IMPROVED MAKE-UP AIR SUPPLY TECHNIQUES

A Report

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ABSTRACT

This report describes the development of an improved system to provide make-up air for combustion and ventilation purposes.

It was concluded that, in order to prevent spillage or backdrafting of naturally aspirating combustion appliances, a maximum house depressurization of 5 pascals provided an acceptable limit. The flow capacity required in an individual house depends on the capacity of exhausting devices installed and the tightness of the envelope. The study determined that a system which could provide 125 L/s would be suitable for the majority of Canadian houses.

In light of these requirements, existing make-up air devices and systems were evaluated. The evaluation also included weather protection, safety, comfort and cost. The conclusion of this review was that there are presently no products or combinations of products that are capable of meeting the key requirements.

Based on the established criteria, an improved make-up air system was developed. This new system is based on controlling flow by sensing pressure differences across the building envelope. A lightweight, flexible diaphragm translates slight pressure differences (2 - 3 Pa) into an electrical signal via a light-operated switch. The signal is used to control one or a combination of fans, duct heaters and dampers.

The make-up air control was designed to operate a two-stage fan and a duct heater. The system was installed in a house and monitored to determine its ability to meet the minimum flow and pressure requirements. The study found that the proposed approach to make-up air supply effectively met these requirements. Its simple construction and operation provide a cost-effective solution to the make-up air problem

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1.0 INTRODUCTION

Buchan, Lawton, Parent Ltd. was retained by CMHC to undertake research and developmental work towards an improved make-up air system for residential housing. This work was divided into three basic activities:

- Development of evaluation criteria for make-up air inlets;
- Examination and testing of existing make-up air devices and systems in light of the above criteria; and
- Development, testing and monitoring of (an) improved make-up air system(s) to better meet the criteria.

The background issues pertaining to make-up air are discussed in Section 2.0. The developmental evaluation criteria and rating of existing make-up air devices and systems are found in Section 3.0.

Section 4 discusses the development of the improved make-up air system with respect to performance specifications and functional requirements. Field testing of the prototype is presented in Section 5.

The improved make-up air system is evaluated in Section 6 in terms of performance and applicability.

Finally, conclusions are presented in Section 7.

2.0 OVERVIEW

During normal operation of a house air is exhausted, usually by mechanical ventilation equipment and vented combustion devices. Make-up air is the air brought into the building envelope to replace this exhausted air. Typical housing stock does not provide a controlled access for make-up air. Instead, it depends on the natural leakage area of the building envelope. As construction methods improve and houses become tighter, leakage areas become smaller and larger negative pressure differences are required across the envelope to produce the same amount of make-up air. There are three principal hazards associated with higher negative pressures:

- Negative pressures created by exhaust appliances could overcome the venting forces used to expel exhaust products from fuel-fired equipment and draw these exhaust products into the house.
- Any air expelled out of the house will, by the law of conservation of mass, be replaced. If there is no easy path for uncontaminated air (from the outside atmosphere) to enter, it may enter from areas where it is likely to be contaminated. The most well known hazards of this sort are the entry of radon-contaminated soil gas through below-grade entry points and formaldehyde-contaminated air from walls insulated with urea formaldehyde foam insulation (UFFI).
- If the ventilation system of a house relies only on exhaust devices, the actual rate of air change will be reduced as negative pressures in the house increase. The significance of this factor varies greatly with the type of equipment used. Some exhaust fans "stall out" on a relatively minor change in exterior static pressures, while others are capable of operating at relatively high static heads.

2.1 Current Regulatory Climate

In the past, these hazards have generally been addressed on an individual basis. The first hazard is dealt with under the term combustion air, the second hazard is addressed as contaminant source control, and the third hazard is examined under the term balanced ventilation.

Installation codes for fuel-burning equipment require the provision of, or at least the consideration of, combustion air supplies. The gas code(1) provisions for make-up air are the most specific and enforced. The oil code(2) provisions are under review and are not generally well enforced. The wood-fired codes have recently been updated and are starting to be enforced in most jurisdictions.

There is a recognition, if not a specific regulation, that limiting the suction forces in houses is necessary when there are likely to be exterior contaminants, such as radon or formaldehyde from UFFI. The R-2000

Program's *Design and Installation Guidelines for Ventilation Systems* (3) has a specific provision to limit the level of house depressurization caused by ventilation devices and describes a method of calculating the size of the make-up air duct that is required in a particular house. The CSA's F-326 Committee is addressing the same issues for all new construction. The control of negative pressures is included as one element of CSA Preliminary Standard F326.1-M1989 Residential Mechanical Ventilation Requirements.(4) Proposed revisions for the 1990 National Building Code include specification of the free areas of make-up air inlets based on installed exhaust capacity.

The issue of providing an assured level of ventilation in houses is not well addressed in current building codes. The National Building Code(5) requires that a house must have a mechanical venting system capable of providing 0.5 air changes per hour. It does not require that the system actually be used, nor does it define whether the stated capacity is "design" or "real". Acceptance, interpretation and enforcement of this provision has not been treated in a uniform fashion in Provincial Codes.

The R-2000 Program requirements insist upon a measured and certifiable level of ventilation. As well, its clauses dealing with pressure differences caused by ventilation devices and the Program's energy consumption budget tend to encourage ventilation solutions which incorporate controlled supply air entry. The CSA's F-326 Committee is also wrestling with the issue of specifying methods of ensuring an adequate level of ventilation in houses. Its Preliminary Standard is very similar to the R-2000 approach.

While measures addressing the above-noted issues have individual requirements, they are all very related. In looking at the house as a whole, one can envision a single system which addresses them all. Ideally, such a system would allow, or force, air to enter the structure at a rate that controls the indoor/outdoor pressure differential to a predetermined level. The air entering the house would be effectively distributed to where it is needed, so there would be no impact on the comfort of the occupants. Furthermore, the system must operate effectively and reliably in all weather conditions, and do so at an affordable cost, both in terms of operation and installation.

In all fairness, it should be pointed out that a "piecemeal" or single function approach can be used to control negative pressure hazards.

Since an appropriate depressurization limit to alleviate spillage concerns depends on the type of appliances in the house, an entirely appropriate regulatory alternative would be to address "pressure tolerance" of the combustion appliances themselves, rather than deal with "make-up air".

It can be argued that external contaminant entry is a building envelope or geographic issue rather than a "pressure" issue. The location of the easiest entry patterns for incoming air and the level of contamination are as important as the pressure difference.

Ensuring adequate ventilation capacities is again very dependent on the type of equipment in the house. In most cases depressurization, even in the tightest house, is a relatively insignificant portion of the static head of a fan. Much more is attributable to duct losses. While this does not hold true for some types of axial flow fans, the issue could be very easily dealt with by simply specifying that fans of sufficient static pressure capacity be used.

These approaches, while logical, are only practical in the development of standards for new housing. It would certainly be desirable to devise methods that are applicable to a wide range of existing housing as well. Furthermore, being able to apply a "single solution" to all make-up air issues has great attraction. Developing something closer to this "single solution" was the purpose of this project.

3.0 ESTABLISHING BASE CRITERIA

To effectively compare and rate existing make-up air equipment, a set of base criteria were developed. These included:

- controlled pressure limits;
- required flow rates;
- comfort -- distribution temperature;
- protection from the elements;
- failure analysis; and
- costs.

Within each of these categories, a rating scale was developed and a weighted ranking assigned. The rating scale ranged from 0 to 3.0. A ranking of 1.0 was given to a system which just met the stated criteria. A ranking of 2.0 was given to a system which met a level of performance which would be considered good for most cases. A ranking of 3.0 was given to a system which performed to a level considered to be optimum.

These criteria were further divided into primary and secondary. Criteria which were deemed essential to health and safety were categorized as primary. These included:

- maximum negative pressure;
- minimum flow; and
- failure analysis.

Failure to meet the minimum requirements of the primary criteria constituted a failure and the device or system was eliminated from further evaluation.

The evaluation of secondary criteria, considered to be less critical in terms of health and safety, considered rankings down to zero.

3.1 Evaluation Criteria and Rating Scales

The following is a summary of the rating criteria. A more thorough discussion of the rationale for choosing the ratings is included as Appendix A.

3.1.1 Required Flow Rates

• Minimum Flow Requirements	40 L/s
• Optimum Flow Requirements	250 L/s

An evaluation of typical flow requirements for very tight and tight conventional houses was used as a basis for these limits. Flows were determined at the maximum allowable negative pressure of 5 Pa, when naturally aspirating appliances or appliances with interior dilution air inlets were used. Maximum negative pressures of 15 Pa were considered allowable when the only combustion devices were of the induced or sealed type.

Rating Scale

- Systems were marked between 1.0 and 2.5 for flows between the minimum and 150 L/s, and from 2.5 to 3.0 for flows between 150 L/s and 250 L/s.

3.1.2 Pressure Control Capability

• Optimal Sustained Pressure Control	±2 Pa
• Minimal Sustained Pressure Control	±10 Pa

Assuming that the peak pressure limits were met, this category gave a judgement of the system to control "sustained pressure differences", defined as the maximum pressure experienced for a minimum of 5% of the day.

Rating Scale

- 0.0 If sustained pressure differences would be more than ±10 Pa.
- 1.0 If sustained pressure differences would be less than ±10 Pa.
- 2.0 If sustained pressure differences would be less than ±5 Pa.
- 3.0 If sustained pressure differences would be less than ±2 Pa.

3.1.3 Distribution Temperatures

The minimum suggested distribution temperature to occupied rooms was 17°C if delivered through floor grilles and 13°C if delivered through high wall or ceiling grilles. The systems were judged on their consistency in meeting these requirements for typical design conditions.

Rating Scale

- 0.0 Supply temperature to occupied rooms below minimum requirement
- 1.0 Supply temperature to unoccupied rooms below minimum requirement
- 2.0 Under normal operating procedures, will deliver air to occupied rooms at minimum but may exceed comfort levels during extreme conditions
- 3.0 Meets minimum requirements under all conditions

3.1.4 Protection from the Elements

Each system was evaluated as a whole for its potential to withstand weather-induced problems, specifically:

- the potential for freezing, malfunction or blockage;
- protection from wind effects;
- protection from interior condensation; and

- the ability and need to incorporate air cleaning elements on the incoming air stream.

Rating Scale

- Units were rated from zero to 3.0, based upon comparison to each other, rather than some predetermined criteria.

3.1.5 Failure Analysis

Suggested Criteria:

Minimum Requirement

- The potential for a short-term life-threatening hazard due to any mode of failure of the device must be no higher than if no device was installed.

Optimum Requirements

- A high reliability was expected, the consequences of any foreseen failure were such that all primary criteria with regards to flow volumes, pressure control and comfort were met and any failure was readily detectable.

Rating Scale

- Those systems which did not meet the minimum requirements and therefore could "cause" hazards failed the evaluation.
- Systems which were judged to be unreliable or whose failure would negate any advantage of having a make-up air inlet system received a rating of 1.0.
- A rating of 2.0 was given to very reliable systems whose failure would effectively negate any advantage of having a make-up air inlet.
- A rating of 3.0 was given to systems which met the optimum requirements described above.
- For systems which would likely encounter problems of user intervention, 0.5 was deducted from the rating.

3.1.6 Costs

Costs of each system were assessed using the formula:

Annual Costs = (Capital Costs x 0.15) + Annual Operating Costs

Where:

- Capital Costs included supply and installation of the device in a typical house, less any savings achieved through the deletion of items such as combustion air inlets for combustion appliances and fireplaces.
- Annual Operating Costs included estimates for maintenance and power requirements, plus the auxiliary energy costs of heating that portion of incoming air over 0.35 air changes per hour to room temperature.

This equation is roughly equivalent to an annual operating cost including amortization of initial costs. Systems can then be compared by evaluating the costs that would be incurred to achieve individual overall performance levels.

3.2 Types of Available Devices

3.2.1 Overview

The majority of make-up air products currently on the market are, in reality, individual components of a make-up air system. Presently, there are no integrated make-up air systems which address all make-up air needs.

Currently available make-up air products can be categorized as performing one or more of five functions that are desired in a make-up air system:

- to provide an air passage through the envelope;
- to provide a driving force;
- to control air flow;
- to activate a flow control device; or
- to heat incoming air.

In order to increase the ability to bring make-up air into a house, the leakage area can be increased by introducing holes into the building envelope. These holes are usually either a duct system or a series of individual vents. The size of the openings required is dependent on the size and tightness of the house, resistance of the system to the air flow, and the available driving force.

In a passive duct or vent system, the driving force for air flow is the very indoor/outdoor pressure difference that one is attempting to control. Due to the low pressure differentials considered allowable, it is questionable whether passive ducting is sufficient to provide an adequate supply of make-up air.

The alternative is to use mechanical driving forces (fans). One approach is to make use of existing equipment, such as a furnace circulating fan. Approximately 20 Pa of draw exists in the return ducting near the furnace. A hard duct connection from the return duct to the exterior of the house provides a simple system which requires no more equipment than a standard passive duct. This does, however, introduce some control problems which will be addressed later.

It will also have some effect on the operation of the heating system. By essentially introducing a hole into the return plenum, the pressure experienced in the return will be subsequently lower.

The other approach is to use a separate fan. There are a variety of fans available, both centrifugal and axial, that could produce the desired flow. In the analyses that follows, a "fan" refers to any product (of which there are several choices) which produces a head designed to achieve the required flows.

When flow is not directly related to the make-up air requirement (pressure), it is desirable to include a flow control element. The most common flow controller is a damper. There are a variety of dampers on the market which differ primarily in their activation method: manual, thermal, barometric or electric. With the appropriate activation device, a fan can also be a flow controller. There are also some "constant flow regulators" which use a bladder rather than a damper to restrict the flow.

In cases where an electric damper or fan is used as a flow controller, an external signal is needed to control switching. The most common approach is to use the furnace control to activate flow control dampers and/or fans. It is also possible to use the switch which activates any exhausting appliance as a triggering device. The switches could be connected in parallel, so that the flow controller could be opened by the operation of any device resulting in a requirement for make-up air. No devices which performed this action indirectly (i.e. by indoor/outdoor pressure) were found in the search for equipment.

In order to achieve the desired levels of comfort, it may be necessary to heat the make-up air in some systems. The extent to which this is necessary is dependent on the climate, air flow and level of mixing prior to introduction into the occupied space.

To analyze the benefits of the individual "make-up air products", it is necessary to examine their performance within an entire system. To do this, each device examined has been evaluated as part of a "base system". Four types of base systems were defined:

1. passive openings;
2. duct to return duct of a forced air furnace;
3. duct with in-line supply fan; and
4. balanced fans (supply and exhaust).

3.2.2 Envelope Penetrations

Envelope penetration products can be broken down into two basic types: products designed to act as a single large entry and those intended to be distributed to any number of rooms in the house.

The performance of these types of products is directly related to their free area, which must be significant. Table 1 illustrates flows through various size ducts at various pressures, as calculated from ASHRAE's Equal Function Chart, assuming a duct equivalent length of 20 m.

Table 1: Flow Through Ducts of 20 m Equivalent Length (L/s)

Duct size		*Pressure Difference (Pa)*					
(mm)	*([in])*	*5*	*10*	*15*	*20*	*25*	*50*
					Flow (L/s)		
75	[3]	<5	5	7	9	10	14
100	[4]	8	11	14	18	20	30
125	[5]	15	22	28	32	38	50
150	[6]	25	35	45	54	60	85
175	[7]	40	50	70	80	90	130
200	[8]	55	75	100	120	135	180
225	[9]	80	110	140	150	180	250
250	[10]	100	140	180	210	230	330

Figures 1 and 2 illustrate measured air flow versus pressure curves for 150 mm and 200 mm duct hoods, similar to those used to supply make-up air for naturally aspirating combustion devices, with a limited amount of ducting. The 150 mm system does not provide the minimum required flow rates, even at -15 Pa. The 200 mm system provides only 35 L/s - 40 L/s at -5 Pa, the most widely applicable pressure limit.

In houses with significant exhaust capacities, large openings will be required unless mechanical driving forces are used. This will lead to comfort problems, particularly with those devices intended to bring air directly into occupied spaces. Flow control elements such as user-adjustable dampers are not a solution, because discomfort would cause many users to close the port precisely when make-up air is most likely to be needed. For this reason, the "distributed port" system types were excluded from detailed evaluation.

Many of the devices being marketed as "make-up air inlets" are also clearly undersized and do not show any advantage over a standard exterior duct hood.

3.2.3 Driving Devices

No "specialized" make-up air fans were found.

Figure 1: Flow vs. Pressure for a 150 mm Passive Duct

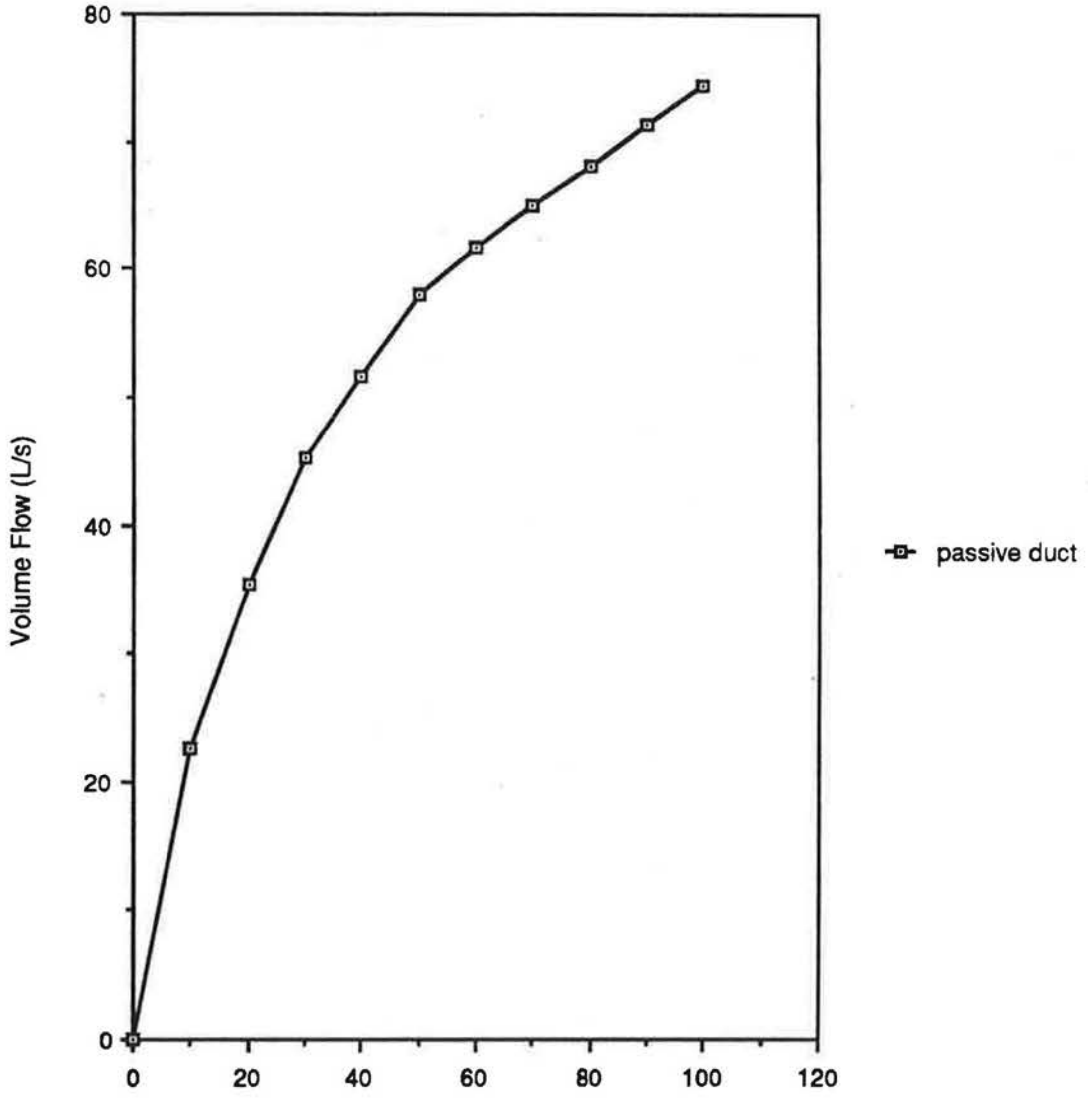
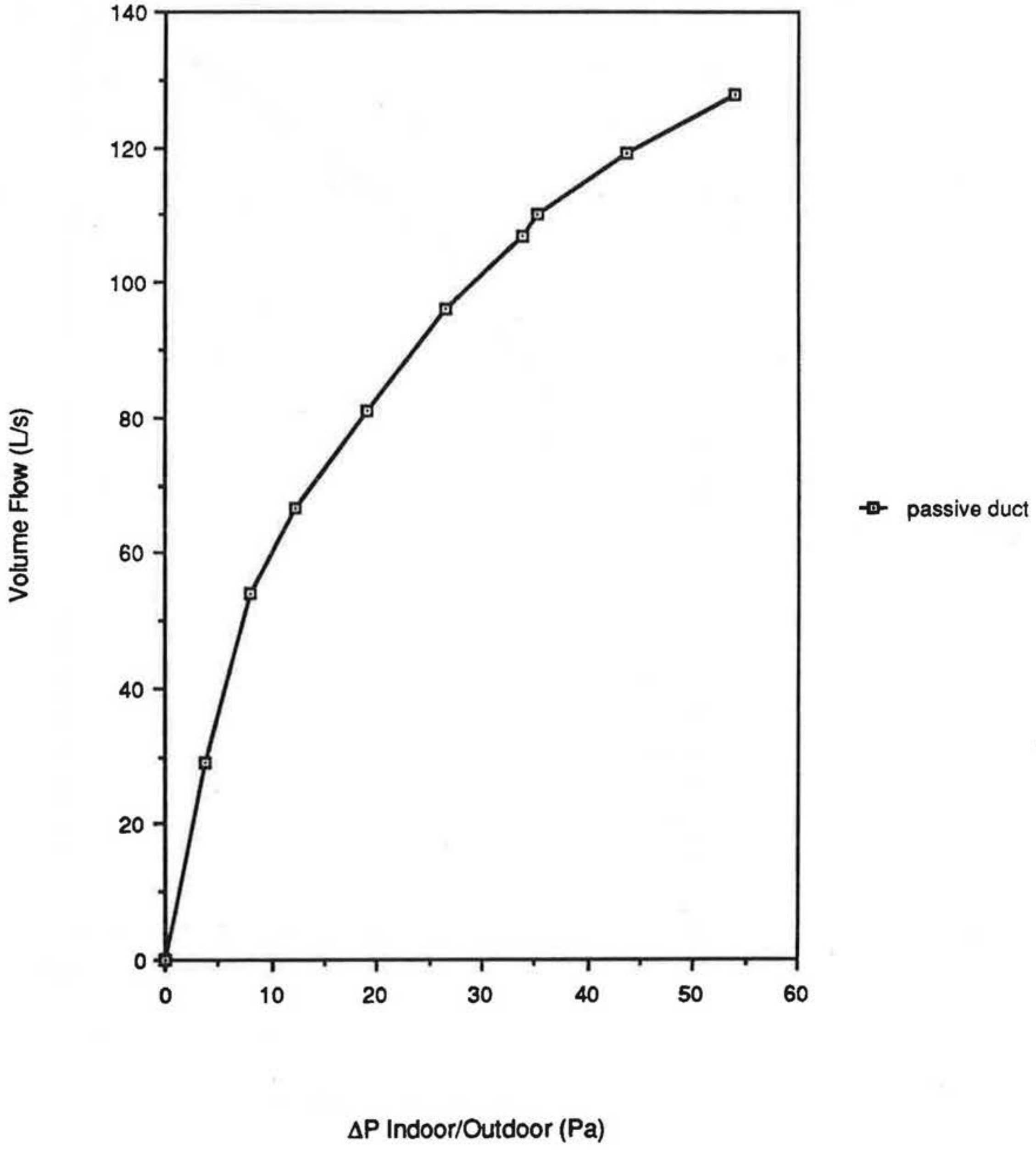


Figure 2: Flow vs. Pressure for a 200 mm Passive Duct



3.2.4 Flow Controllers

A number of generic types of flow control dampers were found.

Manual Dampers

While a number of manual dampers are available, little attention has been directed to them because of their reliance on user judgement for activation.

Thermally Activated Dampers

The thermally activated style of damper utilizes a bimetallic coil, heated by a bypass duct running from the supply duct of the furnace. The system is designed to be connected to the furnace return to utilize the furnace draw to increase flow. For testing purposes, the Wait "Fresh Air Model 970" (Ref. 1, Appendix B) was used.

Local Barometrically Operated Dampers

By counterbalancing the damper, these units can open or close depending on the local pressure differences across the damper. Testing was performed on the Skuttle Manufacturing Company Model # 216 damper (Ref. 2, Appendix B). It is designed to open at 15 Pa, but can be adjusted to open at lower pressures by moving the counterbalance.

Electric Motorized Dampers

The motorized damper is the most popular style of damper available for supplying make-up air. Most have been designed to be furnace triggered and are activated by a 24 volt or 110 volt AC signal. The ACA-PAC series MAC (Ref. 3, Appendix B) has been designed as a combustion air damper and is essentially a terminal unit. The VanEE ACD series (Ref. 4, Appendix B) of dampers and the ACA-PAC series VAC (Ref. 3, Appendix B) are designed to be part of an in-line damper. Both can be purchased with "fail open" configurations. These units operate simply as open/closed two position systems. The VanEE ACD series allows the damper to be adjusted so that it is not completely closed in the "off" position.

Another type of flow control product examined was the American Aldes "Constant Air Flow Regulator" (C.A.R.) (Ref. 5, Appendix B), which utilizes a pressure activated expandable bladder to control flow. These units provide a relatively fixed flow over a broad range of driving pressures (75 Pa - 175 Pa). Currently, there are no equivalent products operating at pressure ranges lower than the C.A.R., therefore they would only be applicable when there are strong mechanical driving forces.

One proposed solution to make-up air control is the U-trap, commonly referred to as the "Saskatchewan Loop". This system involves forming a U-shaped trap in the make-up air ducting (see Figure 3). In theory, the higher density cold air will pool at the bottom of the "U". This pocket of cold air was believed to provide sufficient resistance so that, under ambient conditions (i.e. little or no pressure difference across the building envelope), air would not flow through the loop. When the pressure across the envelope exceeded the resistance of the trap, the air would begin to flow at a rate dependent on duct size and pressure difference.

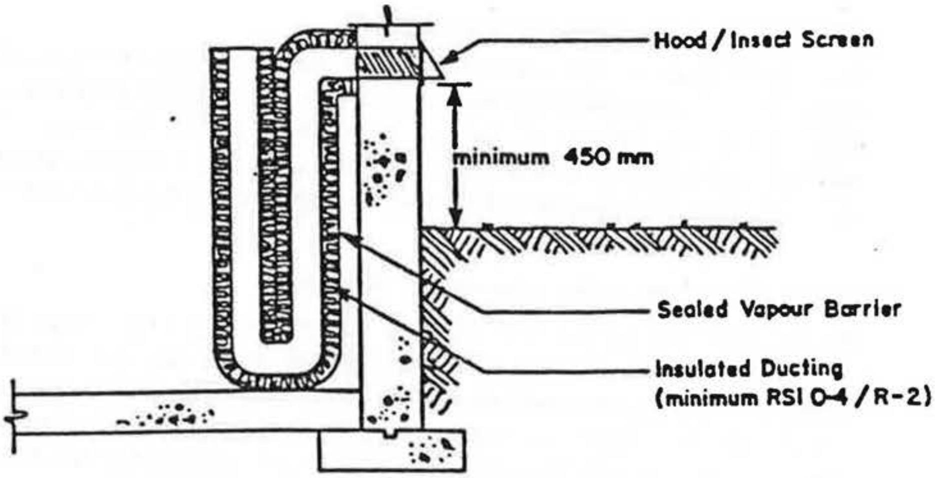


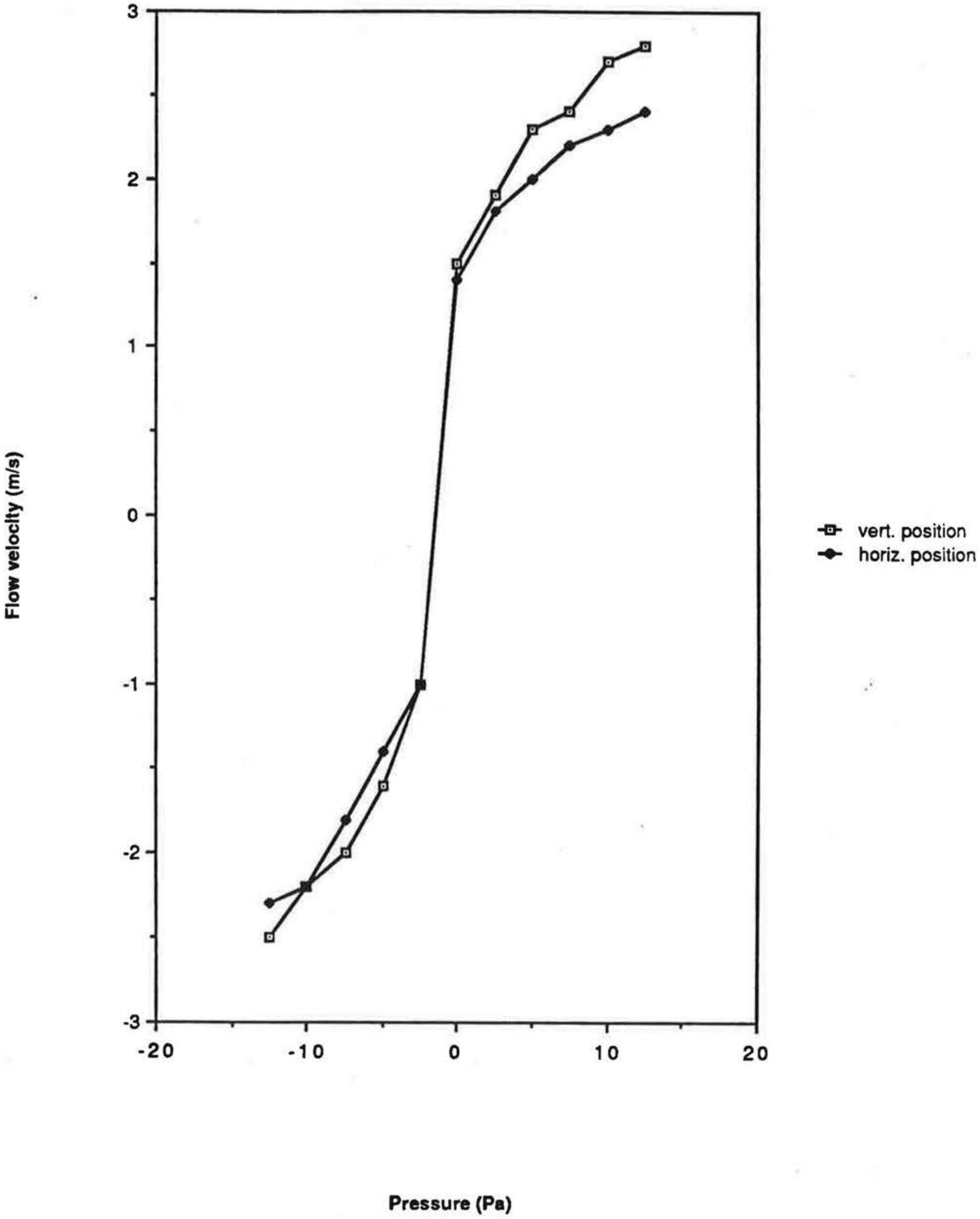
Figure 3: U-Shaped Trap

This proposed system was tested in-house with the U in the vertical position and the horizontal position (typical duct run). The results are presented in Figure 4. The figure indicates that, within the range of normal house pressure, the vertical and horizontal arrangements of the Loop performed similarly, leading to the conclusion that the "Saskatchewan Loop" provides no measurable pressure control.

3.2.5 Activation Devices

Electric dampers and fans provide flow control only when activated by an independent device. This could be accomplished by a relay from another appliance such as the furnace or exhaust fans, or by an independent control measuring parameters such as pressure or temperature. While there was one reference to a pressure control in a trade publication, this proved to be a premature announcement. No independent controls specifically designed for or applicable to make-up air purposes were found.

Figure 4: Flow vs. Pressure (Saskatchewan Loop Test)



3.2.6 Make-up Air Heaters

Four types of heating systems were examined:

- ground source;
- hydronic;
- electric; and
- exhaust heat recovery.

Although there are some who believe that ground source heating is a viable alternative, even rough calculations showed that, in order to heat air from -20°C to 8°C, well in excess of 125 metres of piping would be required. The maximum temperature obtainable is the ground temperature, which is approximately 10°C, therefore additional heating would still be required. Clearly, this is not an effective solution.

Air-to-air heat exchangers can be considered another "passive" source of make-up air heat. Due to their complexity, air-to-air heat exchangers have been examined as a complete system (Heat Recovery Ventilator), not strictly as a heat source.

Electric coil duct heaters are readily available on the market. They are compact, easily installed and easily maintained. Some models, such as the VanEE EDH 6.2, have 2 kW capacity, sufficient for the flow requirements identified in this project. This model has an internal thermostat which can be manually adjusted. A product of this nature allows for flexibility at a reasonable cost.

A hydronic system which utilizes water supplied from a heating boiler or DHW tank was examined. For a gas-fired DHW, a hydronic system could provide a lower cost heating source than electricity, however, no product of this nature is currently being marketed. There were also concerns that extreme weather conditions and/or equipment failure could lead to freezing and pipe damage. These problems must be accounted for in any hydronic system used.

3.3 System Evaluations

Tables 1 and 2 summarize the system evaluation based on the limitation of pressures to -5 Pa and -15 Pa respectively.

Systems that are directly fan driven are essentially pressure insensitive and their flow ratings are not effected by the difference in pressure limits.

The same is not true of the passive ducting and furnace draw systems. As shown by Figure 2, a passive 200 mm duct section was capable of supplying only 35 L/s - 40 L/s at the -5 Pa pressure limit. In order to achieve flows sufficient to compensate for a reasonable exhaust load, it may be necessary to use ducts as large as 200 mm x 350 mm, which could be capable of providing

Table 2: Analysis at 5 Pa Limit

System description weighting	Flow at ΔP 5 pascals 0.25	Pressure Control 0.25	Distribution Temperature 0.2	Weather Protection 0.15	Failure Analysis 0.15	Overall Rating	Captial Costs	Annual Costs	Cost ($)
PASSIVE SYSTEM									
200 mm duct	FAIL	-	-	-	-	FAIL			
200 x 350 mm duct	2.5	2.4	1	1.5	2.5	2.03	200	100	130
200 x 350 mm with multiple appliance triggered damper	2.5	2.3	1.5	2	2	2.10	475	30	101
As above with inlet heat	2.4	2.3	2.5	2	2.5	2.35	575	30	116
CONNECTED TO FURNACE RETURN									
150 mm duct	FAIL	-	-	-	-	FAIL			
200 mm duct	1.9	1.5	2	2.3	1	1.75	225	250	284
200 mm duct with combustion triggered electric damper	1.9	1.4	2.2	2.5	2	1.94	400	10	70
200 mm duct with multiple appliance triggering	1.9	1.9	2	2.5	2	2.03	475	50	121
As above with inlet heat	1.8	1.9	2.5	2.5	2.5	2.18	575	50	136
200 mm duct with a local barometric damper	1.8	1.6	2	2	1	1.70	300	200	245
200 mm duct thermally activated damper	1.9	1.2	2.3	1.5	1	1.61	300	0	45
IN-LINE FAN									
Direct to interior	2.5	1	1	2.5	1.5	1.68	325	355	404
To furnace return	2.5	1	2	2.7	2	1.98	350	350	403
To interior with inlet heat and multiple appliance triggering	2.5	2	2.5	2.8	2	2.35	575	50	136
As above to furnace return	2.5	2	3	2.8	2	2.45	600	50	140
BALANCED FAN									
Without heat recovery	2.3	1.8	1	2.5	2	1.90	1000	350	500
HRV	2.3	1.8	2	2.5	2	2.10	2000	-50	250
HRV with appliance triggered damper on exhaust	2.3	2.3	2	2.5	2	2.23	2200	-50	280
As above with post heater	2.3	2.3	3	2.5	2	2.43	2300	-50	295

150 L/s at -5 Pa. Under a -15 Pa limit, a passive 200 mm section could provide approximately 70 L/s. This certainly increases the range of application, but may still be unable to compensate for some exhaust devices.

The different pressure limits have a much less substantial effect on the flow rating of systems connected to the furnace return. With the addition of furnace draw of 20 Pa, the total driving pressure encountered by the ducting would now be approximately 25 Pa and 35 Pa. This corresponds to an increase in flow from 90 L/s - 115 L/s for a 200 mm duct; an increase of 21%. On the other hand, a change from -5 Pa to -15 Pa causes a 77% increase for passive ducting.

It is important to note that most of the "make-up air devices" examined in this project were not even available in sizes equivalent to 200 mm diameter ducts, but were generally much smaller.

It must be recognized that when a mechanical device such as a furnace fan or an independent fan is being used to provide needed make-up air flow, this flow is provided only when the fan is on, and regardless of whether there is a need for make-up air. If the furnace fan is left to cycle, it may not provide the necessary boost to the make-up air flow when it may be needed. Alternatively, leaving the fan on continuously creates its own problem, because forcing air flow in when there are no offsetting exhaust flows will, at minimum, unnecessarily increase heating costs and the requirements for comfort control. At worst, this can lead to moisture damage to the building envelope induced by positive pressure. Therefore, evaluating the performance of these mechanically augmented systems becomes an evaluation of the type of flow control system being used.

Another important issue which affects systems directly connected to the furnace return must be addressed. The introduction of large quantities of very cold air into the furnace return could lead to premature failure of heat exchangers due to corrosion from condensation and thermal shock. This could create a health hazard and, therefore, it is important that the temperature and amount of air being introduced into the return air system be controlled to reasonable limits. In houses which do not have a dramatic requirement for make-up air, it may be possible to meet these reasonable limits without make-up air heaters. For large capacity systems, make-up air heaters appear to be an important addition to aid in meeting failure analysis criteria.

In summary, passive duct systems would only seem appropriate if they are much larger than those currently used. Improved systems must take advantage of the benefits available from temperature and flow control elements.

Hard duct connections to furnace returns could provide the necessary flow, but flow control and, to a lesser extent, temperature control elements, seem an almost necessary addition.

Table 3: Analysis at 15 Pa Limit

System description	Flow at ΔP 15 pascals	Pressure Sensitivity	Distribution Temperature	Weather Protection	Failure Analysis	Overall Rating	Capital costs	Annual costs	Cost ($)
weighting	0.25	0.25	0.2	0.15	0.2				
PASSIVE SYSTEM									
200 mm duct	1.4	1.5	1	1.5	2.5	1.53	200	75	105
200 mm duct with multiple appliance electric damper	1.4	1.4	1	2	2	1.50	450	25	93
As above with inlet heat	1.3	1.4	2.5	2	2.5	1.85	550	25	108
225 mm duct	2.5	2.4	1	1.5	2.5	2.03	200	90	120
225 mm duct with multiple appliance electric damper	2.5	2.3	1	2	2	2.00	450	25	93
As above with inlet heat	2.4	2.3	2.2	2	2.5	2.29	550	25	108
CONNECTED TO FURNACE RETURN									
150 mm duct	1.1	1.2	2	2.3	1.5	1.55	225	40	74
200 mm duct	2	1.5	2	2.3	1	1.77	225	250	284
200 mm duct with combustion triggered electric damper	2	1.4	2.2	2.5	2	1.97	400	10	70
200 mm duct with multiple appliance triggering	2	1.9	2	2.5	2	2.05	475	50	121
As above with inlet heat	1.9	1.9	2.5	2.5	2.5	2.20	575	50	136
200 mm duct with a local barometric damper	1.9	1.6	2	2	1	1.78	300	200	245
200 mm thermally activated damper	2	1.2	2.3	1.5	1	1.64	300	0	45
IN-LINE FAN									
Direct to interior	2.5	1	1	2.5	1.5	1.68	325	355	404
To furnace return	2.5	1	2	2.7	2	1.98	350	350	403
To interior with inlet heat and multiple appliance triggering	2.5	2	2.5	2.8	2	2.35	575	50	136
As above to furnace return	2.5	2	3	2.8	2	2.45	600	50	140
BALANCED FAN									
Without heat recovery	2.3	1.8	1	2.5	2	1.90	1000	350	500
HRV	2.3	1.8	2	2.5	2	2.10	2000	-50	250
HRV with appliance triggered damper on exhaust	2.3	2.3	2	2.5	2	2.23	2200	-50	280
As above with post heater	2.3	2.3	3	2.5	2	2.43	2300	-50	295

In-line fan systems could receive high ratings if proper flow control elements are incorporated because they can be effectively designed independent of existing systems. This potential is only realized when the control element can detect the actual need for make-up air.

Balanced fan systems do not address make-up air requirements directly. They are, after all, intended to have a neutral effect on the house pressure. However, by replacing individual exhaust devices, they can reduce the need for make-up air. There is also some potential for modifying or adding on to these systems to account for the activities of separate exhaust appliances, as long as a method is provided to detect the need for additional make-up air.

Section 3.4 discusses the affect of various make-up air products on these base systems.

3.4 Effect of Make-up Air Devices

Thermally Activated Damper

When connected to the furnace return, the thermally activated damper was found to be only marginally beneficial. Since the warm air from the supply duct is required to activate the bimetallic coil, there is a lag time between the furnace firing and the supply of make-up air. To avoid spillage, the need for make-up air is highest in cold flue conditions, the period in which the units are still not fully open. This system only addressed the make-up air requirements of the furnace.

When fully open, the damper had little effect on flow and the capacity was essentially the same as a straight duct. The thermally activated damper performed poorly with respect to pressure control as a result of its inability to compensate for other exhaust devices.

Because the make-up air is introduced before the furnace and because the unit is only activated during firing of the furnace, there is little problem associated with distribution temperature.

The damper is opened and closed by the forces from the bimetallic coil. This is a relatively weak force, often resulting in a "sticky" damper. The questionable dependability of this type of damper resulted in a somewhat lower rating with respect to failure analysis and weather protection.

The thermally activated damper that was examined was designed for connection to the furnace return only and, as a result, was not evaluated as part of the other three systems.

Local Barometrically Operated Damper

The local barometrically operated damper that was tested was designed to operate at 15 Pa, which is insufficient to meet the flow criteria for passive duct systems. Attempts to adjust the counterbalance to achieve operation at lower pressure differences resulted in a lack of reliability, as the damper remained in the open position after the pressure differences were removed.

When connected (as designed) to the furnace return, sufficient operating pressures could be obtained to operate the damper. Figure 5 shows how flow was modified from flow for a straight duct. With very precise tuning, so that the step in air flow shown on Figure 5 was acquired at a pressure slightly above the return air static pressure with no house depressurization, the device could provide a measure of pressure controlled flow. However, this was judged to be unreliable. Therefore, the local barometrically controlled damper is not an effective method of providing make-up air for any other exhaust system but the furnace. It operates only in conjunction with the furnace fan and is relatively insensitive to fluctuations in house pressure.

In essence, the local barometric control performs the same function as the thermally activated damper. Its higher ranking was due to the superior construction and near-immediate activation. It did, however, have somewhat lower flows due to the damper resistance.

Electric Motorized Damper

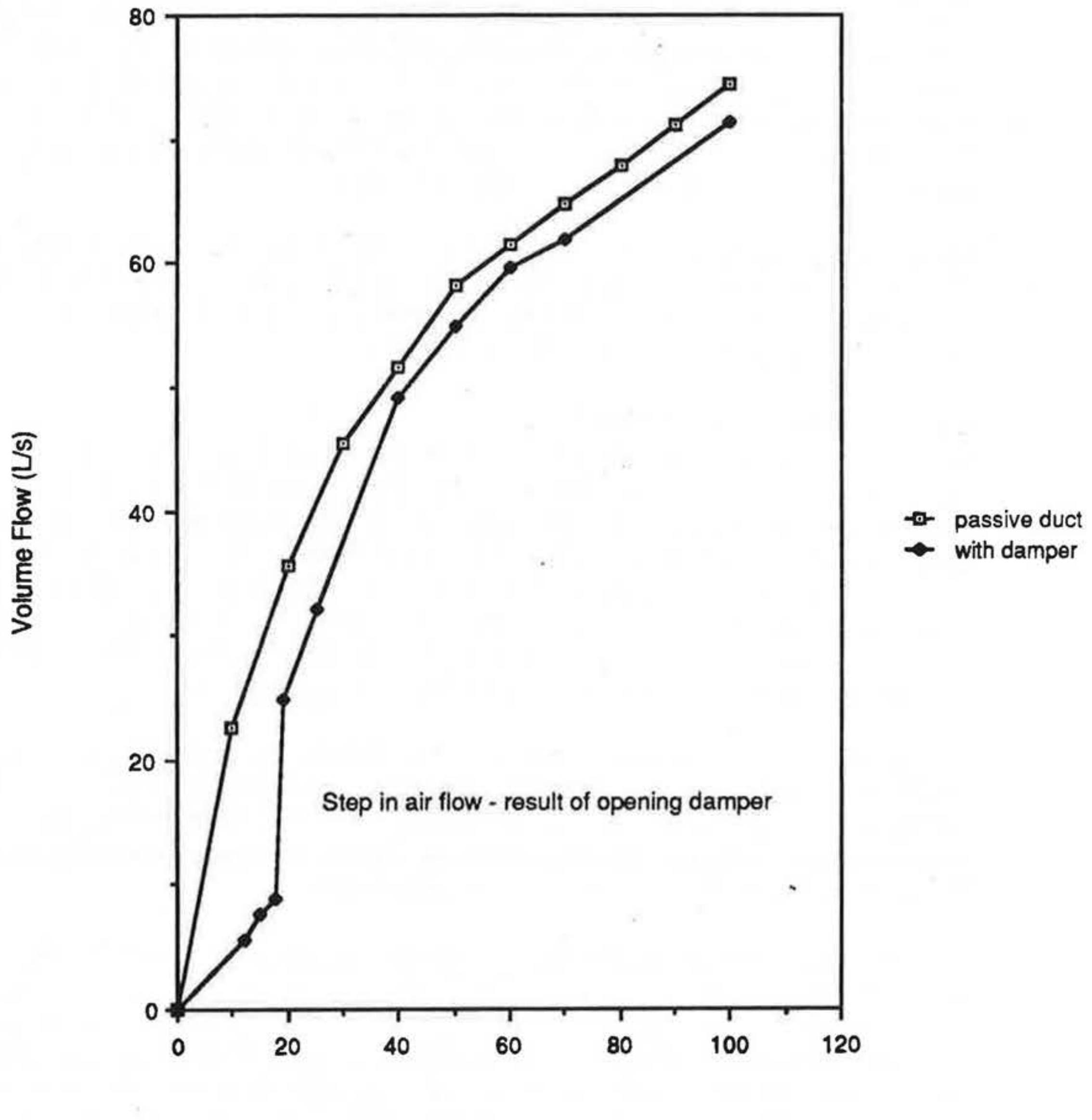
The electric motorized damper is essentially ineffective on its own, since it does not contain its own activation system. The value of this type of damper is directly related to its activation device. It has generally been intended to operate using the furnace control as an activator. In a passive system, the furnace-triggered damper will increase the rating for distribution temperature, assuming that the cold air is distributed through the furnace. It will also reduce the wind effects and the probability of user intervention. For this reason, its rating was somewhat higher in the last two categories.

When utilized in a system connected to the furnace return, the performance of the electric motorized damper was comparable to that of the thermally activated damper with respect to pressure flow and distribution temperature. Unlike the thermally activated damper, however, there was no lag time between furnace firing and activation.

Triggering of the furnace does not solve the problem of excessive negative pressure due to the other exhaust devices: the furnace combustion air is only one issue. The addition of triggering from other exhaust devices provides broader application. In passive ducting this is an effective technique and, if the duct size is large enough to provide sufficient flow, it could be a relatively effective solution, particularly with the higher allowable pressure scenario.

Some problems remain when this multiple triggering is used with a fan or system connected to the furnace return. Since the range of exhaust capacities varies for each appliance, a system that can handle peak flows will positively pressurize the home at lower exhaust flows.

Figure 5: Flow vs. Pressure for a Barometric Damper



Balanced Fans

A balanced fan system, such as an HRV with multiple triggering, would perform somewhat differently since, in effect, it would choke off the exhaust rather than the supply air. This type of device ranked in the top five because of its ability to satisfy all criteria to a reasonable level. As with all HRV systems, its flow rating was limited due to a typical capacity of approximately 100 L/s on high speed.

An HRV would only have to be connected to a few exhaust devices since there would be a limited number of independent fans. The amount of additional effort to "wire in" the remaining devices would be significantly less than for unbalanced fan systems.

There is some concern about choking the flow of an HRV. They are designed for balanced flow and reducing the exhaust could have adverse affects on efficiency and possibly resulting in a frosting problem. This resulted in a corresponding reduction in the weather protection rating. The reduction in "heating" of incoming air may also require a make-up air heater.

Duct Heating

The option of adding a duct heater is available for any of the previously mentioned systems. For passive ducting, this is considered essential due to the probability of user discomfort and intervention. Higher ratings in distribution temperature and failure analysis resulted for passive systems utilizing heaters.

The use of heating is not always necessary for systems connected to the furnace return. A heating unit would be less necessary in any system operating solely during furnace operation.

In multiple triggering or constant furnace fan operation systems, cold flow is mixed with return air at the indoor air temperature. The temperature of this air mixture is dependent on the volume of air being recirculated and the quantity and temperature of make-up air being introduced. Calculations based on "normal" flow rates showed that mixed temperatures during extreme conditions may be less than the minimum distribution temperature of 17°C. The addition of a duct heater would eliminate this problem and thus improve the performance.

The use of a fan only increases the potential for discomfort (due to higher flows). As with passive ducting, systems using a fan should use duct heating when air is dumped directly into the interior living area. If air is supplied to the furnace return, heaters will increase the performance of the unit but, again, are not always essential if relatively low flows are required.

HRVs are, effectively, inlet heaters with heating limits defined by their effectiveness. Based on effectiveness values of 75%, additional make-up air heating is required when independent air distribution systems are used. If mixing through a furnace system is provided, the benefit is much less.

4.0 PROTOTYPE DEVELOPMENT

4.1 Design Issues

Clearly, the available devices are only piecemeal solutions to the make-up air issue. In developing a comprehensive system, key design factors had to be established. These were separated into performance and functional requirements.

4.1.1 Design Issues

Pressure Control Capability
As part of the first stage of this project, the maximum and minimum allowable house pressures were chosen. The choice of a minimum limit was based on issues such as backdrafting, spillage of combustion appliances, stalling of exhaust equipment and soil gas contamination. For houses equipped with naturally aspirating appliances, a negative pressure limit of 5 Pa was selected.

Positive pressures do not pose the health and safety risks posed by negative pressures. There is, however, a need to prevent long-term positive pressures due to the increased heating costs associated with higher exfiltration and, in the very long-term, the potential for moisture problems in the building envelope.

Minimum Flow Requirements
An evaluation of passive systems in an earlier report determined that the duct size required to provide the necessary flows would be excessive. As a result, a forcing fan is necessary. A review of typical exhaust requirements indicated that a fan producing flows of 100 - 125 L/s would be suitable. In a few cases, where the house has a very tight building envelope and one or more exhaust appliances with capacities exceeding 150 L/s, it may be necessary to increase the supply capacities accordingly.

Flow Control
The system must function only when the design pressures are being approached. Continuous operation would, in effect, lower the neutral pressure plane, thereby increasing exfiltration and heating costs.

Tempering of Supply Air
Clearly, the make-up air unit must supply the required flows to the house without causing occupant discomfort. If the make-up air is being supplied directly to the living space, it must be preheated. In cases where make-up air is being delivered to unoccupied rooms, the supply temperature can be below room temperature, but should not be allowed to fall much below 10°C because of the increased likelihood of user intervention during colder months.

Heating Control

Since the inlet air flow will cover a wide range of temperatures, the heating mechanism must include regulation of the supply temperature.

4.1.2 Functional Requirements

Although a proposed design may meet the design specifications, a number of functional requirements must also be addressed for the design to be feasible. Analysis of the issues associated with make-up air indicated a need for the following functional requirements:

- the device should incorporate an element of damping to eliminate short cycling due to variations in pressure that could be caused by wind effects;
- the device should require minimal field calibration, but should lend itself to shop calibration for different purposes (since there are many potential applications);
- the long-term durability of the device is very important and set point stability, particularly with respect to time and temperature, should be a key element;
- with the assumption of a relatively high capacity fan, the device should have a minimum of two operating stages or levels;
- the device should pose no greater risk to health and safety than if no device was installed;
- the complete system should be simple and economical; and
- installation of the system should require minimal retrofit work.

4.2 Design Description

The key element of the prototype system was the pressure-activated control unit. The basic principle involved the use of a lightweight slack diaphragm, subject to interior house pressure on one side and averaged exterior pressures on the other (Figure 6). Pressure taps on each of the four sides of the house allow an averaging of the exterior pressure. When the house is subject to relatively low negative pressures (1 - 2 Pa), there is a net flow into the volume directly below the diaphragm, which causes it to inflate. In essence, the device does not measure the pressure directly, but rather the flow induced by it. It was felt that any mechanical switch which was sensitive enough and capable of working at the low activation forces available would be too fragile for the purpose envisioned. To avoid this problem, a light emitting diode and photo-sensitive transistor were used to detect displacement of the diaphragm.

A lightweight brass strip, suspended from the diaphragm and sealed in a translucent case, was used to turn the optocouplers on and off.

The logic level output of the optocouplers was used to control power relays via the necessary circuitry.

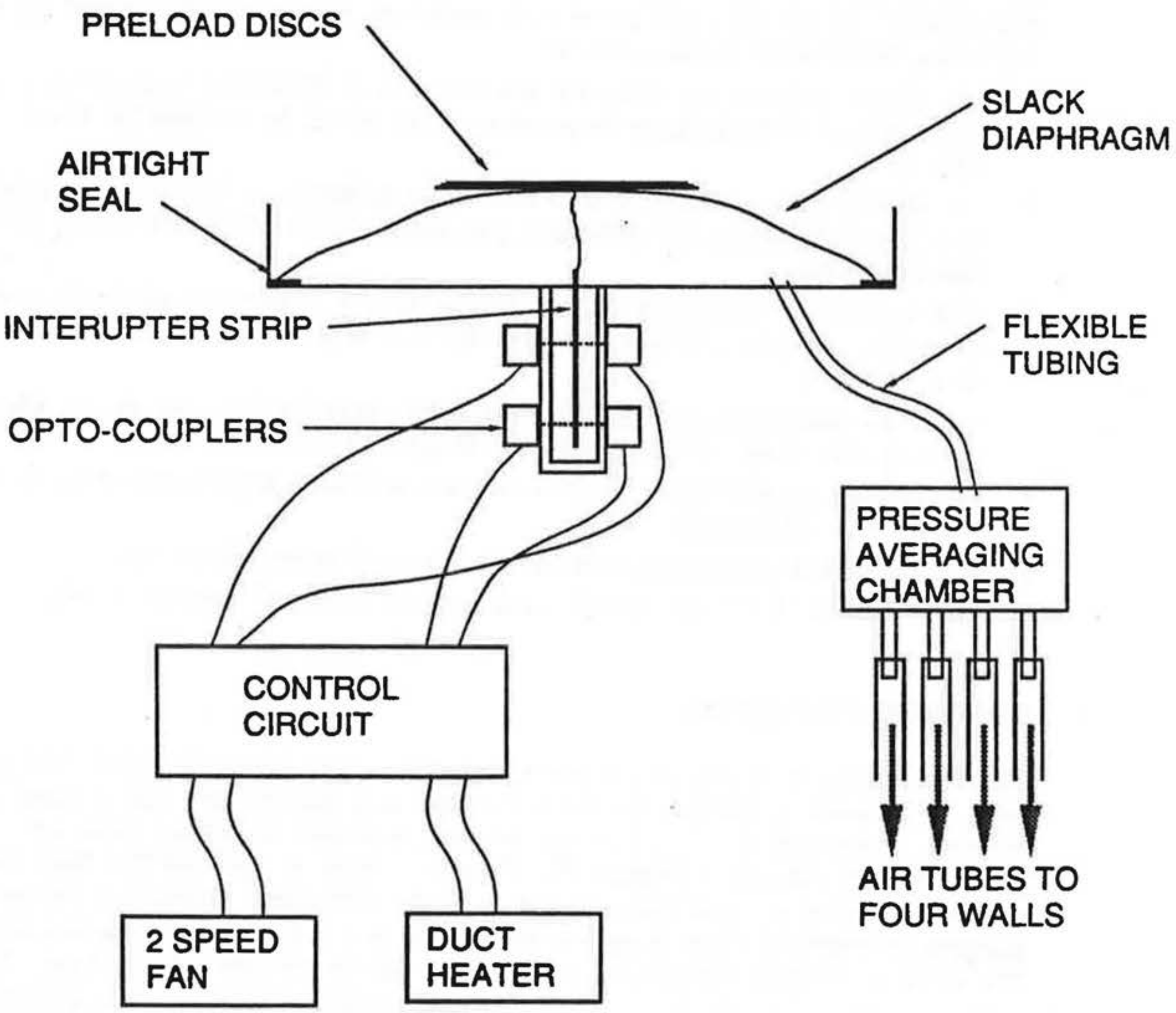


Figure 6: Schematic of Basic Design

This basic design allows for flexibility in adjustment of reaction time and activation pressure by varying several parameters, such as:

- preload on the diaphragm to control pressure set point;
- optocoupler location to adjust the "dead bands" between off/low speed/high speed operation;
- volume below the diaphragm; and
- capillary tube diameter, which acts as a damper in the pressure measurement circuit.

The fan, duct heater, electric dampers and remaining equipment in the make-up air system are easily obtainable in a variety of sizes and styles and, as such, do not pose a design constraint. For testing, the control prototype was used to control a two-speed fan and duct heater. It should be noted that the output can also be used to activate dampers, turn off exhaust appliances or any combination of these. A more detailed analysis of design is presented in Appendix C.

5.0 PROTOTYPE TESTING

The prototype make-up air system was installed in a typical house. Testing was performed to evaluate its ability to provide make-up air with respect to the design criteria.

5.1 Apparatus

5.1.1 Make-Up Air System

The prototype consisted of:

- one 2 speed fan;
- a 2 kW duct heater;
- a pressure sensing diaphragm;
- a control circuit; and
- a four wall pressure averaging system.

A schematic of the test set-up is illustrated in Figure 8. The fan drew outdoor air through a 200 mm flexible duct, which was reduced to 150 mm hard ducting on the supply side of the fan. The 2 kW duct heater was placed downstream from the fan. A manual damper was installed to allow the inlet to be closed off to test typical house operating conditions. The pressure averaging chamber had a volume of approximately 2 L and was fed by the four wall taps.

The installed capacity of the fan was approximately 100 L/s on high speed and varied from 30 - 60 L/s on low speed. The installed system is shown in Figure 9.

5.1.2 Monitoring Equipment

The monitoring equipment consisted of:

- Sciemetric Model 8082 A Data Acquisition System;
- IBM PC and monitor;
- Electronic Magnahelic pressure transducer;
- Dwyer inclined manometer;
- Wallac hot wire anemometer;
- two temperature probes; and
- a 150 mm flow measurement section.

The Sciemetrics Data Acquisition System was installed in order to obtain long-term monitoring data. The following items were monitored:

- supply temperature;
- inlet temperature;
- indoor/outdoor pressure difference;
- low speed status (on or off); and
- high speed status (on or off).

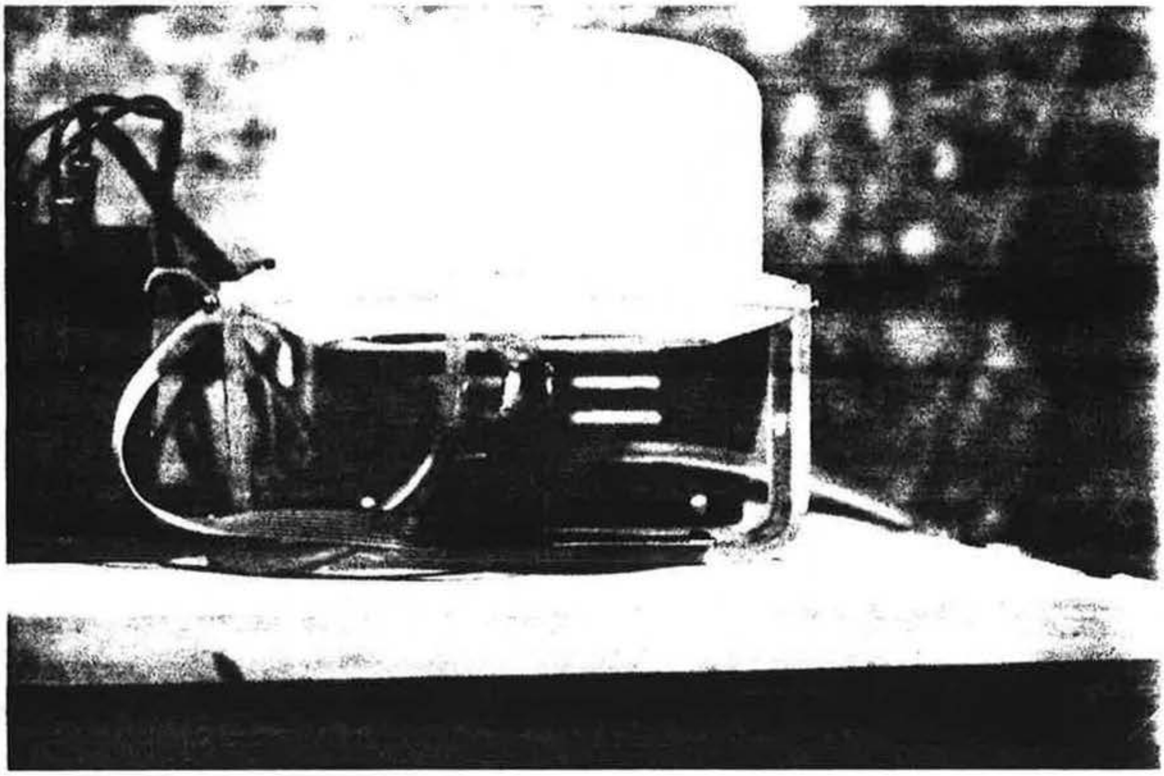


Figure 7: Final Prototype

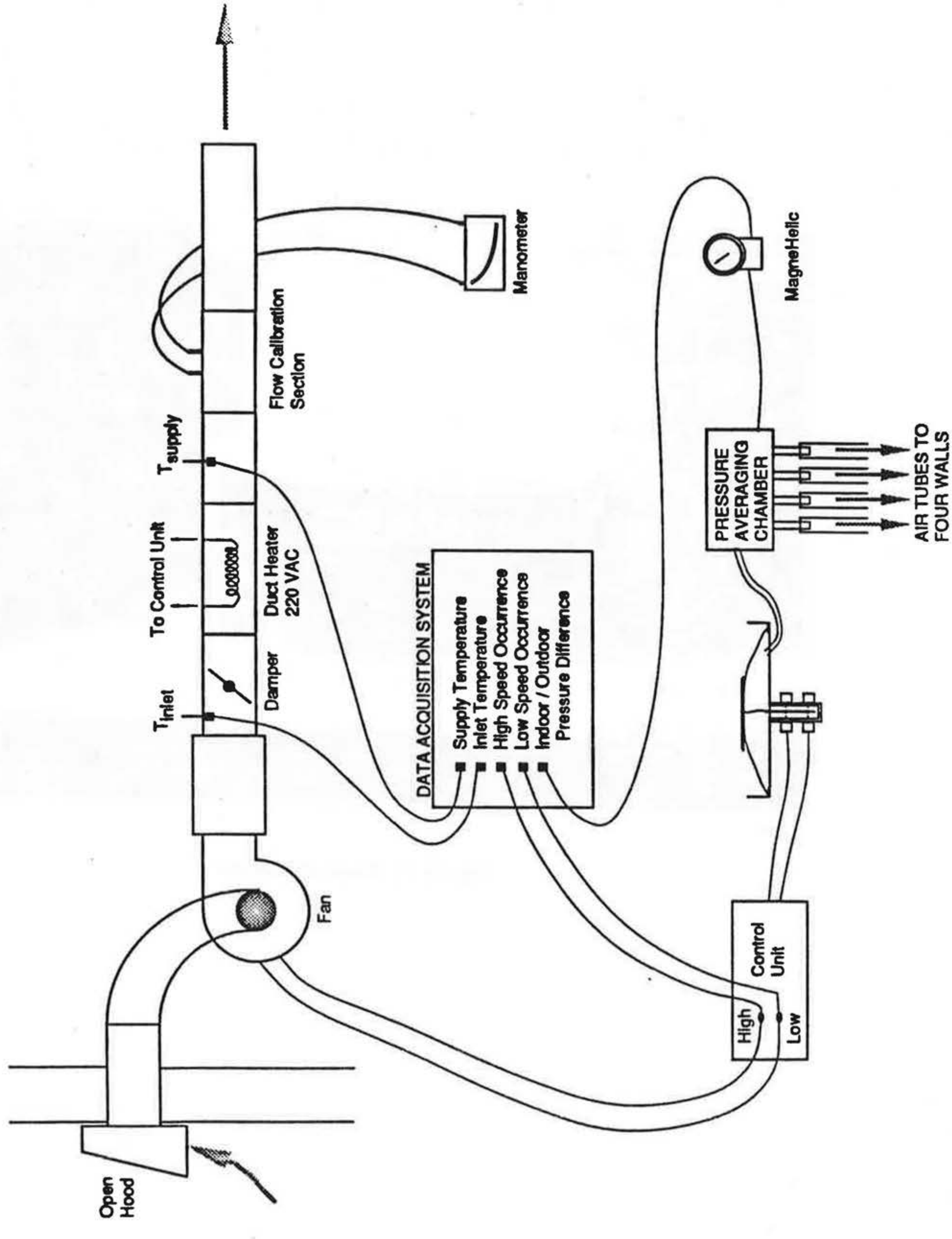


Figure 8: Test Set-Up Schematic

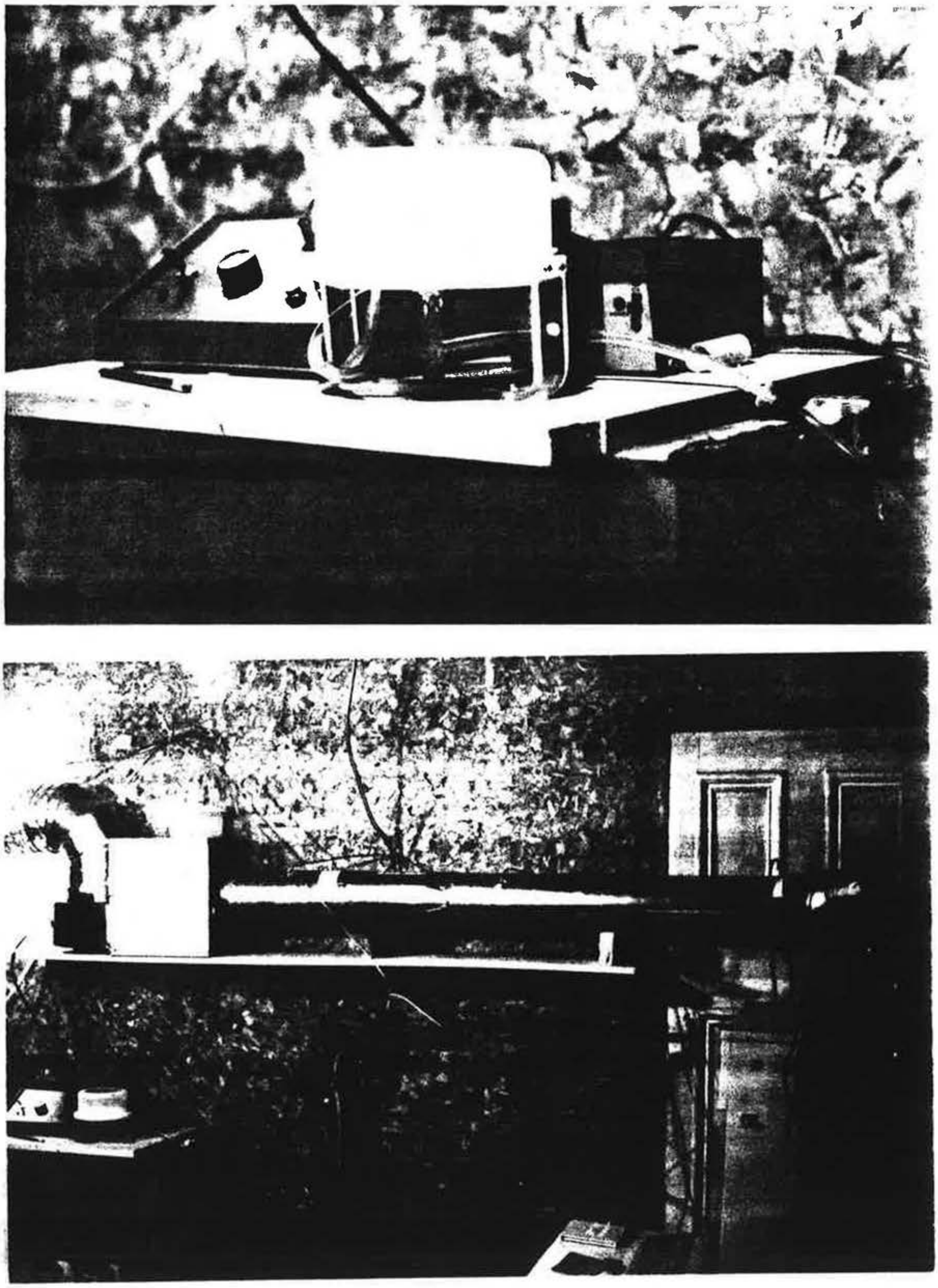


Figure 9: Photos of Installed System

Data was recorded on the IBM PC and, during short-term tests, readings were taken directly from the monitor.

5.2 Test House Description

The make-up air unit was installed in a 465 m^3 (including basement) bungalow in the Ottawa area. The house was approximately 30 years old. A fan test was conducted and the house was found to have an ELA of 0.064 m^2, resulting in an air change rate of 3.75 AC/h at 50 Pa. The flow equation for the house was:

$$Q = 28.8\ (\Delta P)^{0.721}$$

Exhausting devices in the house included an open masonry fireplace, a kitchen fan with a capacity of 46 L/s, a dryer and an oil furnace.

To further increase the exhaust capacity of the house, an additional exhaust fan with a 195 L/s capacity was placed in a basement window. The fan pushed the air through an enclosure with a sliding top before exhausting it. By adjusting the extent to which the top was open, the exhaust capacity of the fan could be controlled.

5.3 Testing Procedure

The first stage of testing focused on evaluating the response characteristics of the test house. The four wall tap pressure averaging system was installed and house pressures were monitored over a week-long period. The extent to which wind/weather effects affected the averaged house pressure was determined.

Tests were performed to estimate the extent to which the house could be naturally depressurized by operating various combinations of exhaust devices without a make-up air supply.

Tests were performed to evaluate the time delay between the activation of an exhaust device and the resulting increase in house pressure. This data was used to determine the volume damping characteristics of the house.

The majority of testing involving the make-up air system was devoted to development of the design. Preliminary testing was used to obtain appropriate settings for parameters such as:

- preload weight;
- volume below diaphragm;
- optocoupler heights;
- pressure tap tube size; and
- fan speeds.

The system outlined in Figure 8 (page 30) was used for this work. Once workable ranges of operation were achieved, the make-up air system was put through a series of short-term tests which involved activating various combinations of exhaust appliances and recording house pressure, inlet and outlet temperature and fan status. The short-term tests are essentially exhaust cycles which could occur during the operation of the house (with the exception of those tests using the auxiliary fan), and the response of the make-up air system is similar to what would be expected if it was operational at that time.

The make-up air system was monitored for one week of operation under typical house conditions.

5.4 Test Results

The pressure averaging chamber and four wall pressure taps were effective in nullifying wind effects. During the test period, a broad range of wind and weather conditions were experienced. The house pressure measured at the pressure averaging chamber proved to be relatively stable when no exhaust equipment was operating. The damping created by the tubing and the volume of the chamber resulted in stable pressure differences, at least when observed as six minute averages on the data acquisition system.

The lag time between the activation of exhaust equipment and the increase in pressure to a steady state level was notable. The delay before a steady pressure was reached ranged from one to two minutes. This proved to be advantageous, as it reduced any tendency of short cycling of the make-up air system.

The house pressure responses to various combinations of exhaust devices with and without operation of the make-up air system are summarized in Table 4. The house pressure created without the make-up air was as low as -8.1 Pa. With the make-up air unit operational, the low was capped at -5.3 Pa.

The designed control unit was effective in controlling the maximum pressure. With the preloading used, the unit would remain off until the house depressurization exceeded -3.5 to -4 Pa. At this time, it would cycle between on and off in cycles ranging from 30 seconds to several minutes. If the exhaust capacity was sufficient to produce pressures greater than -4 Pa with the make-up air device on low speed, the diaphragm would continue to inflate until the high speed fan turned on. The resulting high/low cycling time was somewhat shorter than the off/low cycling time. This was partly due to the position the diaphragm had to be in to trigger the high speed. The diaphragm was nearly fully inflated and hence there was some tension on the diaphragm, causing it to deflate. For future prototypes, a lower required diaphragm height would reduce this problem. When the

Table 4: Make-up Air Responses to Various Combinations of Exhaust Devices

Test Description	*Exhaust Appliances*						*Pressures Encountered*	
	kitchen fan	*dryer*	*aux. exhaust fan*	*furnace*	*fireplace*	*closed m.a. inlet*	*without m.a. (Pa)*	*with m.a. (Pa)*
Control Test A								
no make-up air fan, stack effect -2.6 Pa, temperature -6°C, wind SW @ 20 km/h, well-stoked fire	X				X		-7.7	
	X	X			X		-7.5	
	X	X		X	X		-8.1	
		X		X	X		-6.9	
		X			X		-5.8	
					X		-4.3	
						X	-4.6	
Control Test B								
no make-up air fan, stack effect -2.6 Pa, temperature -6°C, wind SW @ 20 km/h, fire dying	X	X		X	X	X	-7.8 (some spillage)	
				X	X		-7.0	
Control Test C								
no make-up air fan, stack effect -3.3 Pa, temperature -16°C, wind SW @ 7 km/h	X						-5.0	
	X			X			-4.9	
	X	X					-5.8	
	X	X		X			-6.1	
				X			-3.1	
		X					-4.2	
Initial Design Test								
make-up air fan, stack effect -2.4 Pa, temperature -8°C, calm	X						-3.7	-1.9
	X			X			-4.3	-2.5
	X	X		X			-5.9	-3.5
Final Design Test								
make-up air fan, stack effect -1.1 Pa, temperature -5°C, wind SW @ 6 km/h	X		X				-7.2	-3.9
			X				-4.9	-4.3
	X						not tested	-2.5
	X	X					3.0	-2.9
	X				X		not tested	-5.3
	X	X			X		not tested	-3.5
	X	X			X		-4.2	-2.6
					X		not tested	-4.0

exhausting devices were turned off, there was only a nominal delay before the make-up control would turn the fan off, as the preload would cause the diaphragm to settle.

Due to the high leakage area of the house, the house pressure did not exceed the minimum setting on the make-up air control device to trigger its operation during the week-long testing period under normal household conditions. Consequently, no relevant data was obtained.

Sample test results are presented in Appendix D.

Two units were supplied to independent firms for in-field use. At the time this report was compiled, no tests results were available.

6.0 EVALUATION OF THE MAKE-UP AIR SUPPLY SYSTEM

6.1 With Respect to Design Specifications

Pressure Control Capability

The high sensitivity of the slack diaphragm provides a straightforward, economical approach to solving the make-up air problem. The issue of cycling, although a minor problem in the prototype, can be simply corrected by using proportional controls similar to those used in a variety of other applications. The preloading of the diaphragm permits simple adjustment for the range of pressures required.

Flow Requirements and Flow Control

Since the make-up air controller is capable of operating at the desired pressure limit, the minimum flow requirements became strictly a function of fan capacity on high and low speed. It is necessary to choose an appropriately sized fan for the system, based on the typical exhaust extremes to which a house may be subjected. If it is undersized, the fan may not be capable of reducing the pressure differential below the required limits during peak periods. An adjustable low speed fan (such as that used in the prototype) would allow compensation for significant oversizing.

Due to the preloading of the diaphragm, when the pressure falls below the desired level (ideally 4 - 5 Pa), the fan will turn off. This eliminates excessive operation and the associated higher heating costs due to increased ventilation. In houses without naturally aspirating appliances and, consequently, less stringent pressure requirements, increasing the preload will increase the minimum operating pressure and hence provide only the required flow.

The use of an electric or counterbalanced damper may be required to close off the system when it is inoperational. The relatively small pressures across the envelope are capable of inducing a small but constant flow through the system when not operating, as the only significant resistance is the squirrel cage fan. The duct heaters are not designed to operate at such low flows, therefore tempering the air becomes a problem. Installing an electric or counterbalanced damper that opens only after the fan has turned on will eliminate this problem.

Temperature Control of Supply Air

In most installations, the make-up air will not be supplied directly to the occupied living space, but rather to a furnace circulating system or utility room. The air being tempered is 100% outdoor air and, hence, will require a substantial amount of tempering during the winter months. In these installations, a 2 kW duct heater will provide adequate tempering. (Refer to Appendix E.)

The heating capacity of the duct heater may have to be increased for houses which:

- have above average exhaust capacities;
- are located in very cold climates; and/or
- have make-up air supplied directly to occupied living space.

Due to the wide range of inlet temperatures, a thermostat is an essential addition to the duct heater. The two-stage heater used in testing was equipped with two internal, adjustable thermostats, one for each stage.

Protection from the Elements

The make-up air control unit is not exposed to the outside atmosphere and, consequently, will not be affected directly. However, there is some concern regarding the exterior pressure taps on the four walls. In order for them to function properly, they must be free of debris and moisture accumulation, and the length of the tubing must be free of kinks or bends. Proper placement should alleviate these problems. After installation, tubing should be checked to ensure free passage of air. For controlling long-term problems, it may be necessary to install a protective hood on exposed taps.

Failure Analysis

There are two possible modes of failure:

- failure to turn on when house pressure limits are exceeded; and
- failure to turn off when house pressures are below the set limits.

In the first mode of failure, the house pressure will react as if no make-up air unit was installed. In the second case, constant operation of the fan will lower the neutral pressure plane, resulting in increased exfiltration. Although this will lead to higher heating costs, it poses no health risk.

Performance Evaluation Summary

ANALYSIS AT 5 Pa LIMIT

Criteria (weighting)	Rating
Flow at 5 Pa (0.75)	2.5
Pressure Control (0.25)	3.0
Distribution Temperature (0.20)	2.5
Weather Protection (0.15)	2.5
Failure Analysis (0.15)	2.5
Overall Rating	*2.63*
Capital Cost	$600
Annual Operating Cost	$50
Net Annual Cost	$140

The rating obtained by this "improved" system exceeds any of the systems analyzed, at both the -5 Pa and -15 Pa pressure limits. In comparison, HRVs with an appliance triggered damper on exhaust equipped with a post-heat obtained a rating of 2.43. The net annual cost of the latter unit was $295, substantially higher than the improved system.

6.2 Installation

One key feature of any marketable make-up air product will be the ease with which it can be retrofitted into existing housing stock, as well as new installations.

The make-up air device lends itself well to retrofits, since it is essentially a stand-alone system. The control unit, fan, duct heater and required ducting can be installed in the header space. The penetration through the building envelope will be a 150 mm or 200 mm diameter hole with a weather hood.

One of the major advantages of using optocouplers over mechanical switching lies in their durability. The sensors can be calibrated during manufacturing and can be installed with little or no adjustment. The system lends itself well to rough handling and misalignment as there are few moving parts.

There are two areas which may present some problems in a retrofit. The most significant is the installation of the four wall pressure taps. For new construction or in homes with unfinished basements, this does not pose a large problem. The flexible tubing can be run through the header space and fed through the building envelope on each wall. Even for homes with finished basements, this would not be very disruptive.

The second area of concern is the wiring of the duct heater. Ideally, the make-up air unit should be capable of being plugged into a 110 volt outlet. Unfortunately, if a 2 kW duct heater is used, 220 volts are needed and it will have to be hardwired.

6.3 Cost and Producibility

The cost of a make-up air system lies not so much in the pressure controller, but rather the fan and duct heater.

The control mechanism has been designed to minimize manufacturing costs. The control circuitry used costs approximately $35 per unit for one-off production without the solid state relays. The solid state relays add an additional $60 per unit to the one-off cost. For production, the solid state relays can be replaced by more economical power transistors and mechanical relays. Combining this with the reduced costs of the remaining circuitry due to volume discounts, it should be possible to purchase the complete control circuitry for less than $45 per unit.

The casing for the diaphragm can be quite easily constructed using injection molding. The cost per unit will vary with the size of the production run, as tooling costs will constitute a significant portion of the fixed costs. For runs in excess of 10,000, the predicted per unit cost will be in the $3 - $8 range.

Including all additional hosing, cases and related hardware, it is predicted that the control unit can be produced for $100 - $150, depending on volume. This compares to $130 for a two-speed fan and $250 for a two-stage 2 kW duct heater. In addition, there is the installation cost and additional ducting and hardware, assumed to be approximately $150. Based on these figures, the control unit constitutes only 16 - 22% of the installed cost of approximately $650. The cost can realistically be halved if the design is integrated into a generic package, which includes the fan and duct heater, designed for simple retrofit.

7.0 CONCLUSIONS

With the construction of tighter houses and the advent of the proposed continuous ventilation requirements of CSA F326, an effective system is necessary to introduce make-up air to the living space.

For a house to function safely with respect to spillage or backdrafting of combustion appliances and/or soil gas contamination, a limit for house depressurization must be set. In order for the majority of existing housing stock to operate safely, a negative pressure limit of -5 Pa is reasonable. This is based on spillage characteristics of naturally aspirating appliances. In order to achieve this limit, a make-up air system must be capable of introducing a 100 - 125 L/s (for typical exhaust capacities) of make-up air when required.

The make-up air unit must supply air on an as-needed basis, as continuous operation will result in a net positive pressure in the house. This will result in higher heating costs and exfiltration-related problems. In addition, the air must be supplied to the living space at a comfortable temperature.

Currently, no device or integrated system component being marketed as make-up air products are capable of achieving the minimum requirements of an effective make-up air system.

The key elements in the design of a make-up air supply system are pressure and flow control. The control of make-up air utilizing the "slack diaphragm" approach that was developed in this project proved to be an effective solution. Prototype testing indicates that a control of this nature, when integrated with the appropriate equipment (a two-stage fan and duct heater), meets all the fundamental requirements.

Although there is a sizable amount of work still required to bring this control unit to production, it is our opinion that, with refinement, it can be implemented as a commercially viable product which directly addresses and solves the problems associated with the supply of make-up air.

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APPENDIX A

APPENDIX A: EVALUATION CRITERIA AND RATING SCALES

A.1 Controlled Pressure Limits

Suggested criteria:

1. Maximum Negative Pressures (with one cold flue - see Section 3.2)
   - **-15 Pa** when the only combustion devices are of the induced or sealed combustion type and any wood burning appliances are certified for use in mobile homes.
   - **-5 Pa** when naturally aspirating appliances or appliances with interior dilution air inlets are used, or in areas where there is a high concern about soil gas entry.

Commentary:

Combustion Product Spillage

The "heating appliances" most susceptible to combustion product spillage are naturally aspirating gas appliances. There is a considerable body of work(6, 7, 8) dealing with these appliances which shows that negative pressures in excess of 6 to 10 Pa will preclude establishment of a draft in a cold flue. Therefore, for naturally aspirating appliances, negative pressures in excess of these could cause spillage and backdrafting concerns.

Luckily, natural gas is a fairly clean fuel which poses relatively few of the more dangerous combustion-related contaminants. Only in very rare cases has prolonged spillage led to life-threatening conditions (usually because of high carbon monoxide levels due to exhaust recirculation or a badly maintained off-tuned burner). However, long-term exposure to the exhaust products does carry the risk of chronic problems, therefore sustained spillage is to be avoided.

The exhaust products of wood burning appliances pose a much greater concern.

Sheltair(6) reported on one open fireplace which would not establish a draft at pressures of -3 Pa. The remedial measure suggested was to provide a direct combustion air supply and seal the fireplace with glass doors. Most other literature indicated that the cold [flue] vent establishment pressure (CVEP) for open fireplaces was more in line with pressures reported in the study of naturally aspirating appliances.

The CVEP is less critical in fireplaces because they are manually started and the lack of initial draft is readily detected. Spillage while operating, particularly with dying fires, is a much greater concern. McGugan of the Ontario Research Foundation suggests that a -10 Pa indoor/outdoor difference will lead to unacceptable exhaust spillage from a conventional fireplace, but at -5 Pa there will be little spillage.

There are some fireplaces and other woodburning appliances which have been tested for spillage at levels up to 17.5 Pa under U.L.C.'s mobile home standard(9). In this test, carbon monoxide levels are monitored through a burn cycle. If carbon monoxide levels of 100 ppm or more are detected near

near the face of the device it is deemed to have failed the test. The actual contribution to a house at this level of carbon monoxide generation in the last stages of a burn is debatable. However, many feel that sustained operation at 17.5 Pa, even with these appliances, is to be avoided.

Induced draft appliances (with a fan on the exhaust side of the combustion chamber) or forced draft burners (with a fan on the supply side of the combustion chamber) will establish the draft at any reasonable negative pressure. They can, however, pressurize the combustion system downstream from the fan. Combustion products could then be forced into the house from any joints in the vent or stack, from the draft damper, or from the combustion chamber itself. This is a very common occurrence in the start-up phase of oil burner operation. This start-up spillage is not as significant a problem as full backdrafting until full draft is established.

With a conventional oil burner, once full heat generation is obtained, chimney draft pressure is controlled to approximately 15 - 20 Pa below indoor pressure. However, combustion chamber pressure could still be positive. Sheltair's work found that operating at indoor pressures of greater than -10 Pa can create "excessive" spillage and even interfere with the combustion process. This seemed especially true for the new high pressure burners such as the Riello burner. Significant start-up spillage occurred in the start-up phase at even lower negative pressures. Sheltair suggests a maximum allowable pressure limit of -8 Pa.

Tremayne(10) reported that an add-on induced draft unit established adequate venting at pressures exceeding -80 Pa, the highest pressure level tested in their study. This suggests that induced draft appliances are very tolerant of negative pressures.

Soil Gas Entry

Another major concern is the entry of soil gas during house depressurization. A number of studies, including Nazaroff(11), et al., have shown a strong correlation between negative pressures in a house and the entry rate and levels of radon in the house.

The relationship is not simple, being effected by factors such as soil permeability, recent changes of atmospheric pressure, soil gas radon concentration and the size and distribution of the leakage paths. In one of their tests where a door fan was used to depressurize a house to -8 Pa, radon concentration doubled very quickly and then tapered off to a level which was still significantly higher than before depressurization. Recent unpublished data from testing performed by Proskiw on a house in Winnipeg showed a ratio of approximately four to one between average radon levels while the house was depressurized to -5.7 Pa, and when pressurized to 6.0 Pa for week-long periods.

It is obvious that, in areas where there is a concern about radon or other soil gas contaminants, interior pressure differentials should be minimized. There is much ongoing debate about when concerns with radon should be considered significant, both in terms of exposure levels and geographically. The most frequently used guideline for acceptable radon levels is the 0.02 Working Level (WL) guideline identified by the U.S. Environmental

Protection Agency. This would be roughly equivalent to 4 picoCuries per litre. A recent compilation of sampling data in the United States carried out by Terradex Corporation(12) indicates that 20 to 40 percent of houses in the U.S. exceed this level. This compilation of information indicates that radon exposure levels may be significantly higher than previous estimates. Health and Welfare Canada's study(13), published in 1980, reported radon levels and radon danger levels in 14 Canadian cities. The worst readings were recorded in Winnipeg, where only 15.9 percent of houses were over the 0.02 WL.

There has been much discussion on the relationship between "tight, energy efficient" houses and radon levels(14) It should be noted, however, that newer, tighter buildings do not necessarily have higher radon levels. In some work carried out by Proskiw, currently unpublished, where he compared radon levels in Winnipeg houses, he found that, in a cumulative sampling of 50 ventilated R-2000 houses, the geometric mean of radon danger levels was 0.006 WL, with four percent over the 0.02 WL. In newer, more conventional housing, the geometric mean was 0.009, with thirteen percent over the 0.02 WL. In older conventional housing, (from work carried out by Yuill and Associates), the geometric mean was 0.017, with 40 percent over the 0.02 WL. Proskiw attributes this to the fact that, particularly in Winnipeg, soil shifting has led to basement cracking, so the primary variable is likely to be entry paths as opposed to internal pressures or level of air change.

In order to relate make-up air and soil gas contamination, one must also discriminate between "peak" allowable levels of internal depressurization and sustained or average levels. The long-term exposure to radon is the primary concern and, therefore, controlling average pressures is most important. The short-term peak pressures are less important, but will obviously have an effect on long-term exposure. While, in the ideal case, a make-up air inlet system would greatly limit average negative pressures, soil gas entry concerns do not seem to justify that a system be sized to eliminate short-duration negative pressures.

In trying to determine the ideal average pressure, there are two contradictory issues which must be taken into account and balanced. If primary concern is given to soil gas entry, it would be desirable to operate the building at a slight positive pressure. Some work has indicated that, at levels of pressurization which are roughly double the stack effect, radon levels become negligible, indicating that air leakage is outward.

However, if the building is pressurized, interior moist air can be driven through openings in the building air barrier, with house stack effect increasing the pressures at higher elevations. This could lead to condensation and moisture-related problems in the building envelope. It is the author's judgement that, if one were to suggest a make-up air system that maintained the below-grade areas at a positive pressure, the potential for moisture problems could create a liability problem. However, if sustained negative pressures are allowed, radon exposure would increase health risk by some amount (and there is much argument about the possible magnitude of this risk). While liability concerns regarding this second scenario are less direct, they are potentially much higher.

The compromise solution assumed by most agencies is that the average level of pressure in below-grade areas should be controlled to the -3 to -5 Pa range at which current housing typically operates.

A.2 Required Flow Rates

Suggested criteria:

1. Minimum Flow Requirements
    - 40 litres /second at the maximum allowable negative pressure
    - 60 litres/second at -10 Pa
2. Optimum Flow Requirements
    - 250 litres/second at the maximum allowable negative pressure

Commentary:
The outdoor air inlet must be capable of supplying make up air for three basic functions:

- to replace any unbalanced exhaust or ventilation air flow;
- to replace any air removed by a second chimney (such as a fireplace); and
- to supply air for the operation for the combustion appliance in question (the primary chimney).

There are two pressure regimes to consider. Because the primary pressure control criteria is based heavily on cold flue vent establishment pressures, operating air requirements for the appliance in question, whether it be a fireplace or heating appliance, need not be of concern at the cold flue ΔP. One must still consider the total flow when the appliance is operating, but pressure control is less critical. Most appliances can operate with acceptable levels of spillage at -10 Pa (once the flue is warmed). At this higher pressure, substantially more flow can enter the house than at -5 Pa. This can be estimated as follows.

Flow into a house will be governed by an equation of the form:

$$Q = C\Delta P^n$$

Where:
Q volume flow
ΔP pressure difference
C flow coefficient
n flow exponent ($0.5 \leq n \leq 1.0$)

Assuming the minimum value of $n = 0.5$, the ratio of flows between a 10 and 5 Pa pressure difference would be:

$$(10/5)^{0.5} = 2^{0.5} = 1.41$$

In other words, the operating criteria at -10 Pa will not become the governing flow until the air required to operate the appliance is greater than 40% of the flow considered at the -5 Pa cold flue criteria. If $n = 0.65$, the value would be 1.56. As the following sections will demonstrate, the operating flow is usual only an issue when dealing with fireplaces.

In trying to determine the sizing requirements, it is necessary to make some assumptions about the level of unbalanced ventilation and air draws which may operate concurrently. In current housing, this can vary from zero (an electrically heated house with a fully balanced ventilation system) to more than 400 litres/second (a fireplace, stovetop grill, fan, dryer and heating appliances, all operating at the same time). The suggested flow requirements for the evaluation were based on the following factors:

- The National Building Code requires mechanical ventilation of at least one half air change per hour be installed in each dwelling unit. While this has not been universally adopted in Canada, it has been adopted in many provinces (with significant differences in interpretation). In most cases, these ventilation capacities are made up with the use of exhaust fans. It is reasonable to assume that, at a minimum, make-up air systems must be able to handle this level of exhaust capacity.

- No matter how small a house is, there are minimum exhaust capacities involved. It is suggested that this minimum would include the concurrent operation of a dryer and a single bathroom fan. Combined operating capacity of these two appliances would be approximately 70-100 litres/second. It is reasonable to assume that they could be operating concurrently over a significant period of time in the heating season when another appliance may try to start-up against a cold flue.

- There are a number of exhausting devices which have very large individual flows, notably stovetop grills (many of which have operating capacities in excess of 150 litres/second) and open fireplaces (which can draw in excess of 150-200 litres/second).

- Compared to the numbers above, the operating air requirements of heating appliances are reasonably modest, ranging from amounts as low at 8 litres/second for a condensing gas furnace up to 75 litres/second for a conventionally-fired oil furnace(15). It is interesting to note that, in electrically heated houses in which there is no appliance air requirement, the code requires a 50 litre/second fan in the house for humidity control.

- Leakage into the building envelope will be an outdoor air source. It is relatively easy to estimate the flows that would be contributed by the envelope in various pressure situations, if results from fan depressurization tests (reported in air changes per hour at 50 Pa) are known or assumed and it is assumed that the flow can be described by the flow equation:

$$Q = C\Delta P^n$$

In this equation, the only real variable of concern is the n value. This value must be between 0.5 and 1, and is known to vary from house to house. Numerous people have reported that this number seems to average at a value of approximately 0.65. If conservative calculations for the contribution of make-up air are made, an n value that is somewhat higher should probably be used. If a value of 0.75 is assumed, and a ratio calculation based on the above equation is used, the air flow at 5 Pa, 10 Pa and 15 Pa would be approximately 18%, 30% and 40% respectively of the air flow at 50 Pa. Based on today's standards, one air change per hour at 50 Pa is a very "tight" house, 2.5 air changes per hour is a level achieved by many new houses, and most (but not all) older houses are less tight. However, these two levels are good points to use for judging make-up air contributions.

In determining relative criteria, some assumptions about design operating conditions had to be made; in particular, how many of the many exhausting appliances which could be installed in a house could be operating concurrently, particularly at a time when stack driving forces are low (zero wind and low indoor/outdoor temperature difference). The chances of this "worst case" situation occurring, causing spillage which goes unnoticed to the point that it creates an immediate life-threatening situation, is very slim.

In general, the criteria is based on the assumption that code-required fans are on, as well as one large "user controlled" appliance (fireplace or stovetop grill), when an automatic device such as the furnace starts.

In determining the evaluation criteria, it was necessary to look over a broad range of situations. Table A.2 summarizes some of the possibilities and gives base numbers. It indicates typical flow requirements for various exhaust flow scenarios, calculated for a small house and a large house of two different levels of air tightness. Based on this information, it is suggested that, for any type of practical make-up air system, its minimum flow requirements at the maximum negative pressure levels outlined in Section 3.1 should be 40 litres/second. This was based on the judgement that relatively small proportions of Canadian housing have lower exhausting scenarios. (One notable exception is a situation where heat recovery ventilators or some other balanced ventilation system is installed, in which case the supply fan can be considered as one make-up air inlet.)

A good performance rating that covers the majority of Canadian houses would be approximately 150 litres/second. Evaluation credit should be given to values up to 250 litres/second.

Table A.2: Typical Flow Requirements (L/s)

	Operating at 5 Pa		Operating at -10 Pa	
	Small House	Large House	Small House	Large House
EXHAUST DEVICES	(250m3)	(750m3)	(250m3)	(750m3)
1. FANS @ 0.5 ACH/HR (70 L/s min)	70	105	70	105
2. LARGEST COMMON EXHAUST	125	125	125	125
(Stove Top Grill)				
3. SPACE HEATING APPLIANCES				
a. Natural Aspirating Gas	30	50	30	50
b. Induced Draft Gas	12	12	12	12
c. Condensing Gas	8	8	8	8
d. Conventional Oil	75	75	75	75
e. Condensing Oil	10	10	10	10
4. DHW HEATER				
a. Conventional Gas	10	10	10	10
b.Induced Draft Gas	10	10	10	10
c. Oil	75	75	75	75
5. WOOD BURNING APPLIANCES				
a. Open Fireplace	150	150	150	150
b. Fireplace With Doors And No Comb. Air				
c. Fireplace With Doors And Comb. Air				
d. Non-Air Tight Wood Stove	50	50	50	50
e. Air Tight Wood Stove	17	17	17	17
MAKE-UP AIR FLOW THROUGH THE ENVELOPE				
a. Tight House (1.0 AC/h)	-10	-35	-20	-60
b. Conventional House (2.5 AC/h)	-35	-95	-50	-155
AIR FLOW REQUIRED THROUGH MAKE-UP AIR SUPPLY DEVICE				
Very Tight Houses				
gas heating, no fireplace	60	70	90	105
gas heating, no fireplace, grill fan	115	90	145	125
gas heating, open fireplace	210	220	240	255
- from the fireplace perspective	100	130	240	255
gas heating, fireplace, grill fan	265	240	295	275
oil heating & DHW, no fireplace	60	70	200	195
oil heating, open fireplace	210	220	275	270
electric heat, open fireplace	60	70	200	195
TIGHT CONVENTIONAL HOUSES				
gas heating, no fireplace	35	10	60	10
gas heating, no fireplace, grill fan	90	30	115	30
gas heating, open fireplace	185	160	210	160
- from the fireplace perspective	75	70	210	160
gas heating, fireplace, grill fan	240	180	265	180
oil heating & DHW, no fireplace	35	10	170	100
oil heating, open fireplace	185	160	245	175
electric heat, open fireplace	35	10	170	100

A.3 The Issue of Comfort: Distribution Temperatures

Suggested Criteria:

1. Minimum Distribution Temperature to Occupied Rooms

- **17°C** if delivered through floor grills
- **13°C** if delivered through wall or ceiling grills

(Unless system design suggests that air temperatures and velocities entering the occupied space would have no higher dissatisfaction factor than 30% on Figure A.1 (from ASHRAE) at a normal 2.5 per cent design temperature.)

2. Optimum:

- delivery temperatures match room temperatures and velocities are such that there is less than 10 percent dissatisfaction on Figure A.1 at 2.5 per cent January design temperature.

The above is based on a flow of the lesser of 0.35 air changes per hour or the flow defined in the previous section.

Commentary:

The primary comfort criteria which must be addressed by the make-up air inlet system as a whole is that the air being delivered to the occupied zone be at temperatures and velocities which are not perceived as uncomfortable drafts. There is a significant body of work in trying to define, in engineering terms, specific conditions that are felt to be comfortable. Comfort has been defined in terms of temperature, humidity, air velocity, clothing levels and occupant activity factors.

The real issue for this project is distribution temperatures and effectiveness of air mixing, which is similar to the factors described in ASHRAE F-31.2. The entire distribution system must be looked at and it must be ensured that entry temperatures to the occupied space (0 to 2 m above the floor) can be deemed "acceptable".

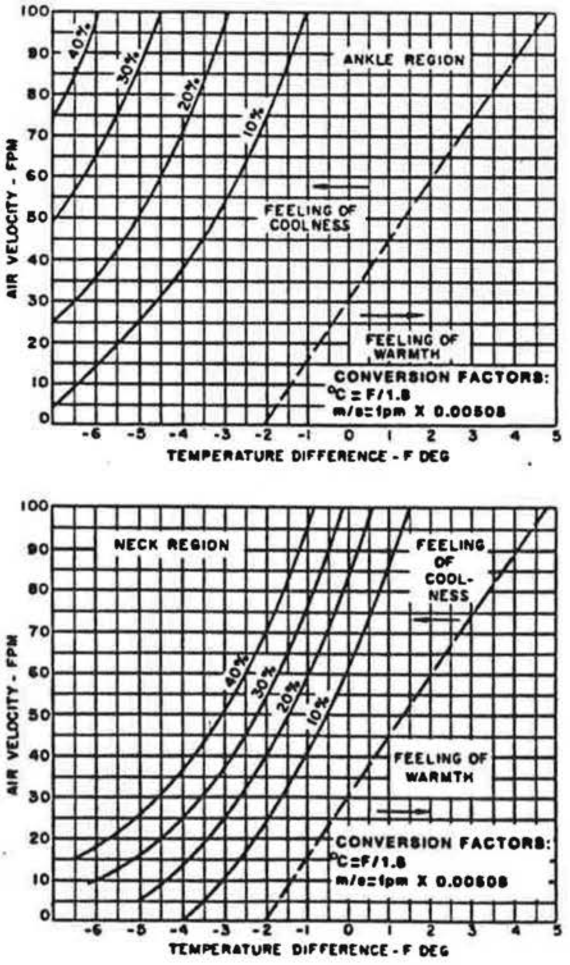
Defining acceptable is, of course, difficult. ASHRAE(16) presents a chart (Figure A.1), drawn from Houghten, which relates the temperature difference of an incoming air stream and the average room temperature and air velocity in the occupied zone to the satisfaction levels. Since local velocities and temperatures are so dependent on the specifics of room layout and grill design, this type of chart is difficult to use in an evaluation of a generic make-up air system. Temperature criteria are far easier to apply in such an evaluation or, for that matter, a standard.

The current draft of CSA F-326 suggests, in its commentary, that the distribution temperatures of air entering the rooms should not be less than 17°C with floor diffusers, and 13°C with high wall or ceiling diffusers (assuming room temperatures of 20°C). These were based on certain assumptions of grill performance, containment and location.

It is suggested that the temperature limits of the F-326 document can be employed as the minimum standard. An exception would occur if some special design factors would lead to the conclusion that air could be entered at a cooler temperature without going above the 30% dissatisfaction level of Figure A.1 at the 2.5% January design temperatures. The 30% factor may sound high, however incoming air temperature will usually be well above the 2.5 percent design temperature. At normal operating levels, the level of dissatisfaction would be lower. As well, the charts in Figure A-1 were designed for air conditioning use and assume summer clothing is being worn. The same logic can be applied to decide what flows should be evaluated. It is suggested that "comfort" criteria be based on incoming flow of the lesser of: *0.35 air changes per hour* or *the maximum flow at which the system is designed to operate* at the interior pressure limits outlined in Section A.1.

The 0.35 level is similar to the figure recommended by both ASHRAE and the CSA F-326 guidelines for the minimum required continuous ventilation for residential buildings.

FIGURE A.1: Percentage of Occupants Objecting to Drafts in Air-Conditioned Rooms



A.4 Protection from the Elements

Suggested Criteria

While there will be no set minimum limits in this category. Units will be evaluated on the potential for weather-induced problems, specifically:

- The potential for freezing, malfunction or blockage;
- Wind effects;
- Interior condensation; and
- The ability and need to incorporate air cleaning elements on the incoming air stream.

Commentary:

Weather-related concerns can be broken down into two areas: those which could cause malfunction or ineffectiveness of the device for its intended purpose and those which could cause secondary problems even though the device is performing its prime function of providing an appropriate amount of make-up air into the house. Much of the former type of problem will be dealt with in the section on failure analysis (3.5). This category is aimed primarily at trying to evaluate the secondary problems.

It is worth commenting on the specific concerns of wind effects. There has been significant discussion regarding the ways in which wind effects the performance of systems which have a single make-up air inlet. While the pressure control performance of such a device is likely to be effected by wind direction and speed, it should be pointed out that the need for concern may not be as high as some contend.

Wind effects the performance of both the chimney and the make-up air inlet. Wind forces could increase suction on a leeward-facing make-up air inlet and increase chimney action. Wind-induced forces follow an equation of the form:

$$p = 1/2\rho V^2 \times C_p$$

Where: p = wind pressure
V = wind velocity at reference height point
ρ = air density
C_p = average wind pressure coefficient

In general, average C_p values over the roof are negative values which are larger in magnitude than on negative C_p values for any wall, especially near ground level. In other words, the wind helps chimney action more than it hampers the air entry into the make-up air inlet, therefore the concern over combustion product spillage is actually reduced by wind.

There are cases, however, where eddy effects from buildings or surrounding terrain can create downdrafts in a chimney. This type of problem could be treated as a chimney problem and, in fact, is not likely to be corrected by improving the make-up air system.

Another concern with wind forces that has been ignored in our evaluation is that wind increases the levels of negative pressures in any building, especially one in which the bulk of openings are toward a leeward side. A single make-up air entry point in a tight house could lead to higher internal negative pressures which could increase the draw of soil gases into the building.

There are some valid reasons to downplay this concern. There is some mitigation of this effect because the increased wind forces will likely drive more air change within the house. Any increase in long-term exposure to soil gas contaminants would depend primarily on average wind speeds rather than the peak values. In Canada these are generally below 20 km/hr. It could also be argued that the contribution of any increase in exposure to soil gas due to leeward facing make-up air inlets is much less than those that are created by the presence of open chimneys.

A.5 Failure Analysis

Suggested criteria:

Minimum Requirement

- The potential for a short-term life-threatening hazard due to any mode of failure of the device must be no higher than if no device was installed.

Optimum

- A high reliability is expected and the consequences of any foreseen failure are such that all primary criteria with regards to flow volumes, pressure control and comfort are met and any failure is readily detectable.

Commentary:

The failure analysis will be looked from three viewpoints:

- The make-up air device in question;
- The control system, if any; and
- The total air entry distribution system.

This is necessary because there are many devices listed for examination that are one part of an overall system. Therefore, it is necessary to look at individual components as well at a total system. Control issues are so fundamental to this project that it is also worthwhile to examine control systems as a separate item.

The particular types of failures which will be examined include:

- recovery from power failures;
- weather-created failures;
- corrosion;
- physical damage;
- user intervention (due to misunderstanding of rule, costs of operation, etc.); and
- various combinations of the above.

A.6 Costs

Costs will not be looked at using the same evaluation system as the above categories. The costs of each system will be assessed using the formula:

Annual Costs = (Capital Costs x 0.15) + Annual Operating Costs

Where:
- Capital Costs include supply and installation in a typical house less any savings achieved through deletion of items such as combustion air inlets for combustion appliances and fireplaces.
- Annual Operating Costs include estimates for maintenance and power requirements, plus the auxiliary energy costs of heating the portion of incoming air over 0.35 air changes per hour to room temperature.

This equation is roughly equivalent to an annual operating cost including amortization of initial costs. Systems will be compared by evaluating the costs to achieve particular overall performance levels.

A.7 Cost Analysis

Making generalized estimates of capital and operating costs of hypothetical systems is obviously prone to much error. The costs of this report are provided as rough estimates despite this realization, because cost implications are very important criteria to most homeowners.

Installation costs have been calculated as the best judgement of the installed costs that a homeowner would pay in a normal contracting market for the retrofit installation of the hypothetical system being evaluated. In a new house, these costs are expected to be somewhat lower.

Operating costs are perhaps the most difficult to estimate because a major component of operating costs is the energy required to heat unnecessary air change. Identifying what is necessary and unnecessary in a hypothetical situation is obviously difficult. The costs shown in Tables 2 and 3 are based on the following assumptions:

- The costs associated with heating 1 L/s of unnecessary air change is \$5. This was calculated using the formula:

  (1.232 x 1 L/s x degree days x 24 hours/day) + 1000 W/kW x \$0.035/kWh

  This \$5 estimate would hold with a degree day value of 4,800.

- A house needs an airchange rate of approximately 50 L/s, aside from specific make-up air issues. This is equivalent to approximately 0.35 AC/h in an average size house.

- In order to evaluate costs, it is necessary to take into account both capital and operating costs. This was done by adding 15% of the capital cost to the annual operating cost. With this evaluation equation, the evaluation is relatively insensitive to capital costs when compared with avoidable operating costs (a situation most people would consider the opposite of current building industry decision making).

When comparing performance rating and costs (Tables 2 and 3), several factors become fairly evident.

- It is possible to achieve good performance with either a passive or fan forced system, but this benefit is only achieved if appropriate control mechanisms to limit unnecessary air flow are obtained.
- The performance factors for passive ducts are only achieved when there are (by current standards) extremely large passive systems installed.
- Using a forcing fan can allow more compact systems, but there is a particularly heavy operating cost penalty unless appropriate controls are developed and used.

APPENDIX B

Wait

FRESH AIR MODEL 970

INTRODUCTION

The Wait Fresh Air Control assists in helping you maintain a healthy home environment with proper oxygen levels while supplying fresh air combustion to your furnace to make up for the air that is being expelled through the furnace exhaust stack, exhaust fans and the walls. The Fresh Air Control unit also assists in reducing odours and humidity build up and helps keep the house smelling fresh.

The Fresh Air Control unit is intended for use in regular to medium air tight houses. It is NOT meant for use in an air tight house (i.e. R-2000 home).

The Fresh Air Control unit is attached to your return air plenum. On the back of the unit is a 6" diameter (150 mm) collar, attached to which is a 6" diameter insulated air duct. This duct leads to the outside wall mounted air intake hood which supplies the fresh air for the unit. Attached to the side of the fresh air unit is a 3" (75 mm) flexible tube connected to the hot air supply.

When the furnace comes on, the hot air will flow into the body of the fresh air unit. The bimetal coil spring will contract and open the damper to let fresh air into the return air plenum. When the furnace turns off, the bimetal coil will relax and close the damper.

ITEMS REQUIRED FOR INSTALLATION (Not included in the product)

Flexible insulated air duct U.L. approved 6" I.D., 2 clamps for the 6" duct, corrosion resisting fasteners for outside intake hood, caulking for the intake hood.

LOCATION AND INSTALLATION OF THE OUTSIDE AIR INTAKE HOOD

If possible, do not install the fresh air intake hood on a wall facing directly into or away from the prevailing wind. The reason is that you may receive consistently too much or too little fresh air due to the wind pressure. Refer to figure #1.

A 6⅛" (155 mm) diameter hole is required through the outside wall for the intake hood and duct. It should be as high as practical above grade, as clogging with debris and snow is a possibility. After you have located and made the opening, check the length of 6" (150 mm) diameter x 15" (380 mm) long duct protrusion through the inside opening in the wall, making sure you have just enough duct to fasten a clamp on. If building wall is more than 12" (300 mm) thick, extra 6" (150mm) galvanized air duct will be needed. If you have excessive duct protruding inside, cut the excess duct off the end opposite lanced end. Engage the duct seam. Now push the lanced end of the duct onto the back of the intake hood. (See figure 1.) Add additional duct if necessary and tape the joint. Use the intake hood and mark four mounting holes on the outside wall. Use fasteners appropriate to the wall surface (i.e. wood screws, concrete anchors, sheet metal screws). Caulk the back side of the vent cover so you have a good seal between the building and the vent cover. Now secure the vent cover to the building (fasteners by installer).

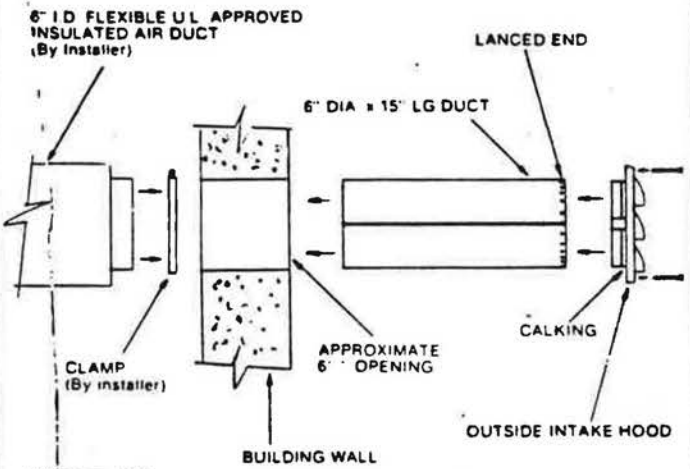


Figure #1

On the inside wall caulk the gap between the wall and the galvanized duct to prevent condensation forming in the wall.

LOCATION OF THE FRESH AIR CONTROL UNIT

See figure 2.

The Fresh Air Control unit goes on the return air plenum, with the by-pass mounting flange on the hot air supply plenum. When locating the Fresh Air Control unit, please note the following: it should be installed as high as possible and still be in reach for adjustment. Damper shaft must be horizontal. The furnace casing should never be cut as it voids furnace warranty.

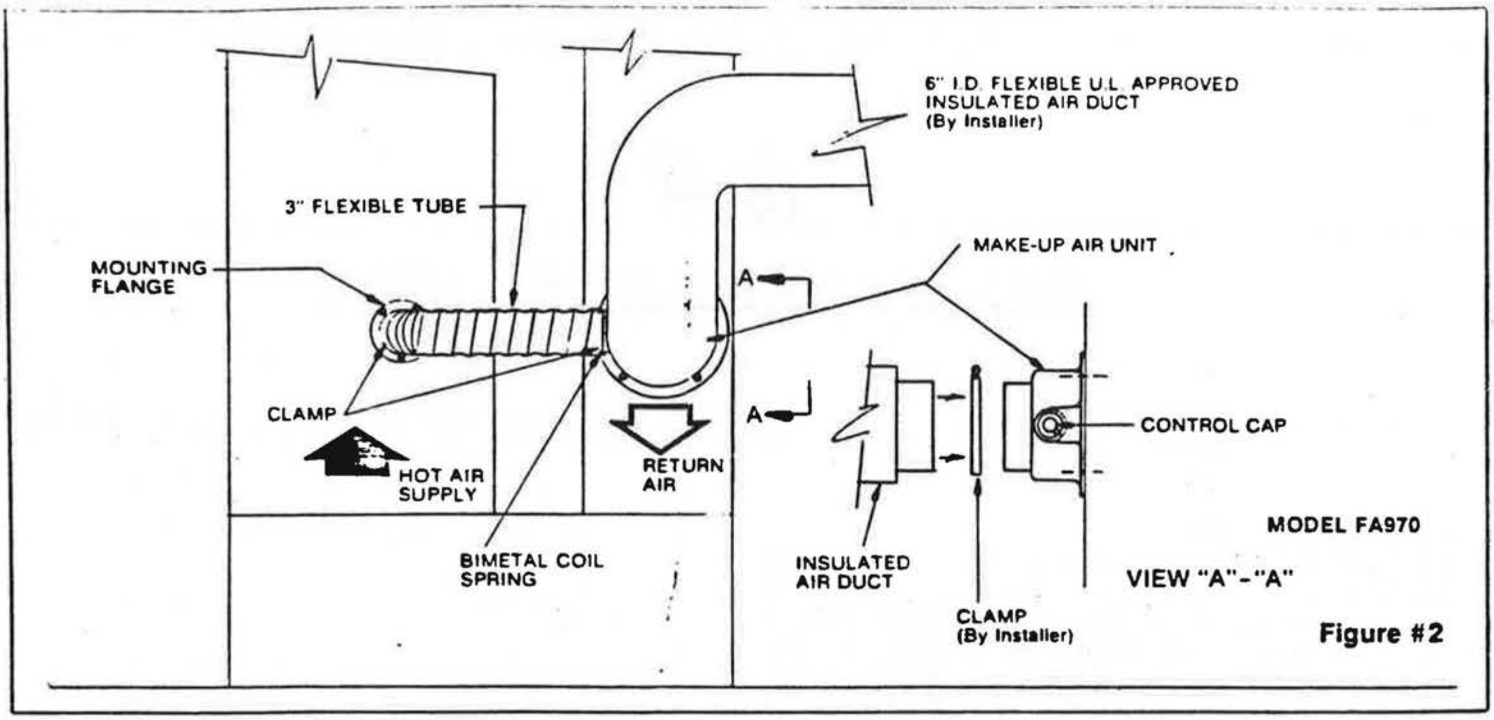


Figure #2

NOTE: If you have a humidifier on your furnace it would be preferable to have the Fresh Air Control unit on the opposite side of the return air plenum from your humidifier.

TYPICAL INSTALLATIONS

After determining the best location for the Fresh Air Control, attach the opening template to the return air plenum. Follow the instructions on the template, drill 4 holes and then cut the circular hole opening. Remove the template, position the Fresh Air Control unit in place on the plenum and attach with 4 sheet metal screws.

Next, attach the by-pass tube opening template to the hot air plenum. Following the instructions on the template, drill 3 holes and cut the circular opening according to the template. Remove the template and attach the by-pass collar to the plenum with 3 sheet metal screws with the raised flange of the collar away from the plenum. Now slide a clamp on both ends of the 3" (75 mm) white tube supplied, slide the tube over the collars and tighten the clamp on the collars. (If additional tube is required, use 3" (75 mm) dryer venting.)

To install 6" (150 mm) insulated duct (provided by installer), slide clamps (provided by installer) over both ends of the insulated duct and tighten it over the collar flange on the back of the fresh air control and the fresh air intake duct going outside. This insulated air supply duct should be supported where necessary to prevent sagging.

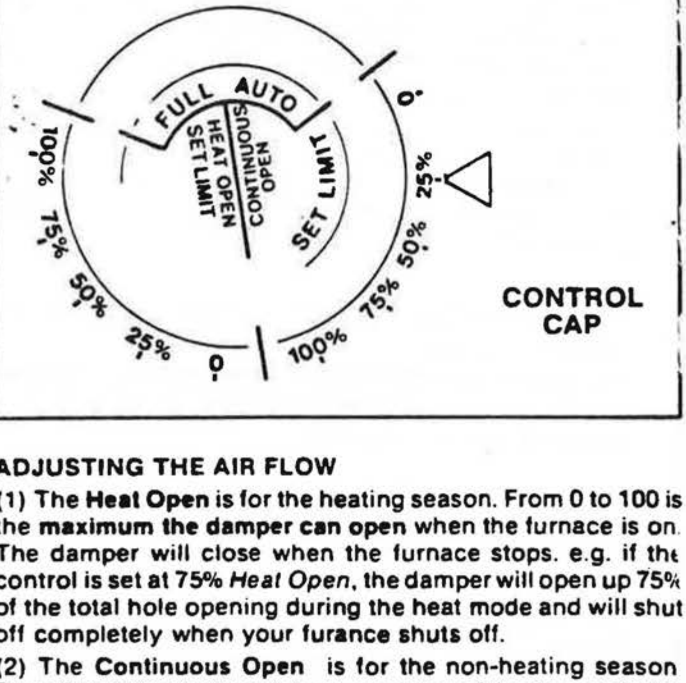
WARNING: Failure to use insulated air duct will cause condensation and related problems. A U.L. approved, insulated air duct should be used.

MAINTENANCE

Keep the inside intake hood clear of grass cuttings, bugs, dirt and also snow in the winter time.

OPERATION OF CONTROL CAP

Figure #3



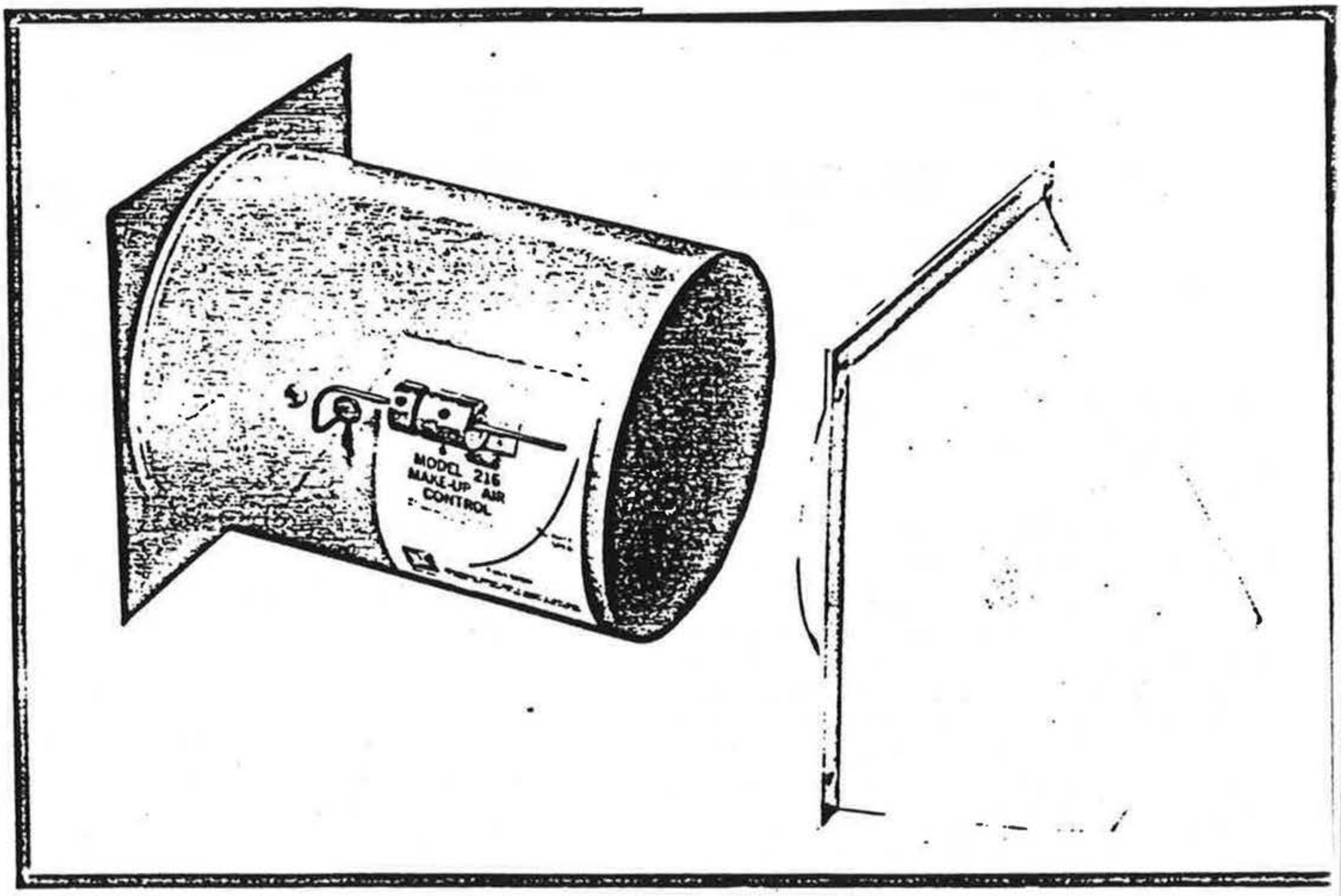
ADJUSTING THE AIR FLOW

(1) The **Heat Open** is for the heating season. From 0 to 100 is the **maximum the damper can open** when the furnace is on. The damper will close when the furnace stops. e.g. if the control is set at 75% *Heat Open*, the damper will open up 75% of the total hole opening during the heat mode and will shut off completely when your furance shuts off.

(2) The **Continuous Open** is for the non-heating season. From 0 to 100 sets the **minimum opening of the damper in the fresh air unit.** The fresh air unit can be used on continuous open with central air to help keep the house fresh and free of odours. e.g. if the control set at 75% *Continuous Open*, the damper will always be 75% open and will not close when the furnace shuts down.

(3) **Full Automatic** works with no restrictions. The damper opens 100% when the furnace comes on and closes when the furnace shuts off.

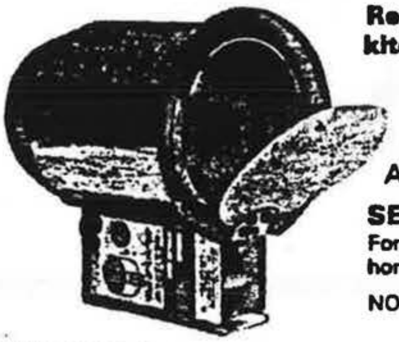
Self Adjusting
Make-Up-Air Control



- Can improve furnace efficiency by providing proper air for combustion.
- Improves comfort by reducing winter drafts & uncontrolled air infiltration.
- Fights domestic air pollution problems by today's tightly constructed homes.
- Enjoy controlled fresh air in your home - winter and summer.

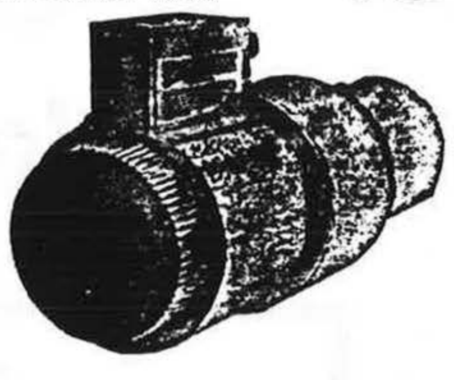
**Saves Energy. . . further
details on reverse side.**

ACA PAC REPLACEMENT AIR CONTROL DAMPER VERTICAL OR HORIZONTAL MOUNT - SERIES MAC AND VAC



Replacement and ventilation air control for dryers, kitchen fans, root cellars, fireplaces, heat recovery ventilators and electrically heated dwellings.

This installation shall be subject to the approval of the enforcing authority.
Air supply shall be in accordance with local codes.



SERIES MAC
For terminating end of horizontal or vertical duct.

SERIES VAC
Installed in-line as part of horizontal or vertical duct.

NOTE: Follow installation instructions and/or local building codes.

SPECIFICATIONS:
Volts 24 AC, 50/60 Hz. - motor 5 watts

SERIES:
MAC - To be mounted horizontally* or vertically on terminating end of air duct.
VAC - To be mounted horizontally* or vertically in-line as part of air duct.

* For installations on a horizontal duct, the operating body shall be oriented either above or below the duct.

TYPE: FC - Power closed, spring open. FO - Power open, spring closed.

MODEL NO.:

- 100 fits 4" diameter duct
- 125 fits 5" diameter duct
- 150 fits 6" diameter duct
- 175 fits 7" diameter duct
- 200 fits 8" diameter duct
- 225 fits 9" diameter duct

Length of insulated duct: 190 mm (7½") c/w duct wrap insulation.
Length of body: 152 mm (6").
Overall length: Series MAC - 202 mm (8"), Series VAC - 404 mm (16"), subject to model number.
Shipping weight: approximately 1.6 kg (3.5 lbs.), subject to model number.

ACA PAC REPLACEMENT AIR CONTROL DAMPER

The ACA PAC REPLACEMENT AIR CONTROL DAMPER is designed to be tight sealing and self cleaning for many years of trouble free service. A seperate 24v, AC, 10 VA transformer is required for each installation.

The 2-wire, 24v AC electric motor actuates the damper to either the closed position, Type FC, or open position, Type FO, subject to various applications.

GENERAL USE: Use Series MAC unless otherwise specified.

1. Replacement Air Control for clothes dryers and kitchen fans. Use power-open Type FO, plus 24v AC transformer connected to exhaust fan circuit.
2. Exhaust Vent Control for kitchen fans. Use in-line Series VAC, power-open Type FO, plus 24v AC transformer connected to exhaust fan circuit. (Not intended for exhaust vent of clothes dryers.)
3. Fresh Air Control for fruit rooms and root cellars. Use power-open Type FO, 24v AC transformer and two thermostats (one inside, contact on temperature rise; one outdoors, contact on temperature fall).
4. Fireplace Fresh Air Control. Use power-open Type FO, 24v AC transformer and manual switch.

USE IN ELECTRICALLY HEATED HOMES

1. Ventilation Air Control connected to fan circuit of electric appliance. Use in-line Series VAC, power-open Type FO, plus 24v AC transformer connected to high speed circuit of circulating fan. See specifications for other combinations.

USE WITH HEAT RECOVERY VENTILATORS

See specifications for various combinations.

AIR DUCT INSTALLATION

Air duct installations shall be in accordance with the National Building Code and/or Local Codes.

ACA PAC REPLACEMENT AIR CONTROL INSTALLATION

Note: Installer must be a trained, qualified person. Name and address of installer and date of installation must be recorded on label located on inside cover of central body. Labels supplied with unit must be mounted as per notes to installer located on labels.

SERIES MAC shall be fastened with screws to the terminating end of an adequately supported air duct.

SERIES VAC may be placed on the terminating end of an air duct or may be placed in-line to form part of the air duct. When mounting the ACA PAC damper in the horizontal position, the control body is to be located directly above or directly below horizontal duct. (Body not intended to operator on its side.) The short section of the ACA PAC duct is insulated, ready to be installed where insulated ducts are required.

LABELS

Follow instructions and warnings on labels supplied with each ACA PAC Control.

ELECTRICAL WIRING

All wiring shall be done in accordance with the Canadian Electrical Code or with Local Codes where they prevail. Additional wire shall be of the same size and type as used with existing control circuits.

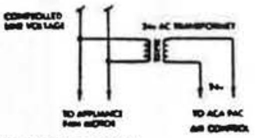
MAINTENANCE

ACA PAC REPLACEMENT AIR CONTROLS have nylon bearings that will last for many years of service. Lubrication is not necessary. Yearly inspection is recommended. For more information, contact your local dealer or write directly to the manufacturer.

INTERCONNECTION TO AN APPLIANCE SUCH AS A DRYER OR KITCHEN FAN

Schematic wiring diagram for ACA PAC Air Control, power-open Type FO, 24v AC, 50/60 Hz. transformer is actuated by appliance fan circuit.

Note: this marking is also on label to be affixed adjacent to appliance wiring diagram.

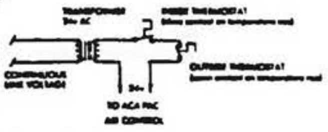


1. Install ACA PAC Replacement Air Control as per instructions above.
2. Turn off electrical power to fan appliance.
3. Connect 24v, AC, 50/60 Hz. transformer, 10 VA minimum, to fan circuit as per wiring diagram and applicable codes.
4. To the 24v transformer, supply and connect two wires with sufficient length to reach the ACA PAC Air Control.
5. Connect these wires to the ACA PAC Air Control terminals.
6. Turn on electrical power to fan appliance.
7. Turn on appliance to operate fan. ACA PAC Air Control will now open.

ACA PAC REPLACEMENT AIR CONTROL FOR COLD ROOMS

Schematic wiring diagram using ACA PAC Air Control, power-open Type FO connected to 24v transformer and two thermostats

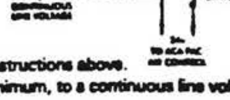
Note: Set inside thermostat at minimum room temperature desired. Set outdoor thermostat at maximum room temperature allowed during summer months. Damper will not open if outdoor temperature is too warm.



1. Install ACA PAC Replacement Air Control as per instructions above.
2. Connect 24v AC, 50/60 Hz. transformer, 10 VA minimum, to a continuous line voltage supply as per applicable codes.
3. To the 24v transformer, supply and connect two wires with sufficient length to reach the ACA PAC Air Control.
4. Connect wires as per schematic wiring diagram. Inside thermostat to make contact on temperature rise; outdoor thermostat to make contact on temperature fall.
5. Turn on electrical power to transformer. ACA PAC Air Control will open when both thermostats make contact.

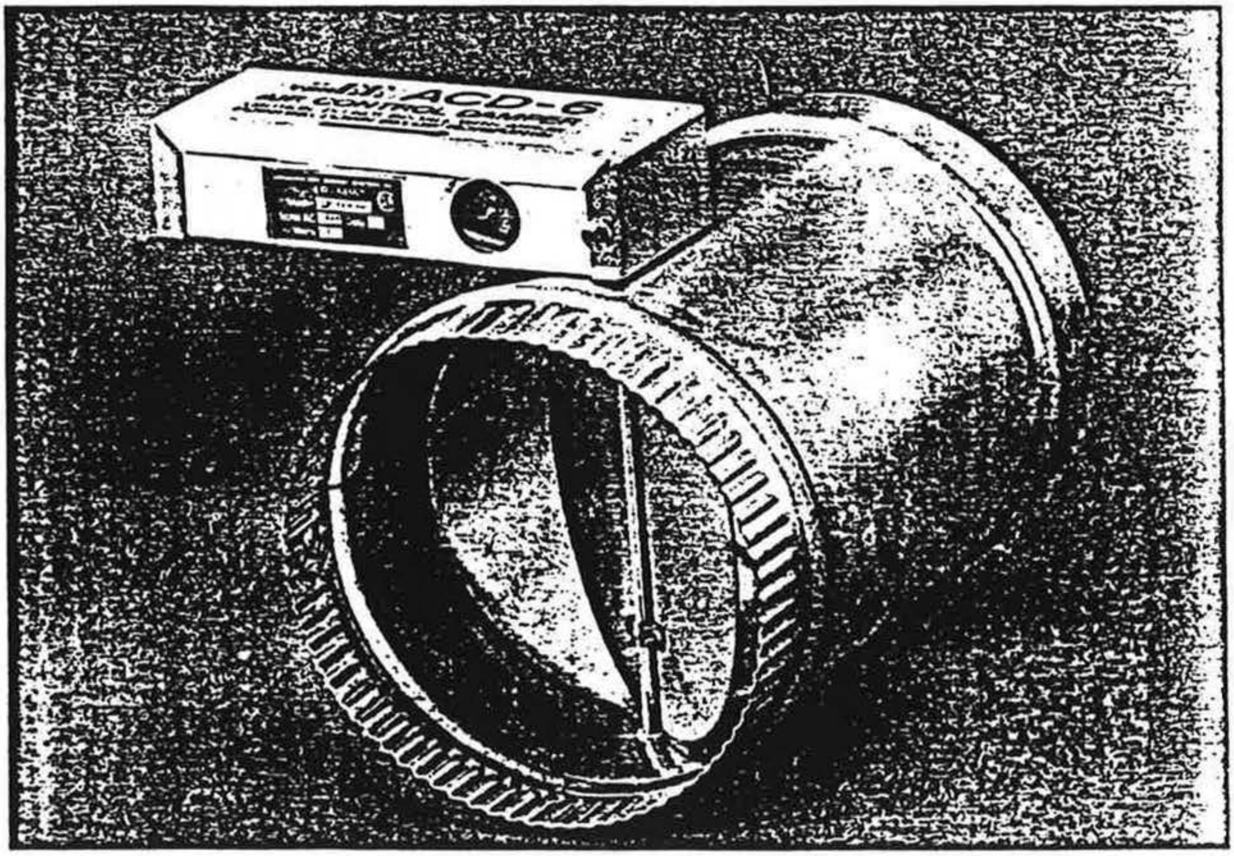
ACA PAC REPLACEMENT AIR CONTROL FOR FIREPLACES

Schematic wiring diagram using ACA PAC Replacement Air Control, power-open Type FO connected to 24v AC, 50/60 Hz. transformer and manual switch



1. Install ACA PAC Replacement Air Control as per instructions above.
2. Connect 24v AC, 50/60 Hz. transformer, 10 VA minimum, to a continuous line voltage supply as per applicable codes.
3. To the 24v transformer, supply and connect two wires with sufficient length to reach the ACA PAC Air Control terminals.
4. To the control switch, supply and connect two wires with sufficient length to reach the ACA PAC Air Control terminals.
5. Connect wires as per wiring diagram.
6. Turn power on to transformer. ACA PAC Air Control will open when switch is on and will close when switch or electrical power is off.

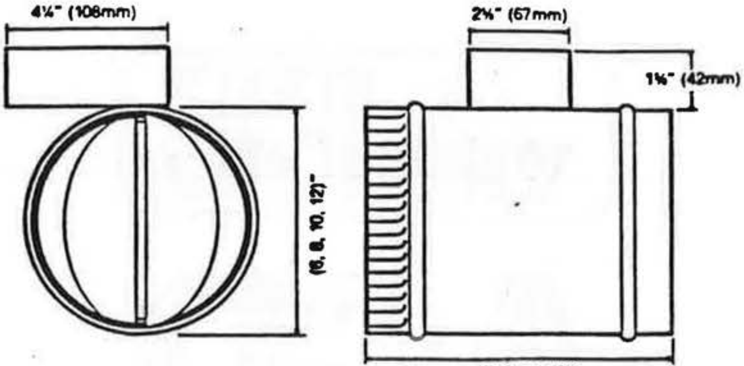
ACD
AIR CONTROL DAMPERS



The vanEE ACD Air Control Dampers are tight sealing dampers designed to be used to control air flows in low pressure air moving systems. They can be supplied in normally open or normally closed models. The operators have a spring return so that power is consumed only when the dampers are operated.

Specifications

- Four sizes are available:
  6" (150mm), 8" (200mm), 10" (250mm), 12" (300mm). All shells are 24 gauge bright galvanized steel with one end crimped.
  All sizes are available for either 24 or 115 VAC operation.
  Dampers may be installed in any position.



Applications

1. In combination with the vanEE EX200 the ACD-6 reduces negative pressures created by exhaust only central ventilation systems.

The ACD-6 is placed at the point of entry for the fresh air inlet to the forced air heating system and wired to the remote switching circuit for the EX200.

The ACD are not designed to supply combustion air to gas fired heating systems. A specialized damper is required for combustion furnaces.

Whenever the controls for the EX200 are turned on, eg., the humidistat calls for humidity reduction or a bathroom switch calls for ventilation, the damper opens allowing fresh air to enter the furnace system.

If the house is heated with a radiant heating system, the fresh air may be supplied to a seldom used room where the cooler outside air will not create discomfort.

2. In existing homes with fresh air supplies to forced air heating systems, the ACD-6 will provide sensible control of house humidity when operated by a vanEE humidistat located in a central location.

3. For zone control of seldom used rooms in homes with forced air heating systems, the ACD-6 can be operated with a wall-mount thermostat.

4. When used with a vanEE 2000 Series Heat Recovery Ventilation System, better control of areas requiring ventilation may be achieved if an ACD-6 is linked to remote switches in bathrooms, kitchens, spas, etc. Areas most frequently used would have no dampers,and normally most of the exhaust air would be drawn from these areas. Seldom used bathrooms, kitchens or hot tub rooms can be fitted with ACD-6 dampers which open only when ventilation is requested by the operation of the control switch.

Many other applications may be possible. Please consult your closest vanEE representative for further assistance.

WARRANTY
SUBJECT TO ANY APPLICABLE CONSUMER PROTECTION LEGISLATION, CES — CONSERVATION ENERGY SYSTEMS INC. WARRANTS THAT THE UNIT AND ACCESSORIES WILL BE FREE FROM DEFECTIVE MATERIALS AND WORKMANSHIP FOR A PERIOD OF ONE YEAR FROM THE DATE OF PURCHASE UNDER NORMAL USE PROVIDED THAT INSTALLATION IS IN ACCORDANCE WITH THE INSTRUCTIONS PROVIDED.

For More Information

CANADA
CONSERVATION ENERGY SYSTEMS INC.
3310 Millar Avenue
Saskatoon, Sask. S7K 7G9
(306) 242-3663
Telex # 074-21645
Callback CES vanEE SKN

USA
CONSERVATION ENERGY SYSTEMS
Box 10416
Minneapolis, MN 55440
1-800-667-3717
Telex # 074-21645
Callback CES vanEE SKN

Constant Airflow Regulator

DESCRIPTION

The Constant Airflow Regulator (CAR) is a device that automatically regulates airflows in ductwork to constant levels. The device operates passively, with no electric or pneumatic controls or independent sensors. The device is dynamic, in that it responds to changing conditions automatically, without any user involvement.

The CAR provides the solution to the problem of balancing forced air systems for heating, air conditioning and ventilation. Mechanical engineers and contractors are well aware of the problems in correctly balancing forced air systems. With conventional practice, the process is difficult, time consuming, and when completed, the whole job is subject to being totally unbalanced inadvertantly by occupant interference. In addition, other factors may later cause imbalance, such as thermal stack effect in tall buildings, and dust clogging the fans, filters and duct. To a large degree the CAR will compensate for these changes.

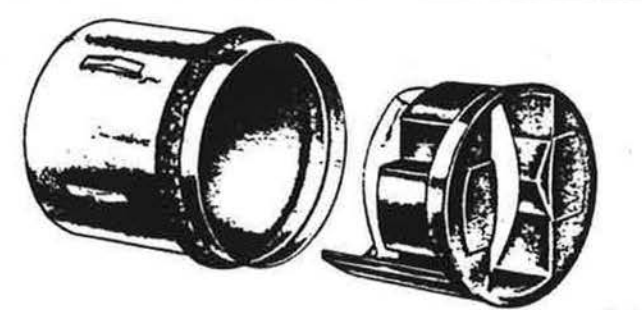


Fig. 1

The sub-assembly consisting of the silicone bulb and its housing is mounted in a rolled galvanized steel sleeve. The total assembly is designed to fit inside standard ducts in both metric and inch dimensions, as well as the duct fittings such as tees, etc. A brush type seal around the circumference ensures a tight fit. A set of spring action metal clips grip the interior of the duct to firmly secure the control in place with minimum installation effort.

The active element is a flexible silicone bulb which inflates and deflates in response to the static pressure difference across the control. The housing is made of polycarbonate (Lexan), for minimum flame spread characteristics. (UL recognized component plastic (QMF 72) conforming to UL94V-0). The CAR is patented and has been used extensively in Europe for ten years. The expected lifetime of the silicone bulb is a minimum of 20 years under normal non corrosive conditions.

PRINCIPLE OF OPERATION

At minimum static pressure, the cross-section shape of the silicone bulb is similar to an hourglass. As the static pressure across the CAR is increased, the silicone bulb inflates, reducing the free area. At the same time, the increasing static pressure increases the air velocity, resulting in a constant airflow. See the airflow characteristics below for more detail.

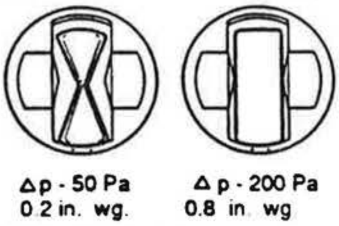


Fig. 2

APPLICATIONS

The Constant Airflow Regulator may be used in any situation where constant airflow is required. It is an indispensible element in any modern constant volume air system. As examples, it may be used in the following cases:

- Stabilizing the airflow in a branch duct (as in heating, air conditioning or ventilation).

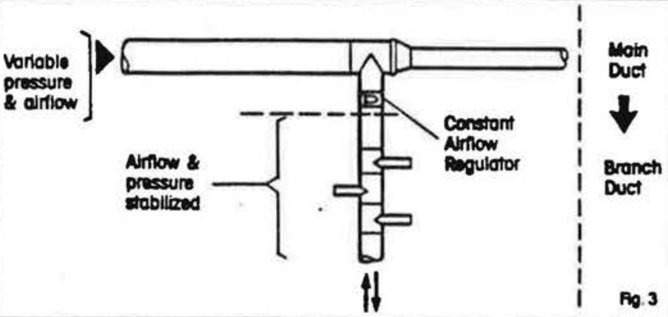


Fig. 3

- Stabilizing the airflow at a return grille. (Example shows the CAR in the duct connector from the boot for a return grille.)

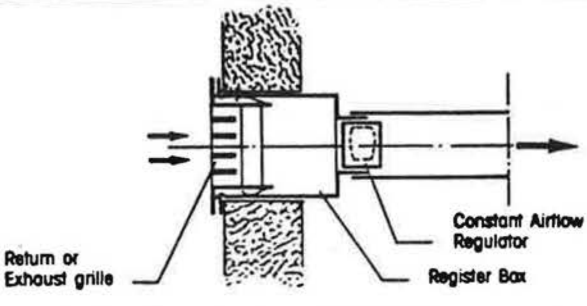


Fig. 4

MANUAL DAMPERS

Manufacturer/Supplier:	Therma-Star Products Group
Model:	Fresh 80 Ventilator
Description:	The Fresh 80 is a through-the-wall ventilator which is comprised of a 3" duct with louvers on the exterior. Flow is controlled by a string operated valve equipped with a filter.
Operation:	The unit has only open and closed positions. The flow in the open position can be controlled by the use of an adjustment screw.

Advantages:
- simple retrofit

Disadvantages:
- insufficient diameter for required flows
- manual operation subject to misuse
- will produce uncomfortable drafts in living space

MANUAL DAMPERS

Manufacturer/Supplier:	Cres Products
Model:	Dragon Fire Breather
Description:	The "Dragon Fire Breather" is a through-the-wall ventilator. The main body consists of a 3 1/2" square hollow duct. The external hood is mounted on a 3" round duct designed to fit into the main body. The flow is regulated by a manually operated rotational damper.
Operation:	The damper is turned to align the vent holes with stationary plate attached to the main body. The rotational damper allows for full control of flow.

Advantages:

- permits full control of flow

Disadvantages:

- the total flow area is equivalent to a 40 mm diameter duct, which is clearly inadequate.
- manual operation subject to misuse
- will result in uncomfortable drafts in living space

THERMAL DAMPERS

Manufacturer/Supplier: Wait Manufacturing

Model: Fresh Air Model 970

Description: A thermally activated bimetallic spring is used to control this make-up air damper. A manual damper allows the damper position to be controlled (eg. minimum 25% open or maximum 80% open).

Operation: A 150 mm duct is fed from the outside wall to the return air duct of a forced air furnace. A 3" flexible duct runs from the supply duct back to the shell of the Model 970. When the furnace is operating, warm supply air is drawn in via the flexible duct over the bimetallic coil, thus activating the damper.

Advantages:

- requires no electrical connections
- allows for some manual adjustment

Disadvantages:

- prone to malfunctioning
- lag time before opening or closing
- does not address make-up air needs of other devices

BAROMETRIC DAMPERS

Manufacturer/Supplier: Skuttle Manufacturing Company

Model: # 216

Description: The model # 216 includes a 6" duct section with a counterbalanced damper. An external arm indicates the position of the damper during operation. An external hood and screen are included in the package.

Operation: Sufficient pressure across the damper will activate it. As delivered, this model is designed to start permitting flow through at 15 Pa. Two counterbalances are mounted on an adjustable external arm.

Advantages:

- simple retrofit
- no electrical connections
- adjustable
- allows for visual confirmation of damper positioning

Disadvantages:

- susceptible to failure due to light activation forces
- subject to wind effects
- chokes flow relative to a passive duct

ELECTRIC DAMPERS

Manufacturer/Supplier:	Hoyme Manufacturing Inc.
Model:	ACA-PAC Series HOM and HOW
Description:	The HOM and HOW series of dampers, designed to supply combustion air, are available in 4" to 9" diameters. They contain electric motors which are used to open a spring loaded damper when the furnace is operating.
Operation:	The damper is intended to be placed near the combustion air inlet, thus the majority of air introduced will be used for combustion. Proper wiring provides fail-safe operation when used with a furnace. A variety of voltage adapters are available from the manufacturer so that auxiliary exhaust equipment can also be wired in. The HOM and HOW series Type F-2 is wired for the use with 2 appliances. A variety of voltage adapters are available from the manufacturer, ensuring no compatibility problems with signalling from other appliances.

Advantages:

- fail-safe open
- dependable operation
- effective for combustion air of oil, propane and natural gas appliances
- duct length insulated

Disadvantages:

- deposits air directly to interior
- furnace triggered - does not supply make-up air for other devices
- may not have sufficient flow for multiple appliances
- subject to wind effects while open
- needs an activation device

ELECTRIC DAMPERS

Manufacturer/Supplier:	VanEE
Model:	ACD Series
Description:	The VanEE automatic control damper (ACD) are in-line units. They are supplied in either normally open or normally closed positions. An electric motor operates the damper.
Operation:	The damper can be purchased for either 24 or 115 volt AC operation. The damper is activated by the electric motor and a spring is used to return the damper when off. Although the units are designed for signal operation, simple parallel wiring of appliances will permit multiple triggering.

Advantages:

- simple, dependable operation
- in-line construction allows for more flexibility
- uses power only when damper is open

Disadvantages:

- cannot be used to supply combustion air to gas fired appliances
- needs an activation signal

ELECTRIC DAMPERS

Manufacturer/Supplier: Hoyme Manufacturing Inc.

Model: ACA-PAC Series VAC

Description: The series VAC air control dampers are in-line units. They can be obtained in normally open or normally closed positions. An electric motor is used to operate the damper.

Operation: The motors are designed for 24 volt AC operation. The damper is activated by the electric motor and a spring is used to return the damper when off. The units can be connected for multiple appliance triggering.

Advantages:

- duct length insulated
- quality construction
- dependable operation

Disadvantages:

- needs an activation device

FLOW CONTROL BLADDERS

Manufacturer/Supplier: American Aldes Ventilation Corporation

Model: C.A.R. (Constant Air Flow Regulator)

Description: The sub-assembly involves a silicon bulb in a housing, assembled in a circular steel sleeve designed to fit tightly inside the appropriate duct section. The silicon bulb acts as a bladder which expands or contracts to control flow.

Operation: The bladder inflates and deflates depending on the difference in static pressure across the control. The increased static pressure increases the velocity but the C.A.R. reduces the free area to achieve the constant flow characteristics.

Advantages:

- simple operation requires no activation device
- no adjustments necessary

Disadvantages:

- available models need pressures in 50 Pa to 200 Pa range which are well in excess of those incurred in the make-up air issue

HEAT RECOVERY VENTILATORS

Manufacturer/Supplier:

VanEE
Lifebreath
Nu-Tone
Air Changer
Environment Air

Commentary: Although there are some differences in operation with respect to the make-up air issues, these variances do not have a significant effect. For this reason, heat recovery ventilators have been treated as generic products in the analysis.

IN-LINE ELECTRIC DUCT HEATERS

Manufacturer/Supplier: VanEE

Model: EDH-6

Description: This unit is a 6" duct heater intended for use as a reheat after the heat recovery ventilator. It is an in-line unit, available with duct mounted thermostats or remote thermostats.

Operation: Air is heated by electric elements. The unit is available in 1 kW or 2 kW models.

Commentary: There are a number of similar units being produced by various manufacturers. The basic operation is the same for all units and as such does not pose a problem in the design of a make-up air system.

APPENDIX C

C.1 Make-Up Air Supply System

From the conceptual design stage to construction of the final prototype, a number of key design areas were examined. This section will examine the critical elements of the unit in more detail.

C.1.1 The Diaphragm

Due to the low pressures being acted on, the weight and stiffness of the diaphragm have substantial impact on the sensitivity of the device. The applied pressures must be able to lift the diaphragm and the diaphragm must be capable of collapsing upon itself under its own weight or with only a nominal amount of pressure. Testing concluded that a supple and lightweight material such as 1 mL polyethylene provided the required physical characteristics. For production, some research should be done to find the best material for long-term use.

The diaphragm must be sealed on the side subject to outdoor pressure. It is very important that the seal be completely airtight, as any leaks would result in slower reaction time and, if substantial, the diaphragm would fail to inflate.

A number of diaphragm diameters were examined, ranging from 75 mm to 180 mm. Initially, it was felt that a relatively large diameter would be necessary to provide sufficient force to lift the diaphragm and interrupter strip. Preliminary testing proved that, not only would a smaller size diaphragm provide sufficient lift, but, in fact, a preload was required to damp the system so the device would not be activated at unnecessarily low pressures (1 - 2 Pa). Paper discs placed on the surface of the diaphragm provided the necessary preload. By varying the number and thickness of these discs, a range of operating pressures could be obtained. The additional advantage of using the discs as a preload was the resulting flatter shape of the diaphragm, which eliminated problems arising from uneven inflation and deflation.

The range of motion of the diaphragm was an additional consideration. Initial testing found that a play of ±30 mm provided sufficient range, without causing the diaphragm to buckle when deflated.

C.1.2 Optical Sensors

Self-contained optocouplers, equipped with a light emitting diode and photo transistor, can be purchased for less than three dollars, but are only capable of operating over a gap of approximately 13 mm.

To make use of these readily available components, a lightweight strip of brass shim stock was hung from the diaphragm so that it was surrounded by a sealed, airtight, rectangular cross-section acrylic tube. The optocouplers were placed around the tube. The acrylic was transparent to the spectral range of the LED and the transistor turned off only when the interrupter strip was placed between the LED and the photo transmitter. The interrupter strip was connected to the diaphragm by a thread to allow for freedom of movement in the tube, which minimized frictional effects. The optocouplers can be shifted along the length of the tube to vary the lag time between low and high speed.

The minimum setting between high and low speed was initially obtained by placing the optocouplers one on top of the other. Due to the width of the optocoupler casings, the gap between high and low was too large for some applications. To avoid this problem, the interrupter strip was reconstructed with two separate zones, one for high speed control and one for low speed control (Figure C.1).

C.1.3 Pressure Sensing

To best sense the average indoor/outdoor pressure difference experienced by the building envelope, a pressure averaging device was required. This was constructed by running a separate tube to each of the four sides of the house and connecting them to a pressure averaging chamber. A separate line was fed from the averaging chamber to the underside of the diaphragm. Flow damping from the four taps could be increased by restricting the tubes with capillary tubes. However, experimentation concluded that 6.4 mm flexible hosing, equipped with standard adaptors at the various equipment interfaces, provided adequate damping with the averaging box used in the prototype.

During periods of low pressure, the diaphragm settles due to the weight of the preload, diaphragm and interrupter strip. With the onset of "high" pressures, the diaphragm begins to inflate but, due to the built-in damping, there is a lag time before it reaches the low speed setting. The length of this time lag depends on the volume of the space under the diaphragm. During testing, it was necessary to use a collar to support the diaphragm just below the low speed setting, thereby minimizing start-up time. By adjusting the height of the collar and, therefore, the "effective" control volume below the diaphragm, the lag time can be adjusted.

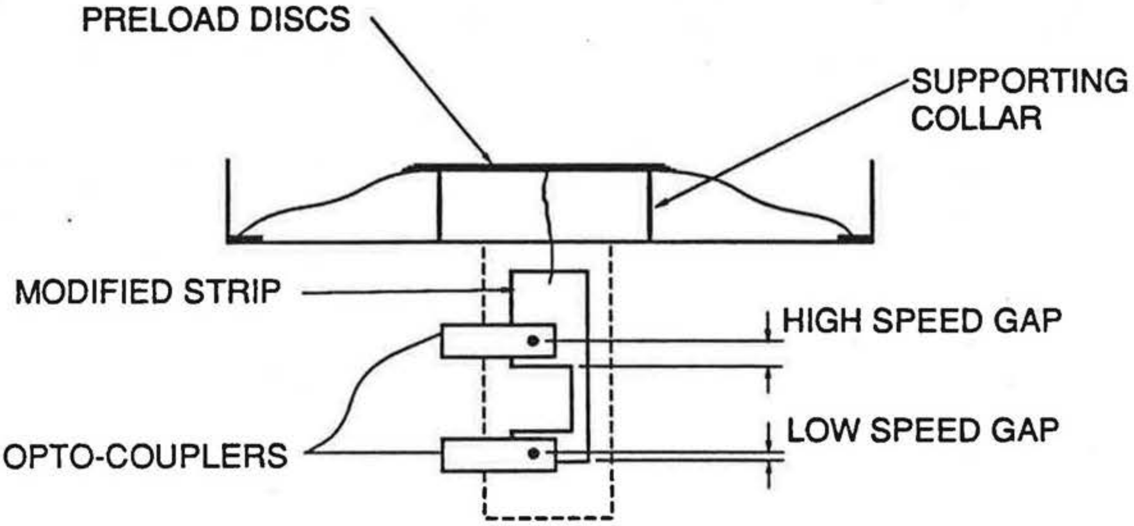


Figure C.1: Optocoupler/Interrupter Modification

C.1.4 Control Circuitry

The output of the optocouplers is a low level logic signal. To achieve the required current to activate a relay or switch, an additional control circuit was required (Figure C.2). The output of the control circuit was used to activate a solid state relay.

For a two speed fan, a series of three relays was necessary. The low speed was controlled by a variable resistor connected in series with the fan. To obtain high speed, the variable resistor was by-passed (Figure C.3).

Duct Heater

To temper the supply air to acceptable levels, a duct heater is required. For in-house testing, a P.M. Wright 2 kW in-line electric duct heater was used. It was a two-stage unit with built-in thermostat.

The duct heater is, in effect, a stand-alone unit. The heater requires a minimum flow to avoid cycling of the automatic reset thermal cutout or failure of heating elements. To avoid this problem, the heater was connected to a relay which was triggered by the circuit powering the fan, thereby activating it only when the fan operates.

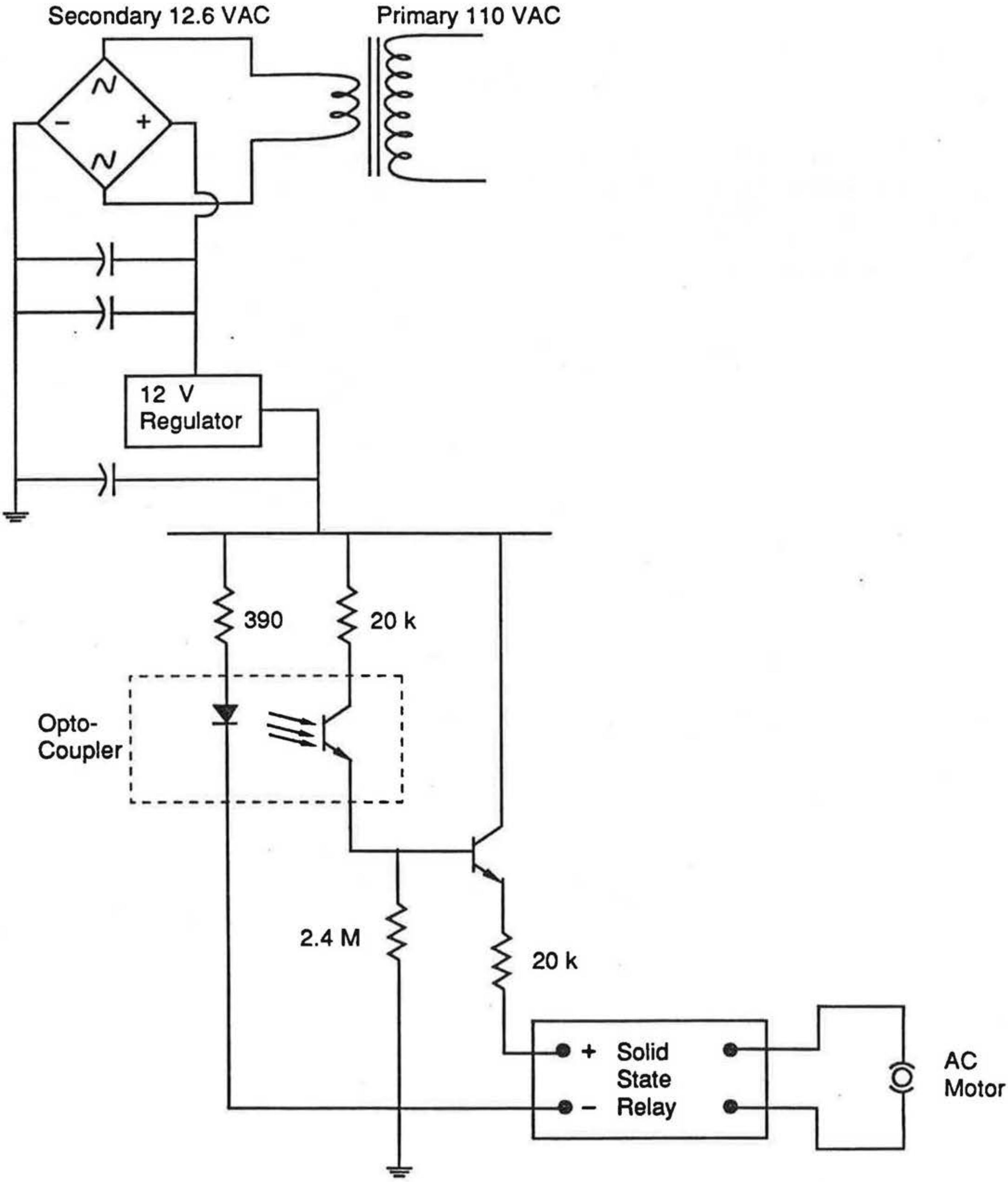


Figure C.2: Control Circuit

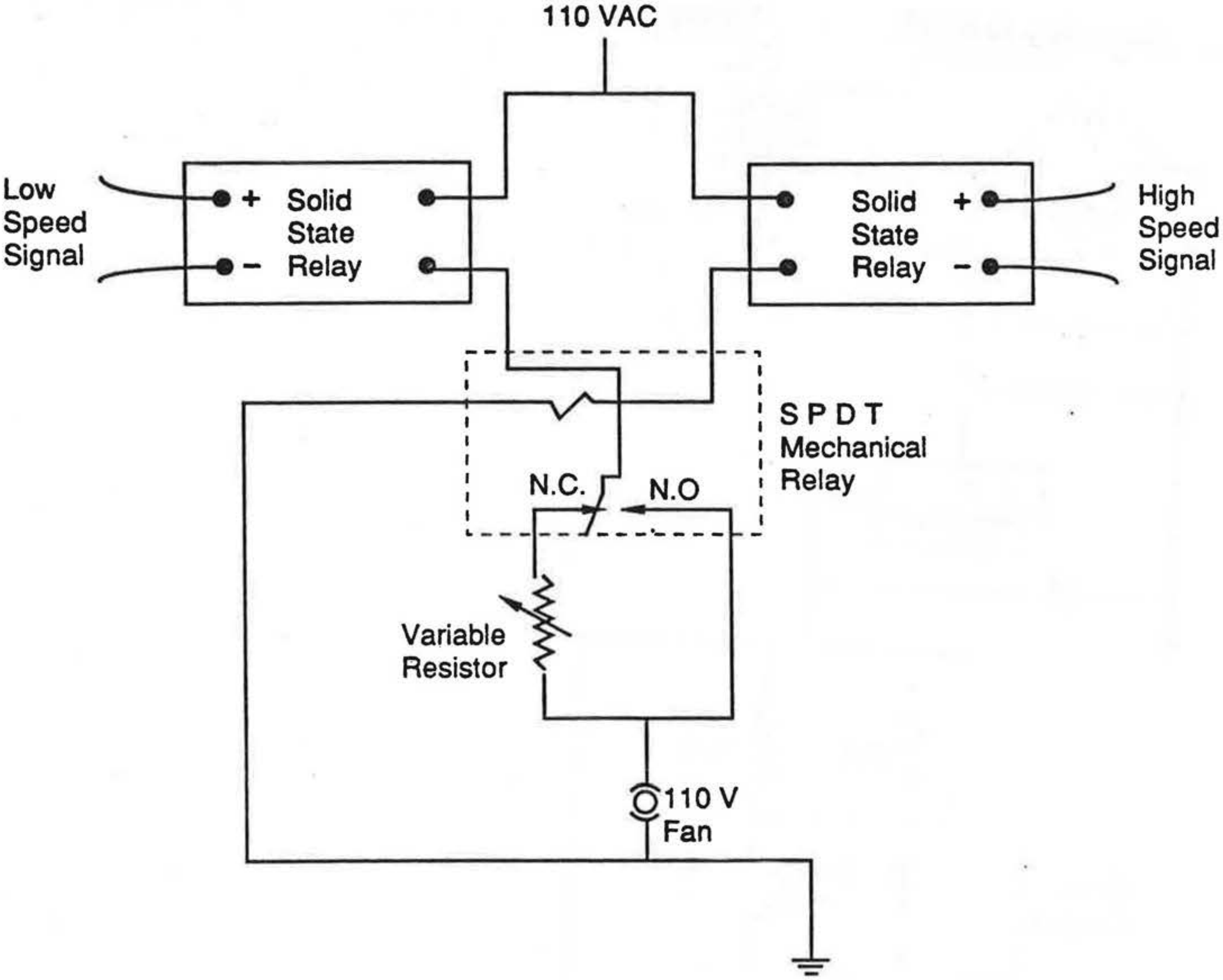


Figure C.3: 110V Circuitry

APPENDIX D

Pressure Monitoring Data

Average Temperature	-6.3°C
Maximum Windspeed	43 km/h
Average Windspeed	16 km/h

TIME	TSUPHT °C	TSUPCD °C	DPAVE Pa	LOWFAN On/Off	HIFAN On/Off
0:19	*****	*****	*****	0	0
0:24	14	12.2	-1.7	0	0
0:30	14	12.3	-1.4	0	0
0:36	13.9	12.1	-1.5	0	0
0:42	14	12.4	-1.6	0	0
0:48	13.8	12.1	-1.4	0	0
0:54	14.1	12.3	-1.6	0	0
4:00	13.3	11.7	-1.5	0	0
4:06	13.1	11.4	-1.6	0	0
4:12	13.2	11.7	-1.6	0	0
4:18	13.2	11.4	-1.5	0	0
4:24	13.2	11.7	-1.6	0	0
4:30	13.1	11.4	-1.6	0	0
4:36	13.2	11.6	-1.6	0	0
4:42	13.1	11.4	-1.5	0	0
4:48	13.3	11.8	-1.6	0	0
4:54	13.1	11.4	-1.5	0	0
8:00	11.7	10.4	-1.5	0	0
8:06	11.7	10.3	-1.5	0	0
8:12	11.4	9.9	-1.5	0	0
8:18	11.4	9.9	-1.4	0	0
8:24	11.3	9.8	-1.4	0	0
8:30	11.2	9.9	-1.3	0	0
8:36	11.4	9.9	-1.4	0	0
8:42	11.4	9.8	-1.3	0	0
8:48	11.3	9.8	-1.2	0	0
8:54	11.1	9.8	-1.6	0	0
12:00	13.5	12	-1.4	0	0
12:06	13.5	11.9	-1.2	0	0
12:12	13.6	12.1	-1.2	0	0
12:18	13.5	12.1	-1.2	0	0
12:24	13.5	12.2	-1.1	0	0
12:30	13.5	12.1	-1.1	0	0
12:36	13.6	12.2	-1.3	0	0
12:42	13.6	12.1	-1.1	0	0
12:48	13.6	12.1	-1.1	0	0
12:54	13.5	12.1	-1.2	0	0

Control Tests A and B

Average Temperature	-6°C
Average Windspeed	(SW) 20 km/h

	kitchen fan	dryer	furnace	fireplace	m.a. damper closed	TIME	TSUPHT °C	TSUPCD °C	DPAVE Pa	LOFAN On/Off	HIFAN On/Off
TEST A						10:18	17.6	15.2	-2	0	0
						10:24	17.7	15.3	-1.4	0	0
						10:30	15.4	12.9	-2.2	0	0
				*		10:36	8.5	7	-3.6	0	0
				*		10:42	5.5	4.6	-3.4	0	0
				*		10:48	4.4	3.6	-5.2	0	0
	*			*		10:54	3.4	2.6	-5.4	0	0
	*	*		*		11:00	2.5	2	-6.8	0	0
	*	*	*	*		11:06	2	1.6	-7.1	0	0
		*	*	*		11:12	2	1.4	-7.1	0	0
		*		*		11:18	2.5	2.1	-6.1	0	0
				*		11:24	3.6	3.1	-5.3	0	0
				*	*	11:30	3.9	3.2	-3.8	0	0
				*		11:36	5.2	4.2	-4.2	0	0
				*		11:42	7.6	6	-0.7	0	0
				*		11:48	8.7	6.8	-4.5	0	0
				*		11:54	9.8	7.7	-4.9	0	0
				*		12:00	11.2	8.6	-4.9	0	0
				*		12:06	12.1	9.1	-5	0	0
				*		12:12	12.7	9.7	-4.9	0	0
				*		12:18	13.3	10.2	-5	0	0
				*		12:24	13.7	10.7	-4.9	0	0
TEST B				*		12:30	14.2	11.1	-5	0	0
	*			*	*	12:36	14.3	10.9	-7	0	0
	*			*		12:42	10.9	8.5	-6.6	0	0
						12:48	8.7	7.6	-4.4	0	0
						12:54	11.4	9.7	-4.2	0	0
						13:00	12	10	-4.2	0	0
						13:06	11.9	9.9	-4.2	0	0
						13:12	12.1	10.1	-4.2	0	0
						13:18	12.2	10	-3.8	0	0
						13:24	11.9	9.8	-3.6	0	0
						13:30	11.5	9.4	-3.6	0	0
						13:36	11.2	9.3	-3.6	0	0
						13:42	11.1	9.1	-3.4	0	0
						13:48	10.8	9	-3.4	0	0
						13:54	10.9	9	-3.7	0	0
						14:00	10.7	9.1	-4.3	0	0

Control Test C

Average Temperature -16°C
Average Windspeed (SW) 7 km/h

	kitchen fan	furnace	dryer	TIME	TSUPHT °C	TSUPCD °C	DPAVE Pa	LOFAN On/Off	HIFAN On/Off
TEST C				10:12	14.1	11.3	-2.6	0	0
				10:18	14.2	11.3	-2.7	0	0
				10:24	14.2	11.5	-2.7	0	0
				10:30	14.5	11.9	-2.5	0	0
				10:36	14.5	11.8	-2.6	0	0
				10:42	14.6	12	-2.9	0	0
	*			10:48	14.7	11.7	-1.1	0	0
	*	*		10:54	14.1	10	-5	0	0
	*			11:00	12.6	7.6	-4.9	0	0
				11:06	11.9	7.2	-5	0	0
				11:12	12	8.1	-4.1	0	0
		*		11:18	12.3	9.4	-3.1	0	0
			*	11:24	12.6	9.9	-3.4	0	0
	*		*	11:30	12.9	9.7	-4.2	0	0
	*	*	*	11:36	13	8.9	-5.8	0	0
			*	11:42	12.4	7.7	-6.1	0	0
				11:48	12.1	7.9	-3	0	0
				11:54	12.7	9.2	-4.3	0	0
				12:00	13.3	10	-3.9	0	0
				12:06	13.8	10.1	-4	0	0
				12:12	13.9	10.5	-4.3	0	0
				12:18	14.1	10.7	-4.3	0	0
				12:24	14.2	10.8	-4.1	0	0
				12:30	14.3	10.9	-3.9	0	0
				12:36	14.5	11	-4.5	0	0
				12:42	14.4	11.2	-4	0	0
				12:48	14.6	11.5	-3.4	0	0
				12:54	14.5	11.3	-3.2	0	0
				13:00	14.4	11.1	-4.1	0	0
				13:06	14.2	10.8	-3.7	0	0
				13:12	14.1	10.6	-4	0	0
				13:18	13.9	10.3	-4.1	0	0
				13:24	13.9	10.9	-3.3	0	0
				13:30	14.2	11.4	-3.2	0	0
				13:36	14.4	11.5	-3.9	0	0
				13:42	14.5	11.7	-3.4	0	0
				13:48	14.4	11.6	-3.2	0	0
				13:54	14.4	11.1	-3.6	0	0
				14:00	13.9	10.4	-3.9	0	0

Initial Test

Average Temperature -8°C
Average Windspeed calm

	kitchen fan	dryer	fireplace	m.a. damper closed	TIME	TSUPHT °C	TSUPCD °C	DPAVE Pa	LOFAN On/Off	HIFAN On/Off
					16:45	22.2	8.4	-0.3	0	0
					17:00	25.2	7.8	-0.5	0	0
					17:15	32.4	7.2	-0.7	0	0
					17:30	32.9	6.7	-0.8	0	0
					17:45	32.7	6.5	-0.8	0	0
					18:00	32.6	6.3	-0.8	0	0
					18:15	32.5	6	-0.8	0	0
					18:30	32.3	5.8	-0.9	0	0
INITIAL					18:45	32.4	5.6	-0.9	0	0
TEST					19:00	32.3	5.1	-1	0	0
					19:15	33	5.1	-1.1	0	0
					19:30	33.1	5.1	-1.1	0	0
			*		19:45	33	5.1	-1.3	0	0
			*		20:00	33.5	5.3	-1.4	0	0
			*		20:15	35.8	5.5	-2.3	0	0
			*	*	20:30	41.5	4.9	-4.1	0	0
			*	*	20:45	40.9	4.7	-4	0	0
	*		*	*	21:00	37.3	2.2	-5.3	97	27
	*		*	*	21:15	5.6	0	-3.5	82	84
	*	*	*	*	21:30	4.2	1.7	-4.2	0	0
	*	*	*		21:45	36.1	4.8	-2.6	0	0
			*	*	22:00	38.7	5	-2.2	0	0
			*	*	22:15	36.6	5.1	-2	0	0
			*	*	22:30	35.7	5	-2.3	0	0
					22:45	36.1	5	-2.2	0	0
					23:00	35	5	-2.3	0	0
					23:15	35.6	4.3	-2.3	0	0
					23:30	34.9	3.8	-2.4	0	0
					23:45	34.3	3.4	-2.4	0	0
					0:00	34.5	3.2	-2.1	0	0

Final Test

Average Temperature -5°C
Average Windspeed (SW) 6 km/h

	m.a. damper closed	kitchen fan	dryer	exhaust fan	TIME	TSUPHT °C	TSUPCD °C	DPAVE Pa	LOFAN On/Off	HIFAN On/Off
FINAL TEST					10:12	15.5	3.7	-4.8	0	0
					10:30	45.3	3.7	-3.8	75	28
	*	*		*	11:00	17.6	0	-3.9	87	87
	*			*	11:15	31.6	1.4	-4.3	124	0
				*	11:30	41.2	5.3	-4.9	0	0
		*		*	11:45	40.9	5.5	-7.2	0	0
	*	*		*	12:00	19.5	1.7	-4.5	121	121
	*	*			12:15	36.8	6.6	-2.5	20	0
	*	*	*		12:30	12.6	5.6	-2.9	41	0
		*	*		12:45	7.9	5.8	-3	10	0
					13:00	10	7.6	-1.1	0	0
					13:15	11	8.4	-1.1	0	0
					13:30	10.9	8.3	-1	0	0
					13:45	10.6	8.1	-1	0	0
					14:00	10.9	8.4	-1.1	0	0
					14:15	10.8	8.4	-1.2	0	0
					14:30	10.8	8.3	-1.1	0	0
					14:45	10.7	8.4	-1.1	0	0
					15:00	10.7	8.4	-1	0	0
					15:15	10.6	8.2	-1	0	0
					15:30	10.3	7.9	-1	0	0

APPENDIX E

Temperature Control

The degree to which the make-up air was tempered was a function of fan speed and outdoor temperature. For electric heating, the equivalent supply temperature translates to:

$$T_S = T_O + \frac{785 \ x \ kW}{Q}$$

Where:
T_S = supply temperature (°C)
T_O = outdoor temperature (°C)
kW = heater capacity (kW)
Q = airflow rate (L/s)

The supply temperature versus outdoor temperature for typical high and low speed air flows are shown graphically in Figure A. The plot illustrates that even a 2 kW duct heater produces marginal results in cold climates, therefore a larger capacity may be necessary.

Testing indicated that the 2 kW heater produced a temperature rise of approximately 20°C on high speed.

Outdoor vs Supply Temperature for Various Flows