pressure. With this scheme, lab hoods can be removed without changing the room temperature control and pressurization. The fume hood exhaust minimum no longer has to be set to meet the maximum room load. This decreases the average air movement because both the air to the fume hoods and the air for cooling are at their individual minimums as often as possible. However, certain minimum air-change rates may be dictated by the need for proper dilution of toxic or nontoxic contaminants.

A fourth scheme uses tempered makeup air, usually to auxiliary air chemical fume hoods (see Figure 4). Makeup air ventilation can be used in both constant volume and variable volume designs. The makeup air ventilation system coupled with the auxiliary air hood was formerly considered to be the most energy-efficient way to air-condition laboratories. Makeup air is not fully conditioned but still must be tempered to +/-5°F (± 3°C) of room ambient temperatures or it will not be comfortable for lab personnel to use the hoods. The makeup air scheme requires higher first costs because a separate fan and duct system is necessary for the makeup air. The flexibility of relocating hoods is now more difficult because each auxiliary hood has both a makeup air and exhaust air duct attached to it. Also, most auxiliary air hoods preclude the savings available from horizontal sash hoods that can reduce the total air required for safe operation by 60%. An auxiliary air hood of the same size has to move all of the air with the associated fan energy costs, but it does save part of the energy to condition air to the room. The horizontal sash hood savings will generally be much more than for the auxiliary air hood. Owners and engineers need to be educated to the economics and flexibility of operation that now favor variable volume horizontal sash hoods over auxiliary air hoods with tempered makeup.

HOOD FACE VELOCITY CONTROLS

Face Velocity Level Considerations

Hood face velocity controls are responsible for keeping average airspeeds through a hood face between certain limits. Face velocity controls accomplish this by either driving a damper in the exhaust or controlling individual hood fans. The face velocity controls are independent of the room pressurization controls, which are a separate and necessary item in a VAV lab design. It is important to discuss the settings of the levels of the face velocity and what they mean since there is some controversy over what is best for a given application.

HOOD FACE VELOCITY CONTROLS

The ASHRAE 110P test for hood safety factor (HSF) is used as a measurement of the breathing zone contaminant concentration. Peterson et al. (1983) included several experiments of HSF as a function of face velocity level.

Although the 110P test can establish a level of optimum face velocity in terms of HSF for a given hood in a given installation, the other major consideration, critical concentration level (Lower Explosive Limit), is not addressed by the HSF test. Hood internal baffle settings, type of experiments, clutter, purge rates, emergencies modes, and even temperature control also affect the face velocity level decision. There are several difficulties in controlling face velocity in a VAV system. Low face velocity levels may cause practical control problems. Certain types of controls, especially direct differential pressure types, are required to operate at low signal levels. Controls with healthy signal levels at low face velocities still have limits of accuracy and drift. In addition, it must be remembered that face velocity controls control average velocity.

Across the open hood face, the velocity is nonuniform in both a spatial and unsteady sense. Below are data taken from an actual installation with very high air-change rates. The test was run by using a standard Scientific Apparatus Makers Association (SAMA) six-point grid in a 5' X 2 1/2' (1.5 X .8m) opening, SAMA Standard LF10-1980.

The overall standard deviation in face velocity is composed of both spatial and time variations across the fume hood. This installation was severe and resulted in significant variations. If one then superimposes some control drift and inaccuracy upon this table, it is possible to see deviations of 40 fpm (.20 m/s) at some places in the fume hood face over time. It is not known to the authors if the deviations would remain this size for lower average face velocity settings. It is possible however, that lower average face velocities mean lower deviations, since supply makeup air, which tends to disturb face velocities stability, is also reduced. This of course, assumes that the control accuracy and repeatability do not deteriorate in absolute terms.

Often a large amount of VAV savings comes from using occupied/unoccupied operation with the fume hoods. When no one is in lab, hood face velocities or flows are reduced, thus reducing makeup air. Whether to reduce face velocities in the unoccupied mode typically depends on what face velocities are considered safe enough when no one is in the lab. Usually, however, when active experiments are underway, labs are considered "occupied" for hood purge reasons.

Occupied/unoccupied hood operation is similar to on/off (high flow/low flow) hood usage. The most common control is a manual switch placed on this side of the hood. Recommended practice is to maintain a minimum of hood exhaust air. During use, the high operation of the hood uses 100% of the design exhaust air. During low operation, as a rule of thumb the exhaust air quantity should be greater than 20% of the design exhaust quantity. This high-low operation can be accomplished with individual exhaust fans equipped with two-speed motors or fans equipped with variable speed drives. For fans serving a number of hoods, individual dampers for each hood control the amount of exhaust air. In this case, a manual switch at the hood face forces the damper from the open position on high to the closed position on low. An alternate to the switch at the hood is an interlock with the room lights. When the room lights go off, the hood goes into its low volume operation. There are two main objections to the high/low form of hood operation. The first is that this scheme relies on the operator to safely operate the manual controls. If the hood is left on low when actually in use, the result may not be very safe. Using the light switch alleviates this problem somewhat, assuming that the hood user will not work in the dark. The other main objection to this scheme is that often the HVAC system is not sophisticated enough to maintain room pressurization and temperature control when the hood is on low. Still, this scheme remains the cheapest and simplest way to gain energy and cost savings when operating fume hoods. Actual results from one successful similar design in a large laboratory showed a 1.5 year payback.

When supply air makeup is not enough to handle the load or ventilation requirement because of low hood exhaust airflow, the designer may chose to allow the thermostat to override the face velocity control. This of course leads to higher than normal face velocities and usually is not acceptable. A better solution is to add another exhaust valve, as exemplified in Figure 3, which opens upon thermostat high temperature output signal. This exhaust together with the hood exhaust(s) is tracked by the supply. Thus total supply flow is increased until the load demand is met.

Types of Face Velocity Control

There are two basic types of face velocity controls available now. The first type, shown in Figures 5 and 6, uses the differential pressure between the inside of the hood and the lab room. This control uses a sensor placed in the wall of the hood, which measures either the differential pressure or the velocity through the sensor generated by that differential pressure.

The outputs of all the sensors in Figures 5 and 6 are connected to the basic control whose output then goes to the damper motor, or fan speed control, etc.

Generally speaking, these differential pressure face velocity controls sense velocities or pressures related to actual average face velocities, but they are not the same or even necessarily completely consistent with the face velocity. For example, a fluid sensor may control average face velocity at 100 fpm (.51 m/s, but have a velocity of only 50 fpm (.26 m/s) through itself. This is a function of hood design and sensor design and location and is not usually a problem. In addition, as the hood sash position is changed, the actual average face velocity may vary up to 30% depending on, again, hood design and sensor location and design.

Figure 7 shows the average face velocity increasing as the sash is closed. Usually, the resulting control deviations are acceptable but they must be understood while in the design phase. Among other items, changing face velocities affect the energy savings analyses.

The second type of control shown in Figure 8 senses actual sash position in some manner. Several pneumatic and electronic versions are available, but they are obviously limited to certain hoods, such as single vertical rising sash types. Multiple door horizontal sliding sashes obviously cannot utilize a sash position sensor in a simple way. There are step versions and continuous versions of position sensor controls, as shown in Figure 9.

INCREMENTAL SAVINGS ANALYSES

Although accurate face velocity control and lab pressurization may improve safety, these controls are primarily evaluated by the energy savings they provide. A simple program based upon BIN methodology is used here to investigate the parameters that affect these savings. The program differs from existing energy calculations for some of the same reasons that laboratory VAV considerations differ from normal building VAV calculations, as stated in the introduction.

A typical laboratory module was selected for this analysis. The base module contained two hoods of maximum 1000 cfm (475 L/s) each. The parameters investigated were:

1. Hood diversity factor (average hood opening).
2. Occupied/unoccupied mode turndown ratios.
3. Hood face velocity levels.

Incremental controls costs included controls installation, power consumption, additional valves (where required), and higher maintenance costs. Energy costs are calculated for the Wilkes-Barre, PA, area.

HOOD SAFETY CONCERNS

Testing has not determined whether all hoods are suitable for variable air volume designs. Hoods handling radioactivity, perchloric acid, and high volumes of particulates may or may not be well suited to variable volume. The designer must consider in these cases whether the duct velocity in the branch from the special hood is high enough at the variable volume minimum to carry materials such as radioactive and other particles.

The containment of contaminants within the hood is the primary function of the hood. A concentration of toxic material in the hood can be isolated so that at the breathing zone of the hood user there is no contamination. Good hood design along with hood face velocities of 100 fpm (0.51 m/s) should provide safe and effective conditions. Designers should remember that due to the impingement of supply air currents on the hood opening, the velocity of the supply air should be less than 20% of the hood sash face velocity at the opening.

To do this, supply air diffusers are usually located away from the face of the hood. Also, diffusers and other supply air terminal devices must be carefully chosen so as not to disturb the flow into the hoods.

Another consideration of hood safety is the dilution of flammables. The volume of air decreases in a variable volume system as the hood sash is closed and the amount of air available to dilute flammables in the hood decreases. It should be a design concern that the inside of the hood should never exceed a safe percentage of the lower explosive limit of any flammable vapors that may be present. For this reason, the variable air volume hood should never be totally off or at zero flow. If flammables or toxics are stored in the hood, exhaust from the hood when it is off would allow these flammables and toxics to build up to dangerous levels. Therefore, it is suggested that a minimum airflow be maintained through the hood at all times. A two-inch-high airfoil opening below the bottom of the hood sash is an effective way to introduce part of the minimum air needed. (It also serves as an entry for electrical leads.) A bypass slot may be provided with variable air volume hoods to provide a minimum of hood air even when the sash is fully closed. A suggested rule of thumb is to maintain a minimum of 20% of design flow at all times. If a bypass is used, it should be positioned where raising the sash will block the bypass immediately. Also, a minimum flow through the hood at the bypass may help to set an adequate supply air minimum for ventilation and temperature control.

Another frequently overlooked safety concern is the fire dampers should not be placed in the hood exhaust duct. In case of fire, the best thing to do is to keep the fume hood exhaust system in operation as long as possible to remove the toxic fumes and smoke. Consult NFPA 45 (1984) as well as applicable local codes and administrative authority for more details of this requirement. Under some conditions, it may be advisable to include an emergency override at the face of the hood that when activated would put the exhaust to full open.

Another safety concern is that hood velocity sensors, controls, and valving be provided with at least a minimum of fail-safe features. Hood exhaust valves where used should be normally open and fail in open position. Variable exhaust fans should have control failure modes that assure some hood flow. Any method of hood face velocity control should have failure modes that keep hood exhaust volumes above a preset minimum.

ENERGY AND COST COMPARISON

A computerized hour-by-hour energy simulation was performed for a major research clinic in La Jolla, CA. The simulation concentrated on the current energy use to condition outside air to supply 14 chemical fume hoods. The existing constant volume system was compared to a proposed retrofit of variable volume hoods with both variable air supply and exhaust.

The savings in energy for the variable volume design result from the reduction of outside air. The constant volume system is always at its maximum volume. The variable volume system only provides the minimum amount of air needed to meet room temperature conditions and to supply the fume hoods. This variation in the volume of air reduces the amount of air that needs to be moved by the supply and exhaust fans. The savings from variable volume fume hood operations are most appreciable during night and weekend hours because during these times the hoods can be set to their minimum volume position. In this study, the fume hoods are to be retrofitted with constant face velocity controllers set to 100 fpm (0.51 m/s). The diversity of use during the day on the hoods is estimated to be 30% and the diversity during night and weekend hours is estimated to be 20%. This procedure does require that facilities personnel intermittently monitor hood sash position and encourage lab personnel to close hood sashes when not in use.

The results from this computer study are shown in Tables 1 and 2. These tables show the heating and cooling energy required to condition the outside air for supply to the fume hoods. Additional utility cost savings are calculated for the savings in fan energy due to the installation of variable speed fan drives. Each fume hood in this case is provided with an individual exhaust fan. The total fan horsepower of these exhaust fans is 7.33 hp (5.5 kW) for a total air volume of 15,400 cfm (7270 L/s). The constant volume system used 64,000 kWh annually for a total cost of $8,320. The variable volume system is estimated for an annual use of 13,000 kWh with a total cost of $1,690.

The supply air fan energy will also be reduced with a variable air volume system compared to the constant volume system. The supply air for this facility is supplied from large central fans so it is not cost-effective to fit these large fans with variable speed drives, especially since the laboratory is only a portion of the whole building. It is estimated that the energy and cost savings obtainable by riding the fan curve amounts to 98,550 kWh annually with a cost avoidance for the VAV system in the first year of $12,812.

The conversion to variable volume for this facility is fairly straightforward. The bypass portion of the hood face is partially blocked off with a plate and face velocity sensors are installed inside the hood. An exhaust damper of stainless steel or other corrosion-resistant material is installed in the exhaust duct from the hood. The exhaust damper should be installed to fail in the open position. A retrofit package is installed in the constant volume supply box to convert it to variable volume. Controls that enable the supply to track the exhaust are connected between the VAV supply box and the exhaust damper.

Variable speed inverter drives are installed on the fan motors with the appropriate static pressure sensors. The costs associated with these retrofits is shown in Table 3, $84,205. (If there is an exhaust fan for each hood, the exhaust damper is not required at the hood.)

The economic analysis for this retrofit project is shown in Table 4. The economic life of the equipment is taken to be 15 years. A discount interest rate of 10% and the lack of tax criteria is due to the institutional nature of the clinic being analyzed. Energy and maintenance costs are escalated 5% per year, which is probably a conservative estimate in this case. Simple payback on the cost of retrofitting the VAV system is three years. The return on investment is 35% and the present worth of the savings is $180,659.

CONCLUSION

The variable volume designs for laboratory air-conditioning outlined in this paper make a strong case for incorporating VAV in laboratory facilities. Paybacks on differential investment in VAV due to energy savings can be as short as one year. VAV designs pay for themselves many times over in energy cost savings and flexibility. Even existing facilities can retrofit variable volume with paybacks of three years and shorter. Pressurization can more easily be controlled and monitored with VAV designs. The following are critical in successful VAV designs.

- VAV laboratory designs must meet the criterion of providing a comfortable working environment for scientists or other users.
- The total HVAC system design must be well coordinated and integrated with the function of all building systems.
- Effective control maintenance and monitoring procedures must be implemented.

In search for energy savings, the HVAC designer and owner should not forget all of the safety considerations that should be paramount in laboratory design. It is only after safety concerns are met that energy and construction cost savings can be implemented.

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TABLE 1

Annual Heating Energy To

Pre-Heat Hood Supply Air

Heat Rate 1000 Btu/h (kilowatts)	Constant Volume hours at rate	Variable Volume Hours at rate
23 (6.7)	420	871
47 (13.8)	826	211
70 (20.5)	760	189
94 (27.6)	673	169
117 (34.3)	731	62
140 (41.0)	423	41
164 (48.1)	455	0
187 (54.8)	368	0
211 (61.8)	396	0
234 (68.6)	391	0
257 (75.3)	275	0
281 (82.4)	307	0
304 (89.1)	333	0
328 (96.1)	87	0
351 (102.9)	177	0
374 (109.6)	90	0
TOTAL HEATING HOURS	6712	1543
Annual Heat Energy 1,000,000 Btu (kWh)	1011 (296)	71 (21)
Therms of Gas Input (85% efficiency)	11,889	839
Annual Cost ($0.68/therm)	$8,085	$571

Analysis is for 14 fume hoods.

TABLE 2

Annual Cooling Energy

To Condition Hood Supply Air*

Cooling Rate Tons (kilowatts)	Constant Volume Hours at Rate	Variable Volume Hours at Rate
3.2 (11.2)	366	1,336
6.5 (22.8)	431	160
10.0 (35.0)	527	0
Total Cooling Hours	1,324	1,496
Total Annual Ton Hours	9,243	5,317
Total Annual Kilowatt-hours	7,394	4,254
Energy Cost First Year	$961	$553

*Analysis is for 14 hoods.

TABLE 3

Cost Estimate To Retrofit

Hood HVAC For Variable Volume

Cost Item	Qty.	Cost	Total Cost
Demolition (Box)	1	$5,600	$5,600
VAV Supply Box Retrofit	14	400	5,600
Hood Exhaust Damper	14	1,143	16,000
Controls	14	1,571	22,000
VAV Fan Drives	14	1,000	14,000
Air Balance and Test	1	3,500	3,500
Sub-total			$66,700
Contractor's Overhead and Profit			$10,005
Design, Plans, and Specifications			$7,500
Total			$84,205

TABLE 4

Economic Performance Of Existing Constant Volume

VS. Retrofit Of Variable Volume *

YEAR	CONSTANT VOLUME COSTS (5% escalation)	VARIABLE VOLUME COSTS (5% escalation)	YEARLY COST SAVINGS DISCOUNTED (i = 10%)
First Cost	-$0	-$84,205	-$84,205
1	-$28,343	-$ 4,376	$23,967
2	-$27,055	-$ 4,177	$22,878
3	-$25,826	-$ 3,988	$21,838
4	-$24,651	-$ 3,806	$20,845
5	-$23,531	-$ 3,633	$19,898
6	-$22,461	-$ 3,468	$18,993
7	-$21,441	-$ 3,310	$18,131
8	-$20,466	-$ 3,160	$17,306
9	-$19,535	-$ 3,016	$16,519
10	-$18,647	-$ 2,879	$15,768
11	-$17,800	-$ 2,748	$15,052
12	-$16,991	-$ 2,623	$14,368
13	-$16,218	-$ 2,504	$13,714
14	-$15,481	-$ 2,390	$13,091
15	-$14,778	-$ 2,282	$12,496
Discounted Totals	-$313,224	-$132,565	$180,659
INTERNAL RATE OF RETURN ON CAPITAL			35.6%
SIMPLE PAYBACK			3 years

*All cash flows are discounted using a 10% interest rate. Costs include only maintenance, utility, and costs. The annual costs are escalated 5% per year. The existing constant volume case has an initial utility cost of $30,178 and a maintenance cost of $1,000. The retrofitted variable volume case has an initial utility cost of $2,814 and a maintenance cost of $2,000. The nondiscounted first year savings are $26,364. The simple payback in this investment of $84,205 is slightly more than three years.

TABLE 5

HOOD FACE VELOCITIES

Readings taken at 30 second intervals at each of six points in the face plane of a fume hood.

A1o	A2o	A3o
B1o	B2o	B3o

TIME	A1	B1	A2	B2	A3	B3	Avg. Read.	Std. Dev.
t_1	81	103	124	131	106	128	112	20
t_2	106	102	108	126	104	114	110	10
t_3	108	99	125	141	102	134	118	17
t_4	90	112	131	150	113	129	121	24
t_5	68	102	121	140	106	129	111	29
t_6	94	110	111	131	107	127	113	15
t_7	81	93	126	145	100	121	111	26
t_8	83	122	123	153	112	115	118	28
t_9	98	97	121	146	116	128	118	20
t_{10}	61	83	125	139	113	136	110	31

NOTE: Velocity values are given in feet per minute.

TABLE 6

Incremental Savings Analyses

CASE #	HOOD DIVERSITY %	OCCUPIED UNOCCUPIED TURNDOWN %	FACE VELOCITY (FPM)	ENERGY SAVINGS %
1	50	100 % no turndown	100	48
2	70	100	100	30
3	80	100	100	18
4	50	70	100	55
5	50	50	100	61
6	50	30	100	67
7	50	100	90	52
8	50	100	80	56
9	50	100	70	60

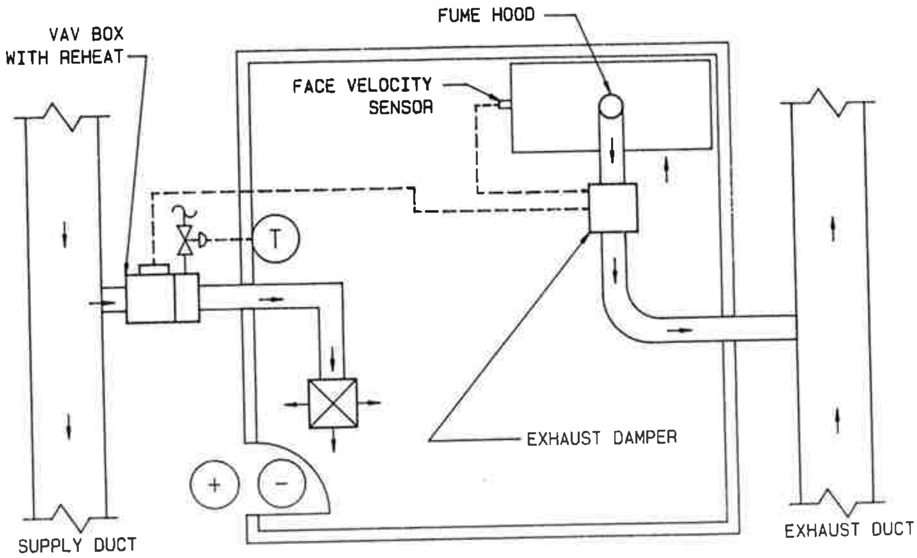

Figure 1. Constant face velocity hoods

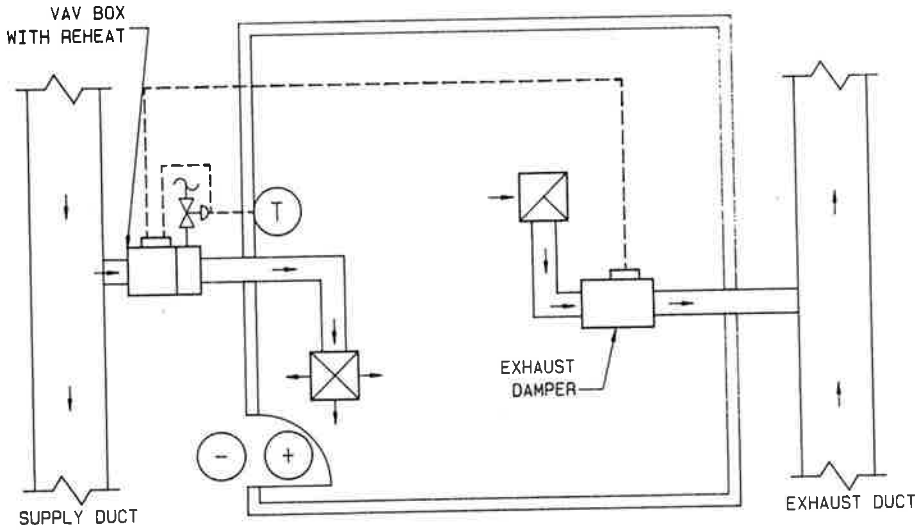

Figure 2. VAV with positive pressurization

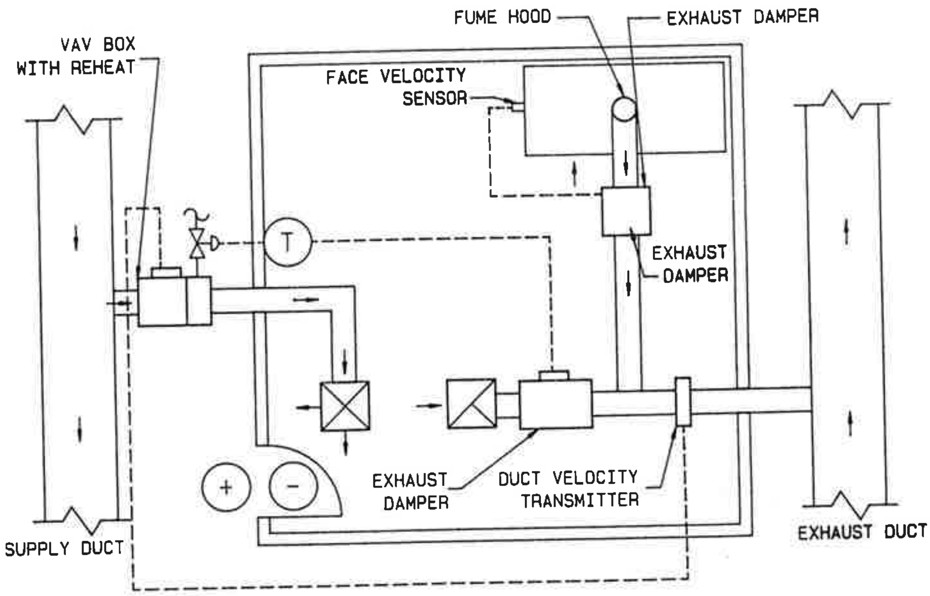

Figure 3. Energy efficient VAV

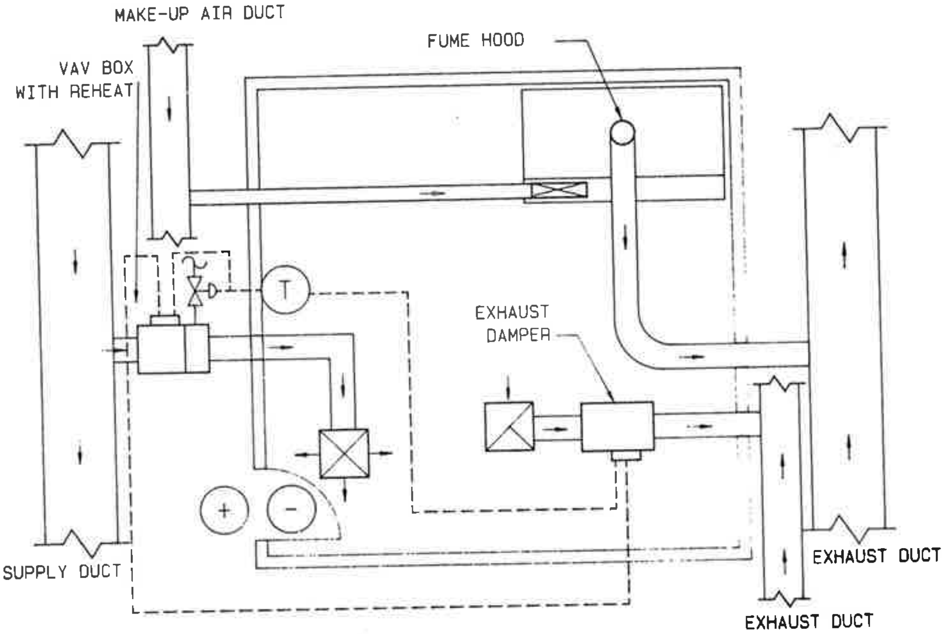

Figure 4. Make-up air with auxiliary air hoods

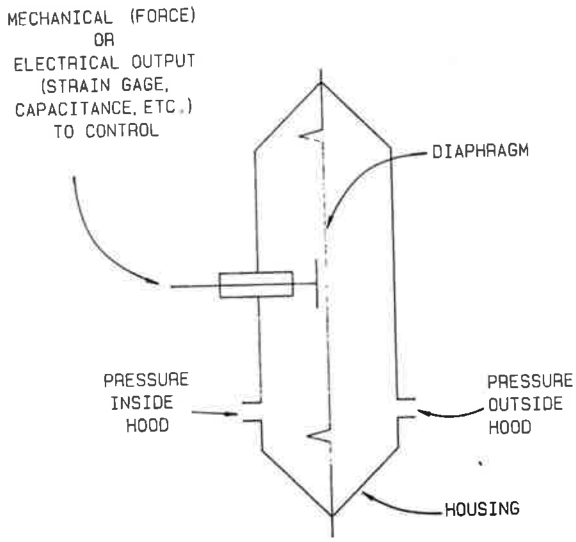

Figure 5. Diaphragm type differential pressure sensor

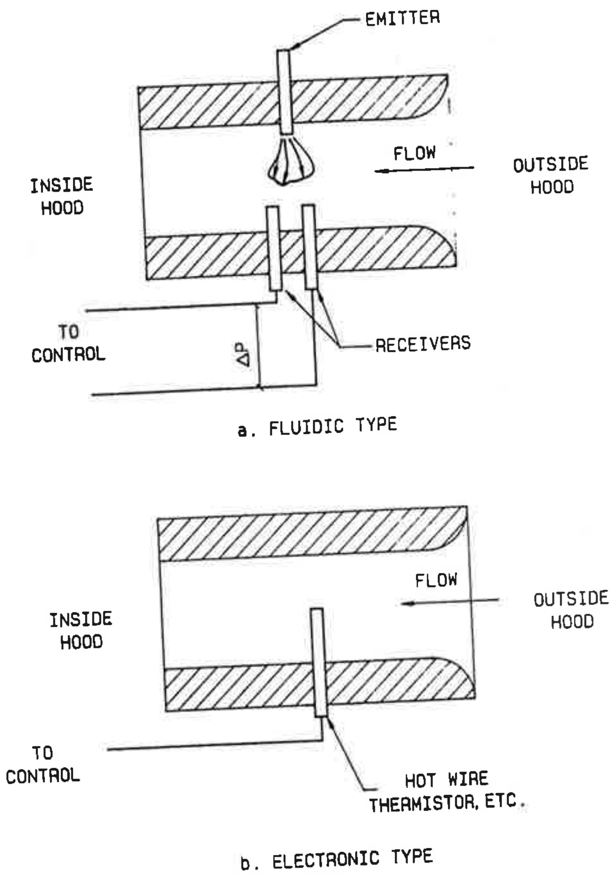

Figure 6. Velocity sensors

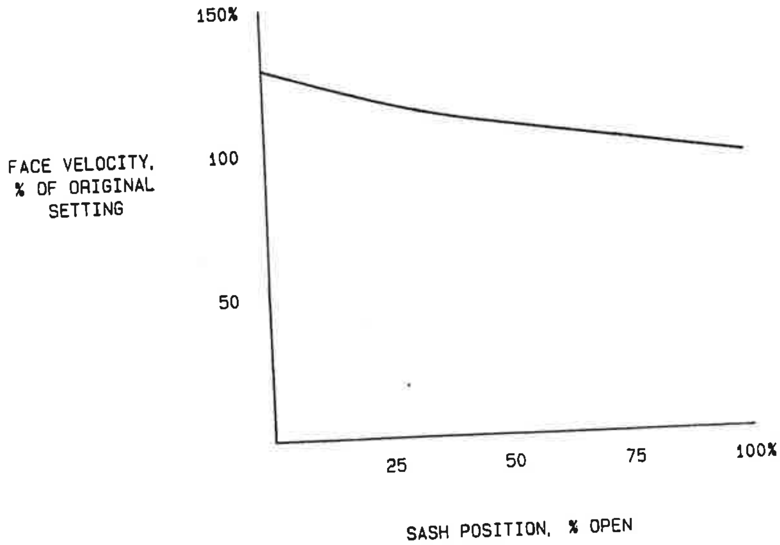

Figure 7. Typical curve of face velocity versus sash position for velocity sensor controls

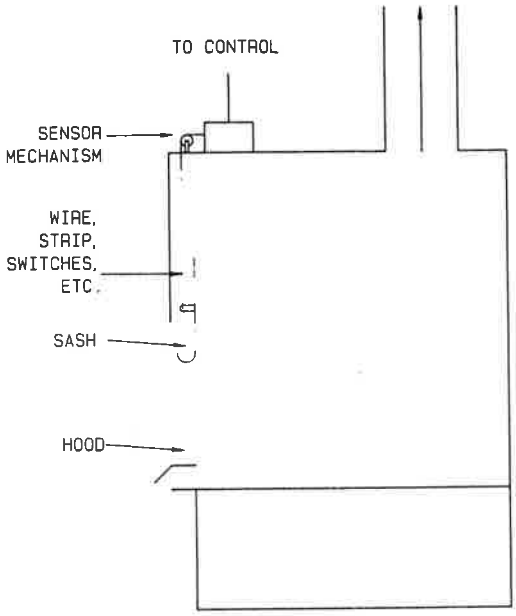

Figure 8. Position sensor operation

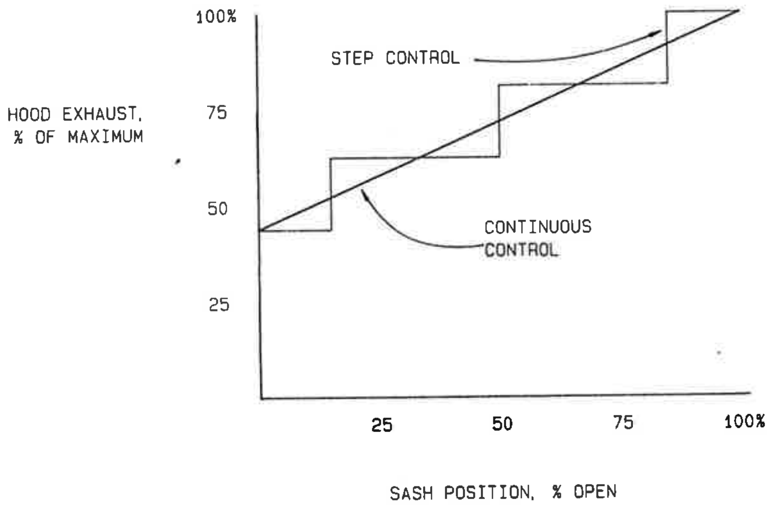

Figure 9. Typical sash position sensor curves for exhaust capacity versus sash position