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INFILTRATION, ENERGY CONSERVATION

AND

INDOOR AIR QUALITY

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### ABSTRACT

In recent years, more attention has been paid to reducing residential energy consumption. One option is to improve the air tightness of a home, thereby reducing up to 24 % of its heating load. However, in tightening a home one must ensure that adequate ventilation is provided. Otherwise, pollutants such as carbon dioxide, formaldehyde, radon gas and tobacco smoke may build up and threaten the health of the occupants. One solution that has been proposed involves the use of air to air heat exchanger systems. Although feasible from the energy conservation point of view, payback periods from their installation make them unattractive to the consumer. TABLE OF CONTENTS

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#### 1.0 INTRODUCTION

1

Infiltration is the uncontrolled flow of air into a building. (Exfiltration is the flow out of a building) This leakage carries an energy loss with it. In winter months, infiltrating air must be heated; in summer months it must be cooled. This paper will consider the role of infiltration in residential space heating. Essentially, the same arguments apply for space cooling, except that the heat flow is inward rather than outward.

Rogers et al. have estimated that infiltration may account for up to 24 % of the heating load in Eastern Ontario homes.[54] This is shown in table 1. As the number of walls exposed to the outdoor environment increases, so do peripheral heat losses and, hence, infiltration heat losses become a smaller proportion of the total space heating load. However, that is not to say that infiltration is not important in, say, single family detached homes. Although peripheral losses account for a larger proportion of the heating bill, infiltration losses also contribute to high home heating costs. Therefore, it makes sound economic sense to decrease or eliminate infiltration losses altogether. TABLE 1.

Peripheral and Infiltration Heat Losses for Different Buildings in Eastern Ontario 54

Type of Residence	Peripheral Losses (MWH/heating season)	Infiltration Losses (MWH/heating season)	
single family, detached	33.7 (86%)	5.51 (14%)	
attached and duplex	23.0 (82%)	4.98 (18%)	
row house	14.4 (76%)	4.45 (24%)	
apartment	7.56 (71%)	3.05 (29%)	

The answer, however, is not that simple. Infiltration is often the only source of makeup air for ventilation and combustion. In decreasing infiltration one may end up with poor indoor air quality. Herein lies the conflict. Energy conservation suggests the elimination of infiltration losses while health considerations necessitate adequate ventilation. Obviously a balance must be found between the two.

One energy efficient solution that has been suggested involves the use of air-to-air heat exchangers in combination with airtight housing. Rather than having infiltration as the only source of ventilation, it is eliminated and replaced with a mechanical ventilation system with heat recovery. Obviously, the installation of such systems implies higher capital costs. However, these may be offset by lower fuel bills. It is necessary, therefore, to find out when the installation of heat recovery systems becomes economically feasible.

This paper will examine the limits on infiltration reduction imposed by health effects. Chapter 2 will deal with the modelling of infiltration and its relationship with indoor air quality. Chapter 3 will examine the health effects of several common indoor pollutants. Finally, chapter 4 will consider the role of air-to-air heat exchangers in overcoming these limits.

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2.0 MODELLING OF INFILTRATION AND AIR QUALITY

In this chapter, the sources and quantification of infiltration will be discussed. The relationship between infiltration and heating load will be presented as will typical results and calculations of the energy savings theoretically obtainable through increased air tightness.

The sources and modelling of indoor contaminant levels will also be presented. Some sample calculations of air change rates necessary to keep pollutant levels below recommended levels will also be included. Finally, the factors affecting indoor air quality and the characteristics of some problem homes will be discussed.

#### 2.1 The Sources of Infiltration

The characterization of the sources of air leakage is important in order to control and evaluate air infiltration. Infiltration occurs mainly through cracks and other openings in the building envelope (ie. mail slots, etc.). The amount of infiltration may be reduced through the use of weatherstripping, vapour barriers, and so on. Nevertheless, some air leakage will occur. Table 2 shows the range and average values of leakage for various sites in the home.

Walls contribute the highest percentage to total leakage. Air may leak in between the sill plate and the foundation, through electrical outlets and plumbing penetrations and through any other openings in a wall. If interior walls are not insulated, open paths between them and the attic provide a means

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TABLE 2

Range and Average Values of Relative Leakage of Various Leakage Sites in American Homes <sup>2</sup>

Leakage Sites	Average Relative Leakage (%)	Range of Relative Leakage (%)
Walls	35	18-50
Ceiling Details	18	3-50
Heating System	15	3-28
Windows and Doors	15	6-22
Fireplaces	12	0-12
Vents in Conditioned Spaces	s 5	2-12
Diffusion through Walls	<1	< 1

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for heat exchange and, therefore, energy loss. Air may also diffuse through porous construction materials. However, this source of infiltration is usually negligible when compared to leakage through cracks and other openings.[2]

Ceiling details also contribute a significant amount to the total leakage. Recessed lighting, plumbing and electrical penetrations leading to the attic are among the ceiling features that increase the air leakage rate.

Windows and doors also admit air into a residence. The tightness of a home depends on the type of window or door used. For example, windows that compress weatherstripping as they close (ie. casements, awnings) admit less air than do sliding windows. Similarly, the tightness of fit between a door and its frame is an important parameter. In addition, the presence of mail slots and, to a lesser extent, the type of doorknob are important factors controlling the amount of air leakage.

Fireplaces allow air to leak in through poorly fitting dampers. Furthermore, fires draw in air for combustion and this air is usually replaced with colder outside air. In that same vein, fuel burning furnaces also require air for combustion. Stricker has found that electrically heated homes have less air leakage than alternatively heated ones.[68] This can be attributed to to two factors. Firstly, in electric homes no air and, secondly, baseboard or required for combustion is ceiling-cable heated homes have no air moving ductwork. Stricker speculates that air ducts and return air paths have leakage paths connecting them to the outdoors.[68] However, Rogers has

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suggested that the reason for decreased air flow is improved air tightness since electrically heated homes are generally newer than others [55]

Finally, no treatment of the sources of infiltration could be complete without a discussion of occupant behaviour. Opening windows, traffic into and out of a home, and other similar practices all tend to increase the air change rate, hence the However, for modelling purposes, these factors heating load. must be omitted for the simple reason that public behaviour is too inconsistent to be mathematically analyzed. It should be kept in mind, however, that predicted air change rates will probably be lower than actual values.

2.2 Methods for Quantifying Infiltration and Comparing Relative Air Tightness

Infiltration rates are usually measured in air changes per hour (ach) or in terms of volume flow rates (cfm or L/s). The air change rate in ach is probably the more widely used method although the volumetric flow rate is gaining popularity. The two may be related through the equation:

> (2.1) Q = nV

where:

Q = volumetric flow rate

n = the air change rate (ach)

V = the volume of the house

There are various ways to arrive at a house air change rate. It may be done analytically or empirically. Several test methods

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are outlined in the Appendix. Given experimental results, there are a number of ways to compare relative air tightness. The ASHRAE handbook considers the average flow in ach at a pressure difference of 50 Pa (n50) using the fan pressurization outlined in Appendix D. [2] Beach suggests dividing the volume flow rate at 10 Pa. (Q) by the area of the building envelope (A) that seperates the the heated volume from the outside (ie. ceilings, walls and floors).[4] Stricker uses the concept of an equivalent leakage area (ELA) which is the area of the sharp edged orifice that would give the same flow pattern as that arrived at using the fan pressurization method. Further, the leakage coefficient (LC) is defined as the ELA divided by the house volume.[63] The relationship between house tightness and the various parameters outlined above is shown in table 3.

2.3 Factors That Affect Infiltration Rates

The extent of infiltration depends on the design, age and condition of the building enclosure, the quality of the materials used, the workmanship and the pressure difference across the cracks and other openings in the building envelope. The pressure difference itself depends on the wind speed and direction, the indoor-outdoor temperature gradient, the shape and orientation of the building and the surrounding terrain.

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TABLE 3

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## Measures for Comparing Air Tightness

Type of Home	ELA <sup>a</sup> (m <sup>2</sup> )	$\frac{LC \times 10^{4^{a}}}{(m^{-1})}$	Air Change Rate (ach)	<sup>n</sup> 50 (ach)	Q/A @ 10 Pa <sup>C</sup> (L/sm <sup>2</sup> )
Leaky	0.158-0.279	3.00-5.91	0.7-1.0	4.55	1.53
Average	0.139-0.232	2.79-3.94	0.4-0.7 <sup>d</sup>	3.57	0.61
Tight	0.078-0.121	2.03-2.79	0.1-0.3	1.49	0.27

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a = converted from Stricker [65]

b = from Dumont et al. [13]

c = from Repace [51]

d = average value for new housing, current U.S. housing is 0.75-1.0 ach (average) [SI]

The design of the home plays an important role. In a study of relative air tightness of homes in the Saskatoon area, Dumont et al. found that bungalows and bi-level homes were generally tighter than 1 1/2 and 2 storey homes.[13] They attributed this to the greater surface area above grade for the latter group.[13] Their results are shown in table 4.

The age of a residence can also be positively correlated with the infiltration rate. In the same study it was found that pre-1945 homes were 2.2 times as leaky as homes built between 1946 and 1960 (at  $\triangle P$  of 50 Pa).[13] This relationship is shown in figure 1.

The quality of materials used in construction affects infiltration rates also. Some materials are more porous than others and, therefore, may admit more air. Furthermore, the workmanship during construction is also a controlling factor. For example, poorly installed vapour barriers will increase the air change rate as will ill-fitting doors and windows.

Another important parameter affecting infiltration is the weather. An increase in the indoor-outdoor temperature gradient also increases the air change rate. Similarly, strong winds also increase the air change rate. To some degree, wind losses can be controlled by the shape and orientation of the building and judicious use of the surrounding terrain. Usually, however, wind effects are the major cause of pressure differences across the building enclosure, particularly in buildings less than 5 storeys high.[38]

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## TABLE 4

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Pressure Test Results Sorted According to Construction Style Conventional Houses 1961-80

	Average Air Change per hour @ 50 Pa	Standard Deviation	Number of Houses
Bungalow	3.04	0.81	46
Bi-Level	3.37	0.85	10
1 1/2 Storey	4.35	0.55	2
2 Storey	4.38	1.68	15
Split Level	4.49	1.81	24



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1 N 2.4 Infiltration and Heating Load

As already mentioned, all buildings have some air leakage. In the heating season an energy loss is associated with infiltration as the incoming air needs to be heated and humidified. The heat required to increase the temperature of the infiltrating air (sensible heat) is given by:[38]

$$q_{s} = \frac{nVCp}{v} (T_{i} - T_{o})$$
(2.2)

where: Cp = the specific heat of air at internal conditions  $T_{i}, T_{o}$  = indoor and outdoor temperatures respectively v = the specific volume of air at internal conditions

Furthermore, the heat required to humidify the infiltrating air (latent heat) is given by: [38]

$$q_{l} = \frac{n Vi_{fg}}{v} (W_{i} - W_{o})$$
(2.3)

where:  $(W_{i}-W_{o}) =$  the difference between indoor and outdoor specific humidity

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i<sub>fg</sub> = the latent heat of vaporization at internal conditions

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Thus the total heat required to condition the outside air to meet indoor conditions can be written:

$$q_{t} = q_{s} + q_{l} = \frac{nV}{v} (Cp(T_{i} - T_{o}) + i_{fg}(W_{i} - W_{o}))$$
 (2.4)

Equation (2.4) shows a direct relationship between infiltration rate and building heating load. In decreasing the air change rate one also decreases the heating load. On any given day  $Cp_*T_1*T_0*W_1*W_0*$  ifg\* and v are constant, as is the house volume. Thus if one were to plot the heat required to condition the air against the air change rate the result would be a straight line. This is shown in figure 2 for the set of conditions listed in the figure.

Obviously, significant energy savings may be achieved through decreased infiltration rates. Sundell estimates that each reduction of 0.1 ach represents an energy gain of 1000-2000 kWh per dwelling annually in the Nordic countries.[70] Similar savings should be possible in Canada.

Let us consider a numerical example. Repace estimates that current North American housing has air change rates between 0.75 and 1.0 ach and that newly built homes range between 0.4 and 0.7 ach.[51] For the conditions specified in figure 2, the heat required to compensate for an infiltration rate of 1.0 ach would be 7.6 kW. For homes of 0.7 and 0.4 ach the corresponding heat required would be 5.3 and 3.0 kW respectively. Thus in tightening the very loose home of 1.0 ach to 0.7 ach a savings of

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FIGURE 2 ENERGY REQUIRED TO HEAT INFILTRATING AIR AS A FUNCTION OF THE INFILTRATION RATE

As detailed in Appendix A, the equation of the lines are:

 $q_1 = 2.11 n$  (kW)  $q_s = 4.55 n$  (kW)  $q_t = 6.66 n$  (kW)

where: q<sub>1</sub>, q<sub>s</sub>, q<sub>1</sub> = latent, sensible and total heat loads respectively

n = the air change rate

The following conditions were assumed:

House volume =  $606 \text{ m}^3$ Indoor temperature =  $22^\circ$  C Outdoor temperature =  $0^\circ$  C Indoor relative humidity = 45%Outdoor relative humidity = 86%

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2.3 kW is realized..... almost enough to heat the infiltrating air of the third home. (The details of this calculation are shown in the Appendix.)

2.5 The Relationship Between Infiltration and Air Quality

The previous sections have shown that it is desirable to minimize infiltration. Minimal infiltration rates would result in decreased energy consumption and, hence, lower fuel bills. Unfortunately, infiltration is often the only source of makeup air in residences. Therefore, a decrease in the infiltration rate also results in higher indoor pollutant concentrations. Thus in decreasing infiltration one may end up with poor indoor air quality.

The first question that must be asked is where do all of these pollutants come from? Basically, the sources of indoor pollutants can be classified into 3 groups: indoor sources; outdoor sources; and indoor and outdoor sources. A contaminant is considered to be from out of doors if its concentration is generally higher outside. Similarly, an indoor contaminant generally has a higher concentration indoors. If the indoor and outdoor concentrations are nearly equal the source is considered to be both indoor and outdoor. Some examples can be found in table 5.

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TABLE 5

Typical Sources of Some Pollutants Grouped by Origin 42

Pollutants

### Sources

Group 1: Outdoor Sources

sulfur oxides (gases, particles)
ozone
pollens
lead, manganese
calcium, chlorine, silicon
 cadmium
organic substances

Group 2: Indoor and Outdoor Sources

nitric oxide, nitrogen dioxide carbon monoxide carbon dioxide particulates

water vapour

organic substances

spores

Group 3: Indoor Sources

radon

formaldehyde

asbestos, mineral and synthetic fibres organic substances

ammonia

polycyclic hydrocarbons, arsenic nicotine, acrolein, etc. mercury

aerosols viable organisms allergens fuel combustion, smelters
photochemical reactions
trees, grass, weeds, plants
automobiles
suspension of soils or industrial
emission
petrochemical solvents, natural
sources, vaporaization of
unburnt fuels

fuel burning
fuel burning
metabolic activity, combustion
resuspension, condensation of
vapours and combustion products
biological activity, combustion,
evaporation
volatization, combustion, paint
metabolic action pesticides
fungi, molds

building materials (concrete, stone) natural gas, water particleboard, insulation, furniture, tobacco smoke fire retardent, acoustic, thermal or electric insulation adhesives, solvents, cooking, cosmetics metabolic activity, cleaning products tobacco smoke fungicides, in paints, spills in

dental care facilities or lab (thermometers breaking) consumer products infections house dust, animal dander The indoor concentration of a contaminant depends on many factors, the most significant of which are the pollutant generation rate and the net removal rate by various mechanisms.[44] Other factors include ambient air pollution levels and the nature of the contaminant itself.

It is difficult to arrive at a model for indoor pollutant levels. For one, there is no such thing as a typical home. Each home must be considered individually as geographic location, furniture and occupant behaviour all affect generation and removal rates. Also, in most cases the mixing of a contaminant is not uniform throughout the home. Dead zones may exist due to the layout of the home or its furnishings. Furthermore, in a residence infiltration is often the only way to dilute indoor pollutants. Since infiltration itself varies with wind speed, temperature gradient and a number of other factors already discussed, it is difficult to evaluate the pollutant removal rate. Nevertheless Traynor et al. have suggested the following expression to describe the change in indoor pollutant levels. It is based on the assumption of uniform mixing throughout the space.[72]

$$dC = PnC_{o} dt + \frac{S}{V} dt - (n+k)C dt \qquad (2.5)*$$

\* This equation is derived in Appendix C.

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where: C = the pollutant concentration

- $C_0 \doteq$  the outdoor pollutant concentration
- n = the air change rate (ach)
- P = the percent transmission of the outdoor contaminant to the indoor environment
- k = the net removal rate by mechanisms other than air exchange
- S = the indoor pollutant generation rate
- V = the indoor volume

Traynor suggests assuming  $Cp_P_n$ , S and k to be constant and thereby generating a solution to (2.5). The solution is:[78]

$$C(t) = \frac{PnC_{o} + \frac{S}{V} (1 - e^{-(n+k)t})}{n + k} + C(0) e^{-(n+k)t}$$
(2.6)

from which we get the steady state concentration as being:

$$C = \frac{PnC_{o} + \frac{S}{V}}{n + k}$$
(2.7)

Although equations (2.5),(2.6) and (2.7) will be used in this report it is important to mention their shortcomings. Two major inaccuracies come immediately to mind. First of all, there is no doubt that the assumption of constant S and n is invalid in most cases. Let us consider formaldehyde gas source strength as an example. Should a home be insulated with UFFI there is a given formaldehyde emission rate that depends on temperature and humidity.[9] The presence of plywood or particle board results in a further emission rate.[22] Furthermore, if the occupants smoke there is a third variable source of formaldehyde gas. Thus, S cannot be constant. Similar arguments can be put forward for a variable air change rate. As already mentioned, n depends on wind speed and direction, the indoor-outdoor temperature gradient and a number of other factors. It therefore cannot be constant. Because of these factors equation (2.6) is not a true solution of (2.5).

The second inaccuracy comes from the fact that the model considers uniform pollutant distribution throughout the home rather than the varying concentrations that will be present. For example, kitchens equipped with gas stoves will have higher  $NO_X$  concentrations than bedrooms in the same home. Thus, (2.6) is subject to more inaccuracies.

Nevertheless, this report will use equation (2.7) to model indoor air quality as a function of infiltration rate. There is really no practical alternative and, although (2.7) is not exact, it does show the general trends. Typical values of k and P can be found in table 6.

Equations (2.6) and (2.7) cannot, however, be used to model all indoor contaminants. They can be used for gaseous pollutants and particulates. They can only be used for radioactive pollutants (such as radon) when S is not related to the infiltration rate. In most cases, however, radon source strength is positively correlated with the infiltration rate.[43] This is

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# TABLE 6.

# Transmission Percentages and Pollutant Reactivities for Different Building Contaminants

Pollutant	Pollutant Removal Rate by Mechanisms Other than Infiltration (h <sup>-1</sup> )	Transmission Percentage (%)	Reference
carbon monoxide	0	100	78
carbon dioxide	0	100	78
nitrogen oxides	1.29	100	80
radon	.0076	100	80
formaldchyde	.40	100	77
particulates	.48	40	77

$$\frac{dR_{i}}{dt} = S_{R} + nR_{o} - (n + k)R_{i}$$
(2.8)

where: R<sub>i</sub> = the indoor radon concentration
R<sub>o</sub> = the outdoor radon concentration
S<sub>R</sub> = the radon source strength
n = the air change rate
k = the net removal rate by means other than
infiltration/ie, the decay constant

Usually, n >> k and under steady state conditions the solution becomes:[43]

$$S_{R} + nR_{0} = nR_{i}$$
 (2.9)

For the most part, one is concerned with the concentration of radon daughters (the short lived decay products of radon). Finding their concentration using (2.8) is a more complex problem. Normally, one assumes an equilibrium factor (ratio of daughters present to that which would be present if a balance between daughter formation and the radioactive decay of radon was achieved.) Studies have shown this equilibrium factor to range





This figure shows that radon source strength is a function of the air change rate. This is to be expected as soil is the major contributor to indoor radon levels and the mechanism of radon entry from the soil is infiltration.

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TABLE 7.

Data from a 101 House Survey of Radon Concentration and Air-Exchange Rate 43

Sample	Radon Concentration (pCi/L) GM <sup>a</sup>	Air Change Rate (h <sup>-1</sup> ) GM	Source (p(	e Magnitude Ci/L·h) GM <sup>a</sup>
16 US Energy Efficient Homes	2.6	0.23		0.61
29 San Francisco Homes	0.4	0.28		0.10
56 Maryland Homes	1.8	0.35		0.62

a: 
$$GM = exp \left[ \frac{1}{N} \sum_{i=1}^{N} ln X_{i} \right]$$

b: In six of the 56 homes, the radon concentration was assumed to be 0.1 pCi/L since the sensitivity of the equipment did not extend below 0.4 pCi/L.

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between 0.3 and 0.7.[80] Because of this it is difficult to determine the radon daughter level accurately.

2.6 The Characterization of Problem Homes

There are really just two causes of high indoor contaminant concentrations: high generation rates or low air change rates. If either or both are present then a potential health hazard exists.

High pollutant generation rates may exist because of furniture, appliances or human activities. Formaldehyde gas, for example, is emitted from particle board, plywood, UFFI and tobacco products. If plywood furniture is brought into a UFFI home the contaminant concentration may become high enough to cause health problems. If, in addition, the occupants smoke there may be dangerously high formaldehyde levels, even though the infiltration rate may be normal. The same is true for nitrogen dioxide.  $NO_2$  may be present in dangerous amounts in homes with gas appliances.[26] Other homes, generally, do not exhibit problems with  $NO_2$ . Similarly, other contaminants may only be present in dangerous amounts after human activities (cooking, smoking). In each such case the high indoor pollutant concentrations are a result of high generation rates only. The infiltration rate could possibly indicate a loose structure.

Low infiltration rates are a problem in electrically heated homes. They are generally more air tight than alternatively heated ones. [68] The generation rate of the pollutant may be low but, because of the low infiltration rate, the indoor pollutant concentration may be high.

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Because of the variation of the causes of indoor air quality problems there is no specific home which typifies the problem. However, table 8 lists some of the characteristics of problem homes encountered in this report. It is by no means a complete characterization, nor does the order of the characteristics imply anything. It is merely a statement of factors which may result in low infiltration rates or high pollutant generation rates. 2.7 Air Change Rate and Indoor Carbon Dioxide

To illustrate the relationship between infiltration and indoor air quality let us consider the buildup of carbon dioxide in a 100  $m^3$  room. Let us assume that the CO<sub>2</sub> generated comes only from breathing (ie. no smokers, plants, fireplaces, etc.) and that the outdoor concentration is  $54 \text{ mg/m}^3$ . Using equation (2.7) the steady state concentration in the room can be found. (see Appendix A for the details of this calculation) The results can be shown graphically in figure 4. As room occupancy increases so does the carbon dioxide source strength. Under low occupancy a 100 cubic metre room will rarely have a carbon dioxide level higher than the 4500 mg/m<sup>3</sup> recommended by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE). As occupancy increases greater air change rates are required to keep the steady state carbon dioxide concentration below the ASHRAE limit (in the absence of any other means of ventilation). Should prolonged exposure occur, the occupants may suffer from headaches, dizziness or other symptoms discussed more fully in Chapter 3.

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Characteristics of Problem Homes

Electric Heating

Gas Stoves (or other combustion appliances) Urea-formaldehyde foam insulation

Smoking

Particleboard or plywood furniture

High occupancy

Proximity to natural uranium deposits



FIGURE 4. STEADY STATE CO<sub>2</sub> CONCENTRATION IN A 100 m<sup>3</sup> ROOM AS A FUNCTION OF OCCUPANCY AND AIR CHANGE RATE

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Figure 4 is based on equation (2.7) The calculations behind it are given in Appendix A.
Obviously, steady state levels imply the passage of time. For any given source strength, the time it takes to exceed the ASHRAE limit decreases as the air change rate decreases. This relationship is shown in figure 5.

These figures indicate that there may be some cause for concern. After relatively short times, carbon dioxide levels may rise beyond acceptable limits. Although the effects of carbon dioxide are not severe when compared to other pollutants, this is is still an important fact. This analysis can be equally well applied to formaldehyde, particulates and any other indoor pollutants. However, calculation of the air change rate required to keep pollutant concentrations below acceptable limits is relatively simple. An example can be found in Appendix A.

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FIGURE 5 TIME REQUIRED FOR THE  $CO_2$  CONCENTRATION IN A 100 m<sup>3</sup> ROOM TO EXCEED 4.5 g/m<sup>3</sup> AS A FUNCTION OF OCCUPANCY AND AIR CHANGE RATE

Figure 5 is based on equation (2.6). The calculations behind it are given in Appendix A.

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3.0 TYPICAL POLLUTANT LEVELS AND THEIR ASSOCIATED HEALTH EFFECTS

There is no doubt that man is exposed to a variety of indoor pollutants. This exposure is quite important as up to 90 % of man's time is spent indoors.[24] Studies have shown that exposure to indoor pollutants may lead to health problems.[51, 39,42] Yet few standards exist for continuous pollutant exposure. For the most part, quoted standards are workplace limits. It is obvious that these cannot be applied to homes. One must bear in mind that workplace limits are chosen so that no harm comes to the majority of the employees. In general, these workers represent the hardier element of society. In contrast, residences typically hold the more susceptible individuals, ie, infants, the sick and the elderly. Furthermore, in theory, workers have made a conscious decision to work in a hazardous environment, the public, however, has no such choice. With this in mind, the standard rule of thumb that has been adopted is to use 1/10 of the industrial levels as a residential standard.[6,75] However, this may vary between 1/5 and 1/20.[70]

In most cases, infiltration provides enough makeup air to keep indoor pollutants at safe levels. However, high pollutant generation rates and a shift to more air tight housing has led to potential health hazards from exposure to indoor pollutants. Recently, two indoor air contaminants have become the focus of public scrutiny. They are formaldehyde gas and sidestream tobacco smoke. To a lesser degree, the health hazard of radon gas has also come to the forefront.

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In this chapter, the health effects of various indoor pollutants will be discussed. Canadian and American standards will be quoted and compared. It must be emphasized, however, that for the most part these standards will be workplace limits. 3.1 Respiration

Before the health effects of various contaminants can be considered a brief review of respiration is necessary. This section will give an outline of the physiology of respiration and gas transport. Also, terms used throughout this section will be defined.

#### 3.1.1 External and Internal Respiration

The respiratory system can be divided into three components: the nasopharyngeal compartment (upper respiratory tract); the tracheobronchial tract; and the pulmonary compartment (lower respiratory tract). The upper respiratory tract includes the anterior nasal nares, the anterior and posterior pharynx, the larynx and the epiglottis. The tracheobronchial tract comprises the entire bronchial tree. Both the nasopharyngeal and tracheobronchial tract are covered in a moist ciliated epithelium. In these two compartments no gas exchange occurs, ie. there is no transfer of oxygen and carbon dioxide. Hence they are known as the respiratory dead space.

Gas exchange only occurs in the pulmonary compartment which is comprised of respiratory bronchioles, alveolar ducts, atria, alveoli and alveolar sacs. The entire space is unciliated and is covered with a moist single layer epithelium. Gas exchange

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occurs primarily in the alveolar sacs. The entire respiratory system is shown in figure 6.

Respiration is made up of two processes: external respiration, the absorption of  $0_2$  and the removal of carbon dioxide from the body as a whole; and internal respiration, which is the gaseous exchange between the cells and the circulating blood.

The process of external respiration is rather simple. Air is inhaled and passes through the nasal passages where it is warmed and takes on water vapour. It is also filtered to a degree with the larger particulates (1-100 µm) being retained in the cilia and mucous.[39] The air then travels through the bronchioles into the respiratory bronchioles, alveolar ducts and into the alveoli. The alveoli are surrounded by capillaries and, at this point, internal respiration begins. Oxygen and carbon dioxide diffuse across the alveolar-capillary barrier (shown schematically in figure 7) with oxygen passing towards the blood and CO<sub>2</sub> leaving it. Since the effectiveness of the diffusion process is dependent on the amount of surface area exposed to the outside air the alveolar sacs are folded in order to maximize surface area. Ganong estimates the total area of contact between the capillaries and the alveolar walls to be 90 sq. m. in both Lungs.[19]

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- 34 -



FIGURE

6

The Human Respiratory System 39



FIGURE 7

Diffusion of Carbon Dioxide and Oxygen Across the Alveolar-Capillary Barrier 19 3.1.2 Oxygen Transport

Haemoglobin (Hb) is a protein that can bind reversibly with oxygen. The reaction is an oxygenation, not an oxidation, as the iron present in Hb remains in its ferrous state. The chemical equations for the formation of oxyhaemoglobin may be written:[19]

 $Hb_{4} + 0_{2} \longleftrightarrow Hb_{4}0_{2}$  $Hb_{4}0_{2} + 0_{2} \longleftrightarrow Hb_{4}0_{4}$  $Hb_{4}0_{4} + 0_{2} \longleftrightarrow Hb_{4}0_{6}$  $Hb_{4}0_{6} + 0_{2} \longleftrightarrow Hb_{4}0_{8}$ 

The reaction is rapid taking less than 0.01 seconds.[19] The deoxygenation is also very rapid. As the  $Hb_40_8$  travels through the body it becomes  $Hb_40_8$  Hb\_40\_4 and  $Hb_40_2$  as the oxygen is removed from the blood. The rate at which it is removed depends on the activity of the tissues through which it passes. During periods of high tissue activity (ie. exercise) larger amounts of oxygen are taken from the blood. In order for the entire body to get enough oxygen this is compensated for by increased heart and breathing rates. During lower periods of activity the breathing and heart rates are comparatively lower.

3.1.3 Carbon Dioxide Transport

The solubility of  $CO_2$  in blood is about 20 times that of  $O_2$  so that in a simple solution there is considerably more  $CO_2$  than  $O_2$  [19]. The  $CO_2$  that diffuses into red blood cells is hydrated to  $H_2CO_3$  which further dissociates into H+ and  $HCO_3$ -. The H+ is buffered principally by haemoglobin while  $HCO_3$ - diffuses into the

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plasma. Some of the  $CO_2$  in the red cells reacts with amino acids (mostly Hb) forming carbino compounds. Under the action of both plasma and red blood cells the  $CO_2$  emitted from tissue throughout the body is transported back to the lungs.

3.2 Typical Indoor Pollutant Levels and Their Health Effects Pollutants may be divided into four categories according to their health effects. These are: carcinogens, anoxics, irritants and odours. Carcinogens are cancer causing agents such as radon and Andersen et al. advocate the no-threshold tobacco smoke. theory, suggesting that there is no threshold below which a carcinogen will not cause a cancer.[1] However the no-threshold theory is disputed by Cohen who contends: "there is certainly no evidence supporting it at low doses."[11] It is largely a question of risk. What may exist is a threshold below which the risk of contracting cancer is acceptable. Biology points to the fact that cancer can be theoretically induced at low concentrations on a cellular level.[31] Thus, the best available control technology should be used but it should be kept in mind that the risk of getting cancer may be sufficiently low at a higher level.

Anoxics interfere with the process of gas exchange. Typically, they combine with haemoglobin (Hb) to produce a compound that will not transport oxygen. Two examples of anoxics are carbon monoxide and nitrogen dioxide.

Irritants are defined as substances producing irritation of the mucous membranes of the eyes and airways or that irritate the skin. An example of an irritant is formaldehyde. Exposure to

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irritants should be kept at minimal levels, although thresholds do exist below which no health effects will be felt.[1]

The final category is odours. They also should be minimized although, in most cases, no adverse effects arise from exposure to common household odours.[42]

#### 3.2.1 Carbon Monoxide

Carbon monoxide (CO) is probably the most important gaseous pollutant. It arises from the incomplete combustion of carbon materials. It is odourless, colourless and does not produce serious symptoms until actual poisoning occurs. Hence it is difficult to tell if indoor levels are too high until the symptoms of overexposure are felt. In Canada, 10 people die and 100 receive in-patient treatment each year due to CO poisoning attributed to the incomplete combustion of domestic fuel.[61]

CO may form in poorly tuned heaters, in gas ranges and stoves, and in garages. In arenas, ice cleaning equipment may lead to dangerous indoor levels. There have been cases of residential CO poisoning due to insufficient infiltration and fireplace use.[61] The operation of a fuel burning appliance removes air from the home which may result in negative indoor pressure which can, potentially, reverse the flow of gases out the chimney.[61] In most cases, however, there is not much danger from indoor CO.

Indoor CO levels depend on indoor sources such as gas appliances, fireplaces and smoking. Average indoor levels range between 0.5 and 5 ppm.  $(0.6-6 \text{ mg/m}^3)$ [42,59] The garage is usually

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the main source although rooms with smokers have reached peaks of 40 - 80 ppm.[39]

CO levels also depend on the time of day. Higher indoor concentration can be expected during cooking periods and during times of high automobile traffic. Of course, this also depends on house tightness. In loose homes higher CO levels can be expected when outdoor concentrations are high, ie. rush hour. Low air change rates tend to keep indoor generated CO indoors. This is shown in figure 8.

Carbon monoxide poisoning is a result of pulmonary absorption. The toxic effect of CO is due to its affinity for haemoglobin (Hb), CO combines much more readily with Hb than does oxygen. Therefore, quite low concentrations of CO will displace large amounts of oxygen from combination with Hb. The result of the combination of CO and Hb is COHb, carboxyhaemoglobin. Its structure makes it impossible for the red blood cells to carry out their oxygen transporting function.

A useful parameter in the evaluation of the severity of exposure is the blood saturation percentage of COHb. The degree of saturation is a function of time and the CO concentration. This is best shown in figure 9. Some effects of CO exposure are listed in table 9.

Since the reaction between CO and Hb is an equilibrium reaction, when the victim is removed from the poisoned atmosphere, the chemical process is reversed. However, survivors of high exposures may suffer from various neurological changes that can persist for years. Some of these include severe pain of

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FIGURE 8 Diurnal Variation of Carbon Monoxide as a Function of Ventilation Rate 39





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# TABLE 9 EFFECTS OF CAREON MONOXIDE EXPOSURE 29

Blood Saturation Level (% COHb)	Symptoms
0 - 10	None.
10 - 20	Tightness across forehead, slight headache, dilation of cutaneous blood vessels.
20 - 30	Headache and throbbing in temples.
30 - 40	Severe headache, weakness, dizziness, dimness of vision, vomiting, collapse.
40 - 50	Collapse more probable, increased pulse and respiration.
50 - 60	Increased pulse and respiration, coma, convulsions.
60 - 70	Coma, convulsions, depressed heart action and respiration.
70 - 80	Respiratory failure and death.

the lower extremities, disturbance of speech, complete or partial loss of vision or hearing, loss of taste or smell, headaches and manic or depressive psychoses.[59]

Various standards have been put forward in an effort to control carbon monoxide exposure. Some are listed in table 10. 3.2.2 Carbon Dioxide

Carbon dioxide  $(CO_2)$  is produced by most living matter. In man it is an essential part of respiration. Air (oxygen) is inhaled and  $CO_2$  exhaled. At rest, 15 L/h of  $CO_2$  are produced, during moderate activity this increases to 45 L/h.[70] A normal atmosphere contains 0.03 % (vol)  $CO_2$ ; exhaled air is about 5.6 % (vol)  $CO_2$ .[39]

Indoor  $CO_2$  concentrations are a good indicator of ventilation need. Typical indoor levels range from 50 ppm (90 mg/m<sup>3</sup>) to 1200 ppm (2160 mg/m<sup>3</sup>).[39] A study done in a San Francisco office showed the effect of occupancy on indoor  $CO_2$  levels. The results are shown in figure 10. After 9 a.m. the  $CO_2$  concentration began to increase dramatically, after 4 p.m. the concentration dropped dramatically. This can be directly attributed to occupancy as typical working hours are between 8 and 5. At peak times the concentration was approximately 0.15 % (vol).

The effects of carbon dioxide poisoning can be as simple as an increase in the breathing rate (in order to exhale  $CO_2$  at the rate it is produced) or as complicated as headaches and narcosis (stupor and potentially unconsciousness).  $CO_2$  is considered to be a simple asphyxiant. It causes symptoms from lack of oxygen rather than its own high concentration. The first physical signs

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TABLE 10

Various Standards for Carbon Monoxide 59

Canadian Ambient Air Quality Standards

	Desireable Range	Acceptable Range
	(mg/m <sup>3</sup> )	(mg/m <sup>3</sup> )
Average over 8 hours	0-6	6-15
Average over 1 hour	0-15	15-35

United States Standards	(ppm)	(mg/m <sup>3</sup> )
Average 8 hours standard for ambient air	9	10
Average 1 hour standard for ambient air	35	40

a = these values may only be exceeded once per year



FIGURE 10 Diurnal Concentration of Carbon Dioxide in a San Francisco Office Building 39

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of anoxia are rapid breathing and heart rates.[64] As CO2levels rise further symptoms include dizziness, headaches, nausea, sweating, unconsciousness and death.[30,64] Figure 11 shows human tolerance to CO2

There have been documented cases of homeowners complaining of headaches which were found to have been induced by high indoor  $CO_2$  levels. Stricker writes of an electrically heated home which was found to be extremely airtight (ie. the leakage coefficient was 2.5 E-4 m<sup>-1</sup>). Its occupants suffered from headaches that were traced to the buildup of  $CO_2$  in their bedrooms as they slept.[64] Upon sampling the air in the master bedroom the  $CO_2$  concentration was found to be 0.6 % (vol).[64]

There is no Canadian standard for indoor  $CO_2$  concentration.[59] The Occupational Safety and Health Administration (OSHA) of the United States proposes an 8 hour occupational exposure limit of 9 g/m<sup>3</sup>. One of the few indoor standards for non-workplace exposure is put forth by the American Society of Heating. Refrigerating and Air Conditioning Engineers (ASHRAE) who propose a limit of 4.5 g/m<sup>3</sup>.[3]

3.2.3 Nitrogen Oxides

There are seven oxides of nitrogen known to exist in ambient air.[62] Of these, only nitric oxide (NO) and nitrogen dioxide (NO<sub>2</sub>) are thought to affect human health. According to Stern, however, there is no data showing NO to be a health hazard.[59] However, NO quickly oxidizes into NO<sub>2</sub> which is known to cause adverse health effects.[20,39,42,59]

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FIGURE 11 Human Tolerance to Carbon Dioxide Exposure 39

Nitrogen oxides occur both naturally and as a result of action. NO is produced by bacterial action, especially during rainy periods.[59] Outdoor combustion sources (ie. cars, industry) also contribute  $NO_X$  to the atmosphere. Indoors, nitrogen oxides arise principally from the emissions of gas appliances and heaters.[42] Figure 12 gives a comparison of  $NO_2$  levels in all electric homes versus homes with unvented gas appliances. Other indoor sources include smoking and automobile exhaust from attached garages.[59]

It has been estimated that 48 % of U.S. homes use gas for cooking.[51] It has also been found that normal stove operation resulted in concentrations that in a sample of these homes/laveraged over 100 µg/m<sup>3</sup> over a two week period. [42] Hollowell et al. found that without external ventilation, gas stove operation results in NO<sub>2</sub> concentrations above 250 ppb.[26] This is shown in figure 13. Both of the above concentrations may lead to health problems.

Nitric oxides are absorbed by way of the lungs. Their effects are felt principally on the respiratory tract and on haemoglobin. [76] When transformed across the lung-blood barrier,  $NO_2$  produces an effect similar to CO poisoning, it interferes with the oxygen carrying capability of the blood.  $NO_2$ combines with haemoglobin to produce methaemoglobin. As with CO poisoning the results are the symptoms of asphyxia.[42]

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Nitrogen dioxide has been associated with respiratory illness in children. A study in England reported that 2554 children from homes with natural gas appliances had a higher incidence of respiratory illness than did 3204 children from

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FIGURE 12 Nitrogen Dioxide Concentrations in All Electric and Homes with Unvented Gas Appliances. 41

Figure a) shows the diurnal variation of NO<sub>2</sub> levels and the corresponding hourly NO<sub>2</sub> concentrations in an all electric residence. Figure b) shows this same relationship for a home with unvented gas appliances.



#### FIGURE 13

### Nitrogen Dioxide Concentrations as Functions of Air Change Rates<sup>42</sup>

The nitrogen dioxide concentrations were measured in 27 cubic meter (950 cubic feet) rooms with a gas oven operated for one hour. Only at 7.0 air changes per hour (ach) was the indoor air quality standard of 9 mg not exceeded.

 $m^{3}$ 

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homes with electric appliances. The investigators concluded that elevated levels of NO<sub>2</sub> might have caused this increased incidence.[26] It has been further speculated that the result of this exposure in children could lead to an increased chance of rapid decline in pulmonary function in adult life.[51]

The effects of NO<sub>2</sub> exposure on the lungs tend to show themselves many hours after exposure. Nitrogen dioxide is an irritant of the mucous membranes, especially those of the trachea and bronchi. Immediate symptoms of exposure to a high concentration include burning, choking sensation, intense thirst, vomiting and coughing (often with the expectoration of a bloody sputum).[76] A summary of the effects of NO<sub>2</sub> on man is given in table 11.

Of course, the higher concentrations will probably not be encountered in residences. Perhaps a more pertinent result is put forward by Stern.[62] He quotes a study in which 5 subjects (21 - 40 years of age) were exposed to 5 ppm of NO<sub>2</sub> for ten minutes. The result was increased airway resistance 10 minutes after exposure; another increase in resistance 20 minutes after exposure; and a marked increase in resistance 30 minutes after cessation of exposure. Expiratory resistance increased 77 % (average) and inspiratory resistance by 92 %.[62]

Various standards have been put forward to control NO<sub>2</sub> exposure. Some are given in table 12.

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TABLE 11

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Effects of Nitrogen Dioxide Exposure on Humans 42

	Nitroger Concen	n Dioxide tration	
Effect	$mg/m^3$	ppm	Time to Effect
Odour threshold	0.23	0.12	Immediate
Increased airway resistance	1.3-3.8	0.7-2.0	20 minutes <sup>a</sup>
	7.5-9.4	4.0-5.0	40 minutes <sup>b</sup>
	9.4	5.0	15 minutes
	11.3-75.2	6.0-40.0	5 minutes
Decreased pulmonary diffusing capacity	7.4-9.4	4.5-5.0	15 minutes
Bronchitis, Broncho- pneumonia	47	25	6-8 weeks
Bronchitis, Focal pneumonia	94	50	6-8 weeks <sup>C</sup>
Bronchitis fibrosa obliterans (fatal)	28 <b>2</b>	150	3-5 weeks <sup>C</sup>
Bronchopneumonia (fatal)	564	300	2-10 weeks <sup>C</sup>
Acute pulmonary edema (fatal)	940	500	within 48 hours <sup>C</sup>

a: exposure lasted 10 minutes. Effect on flow resistance was observed. 10 minutes after termination of exposure.

b: exposure lasted 10 minutes. Maximal effect on flow resistance was observed after 30 minutes.

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c: time between exposure and termination of effect.

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TABLE 12

Various Standards for Nitrogen Dioxide 59

### Canadian Ambient Air Quality Standards

	Desireable Range (ppb)	Acceptable Range (ppb)
Average over 1 hour		0-220
Average over 24 hours	_	0-110
Annual arithmetic mean	0-32	
Ontario		
	limi (ppb	t )
one hour ambient air	200	
24 hour ambient air	100	
United States Standards		
	ppm	
8 hour time weighted average (permissible exposure limit	5	
U.S. ambient air quality star (annual arithmetic mean)	ndards 0.05	5

<u>NOTE:</u> 100  $\mu g/m^3 = 55 \text{ ppb}$ 

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3.2.4 Radon and Radon Progeny

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Radon gas is part of the uranium-238 decay chain, shown in figure 14. It is inert and is the first radioactive decay product of radium-226. It is usually present in trace amounts in residences. [67] In Ontario, high indoor radon concentrations have been found in Bancroft, Port Hope and Elliot Lake.[67]

Radium=226 has a half-life of 1600 years and is present in rock and soil and, therefore, in masonry building materials. Because of its lengthy half-life, once there is radium present in building material the result is a source of radon for the life of the building. Studies have shown that stone and concrete homes generally have higher radon levels than do wood homes.[1,33] This is shown in table 13.

Stone and rock homes may not be the only ones to have problems. Radon is water-soluble and can enter through a building's water system (especially if the water is from springs or wells). Furthermore, as it is a gas, it can diffuse through soil and building material to emerge inside a building. In fact, Nazaroff et al. suggest that soil is the major source of radon in a significant portion of U.S. homes.[43]

The health hazard associated with radon is not due to the gas itself but, rather, its progeny. The major hazards are associated with polonium-218, lead-214, bismuth-214 and polonium-214 (RaA, RaB, RaC and RaC' respectively). These four daughters have a particularly short half-life and, hence, are more active than other daughters. Also, with the exception of RaB, they are all alpha emitters and, therefore, constitute a

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FIGURE 14 DECAY CHAIN OF URANIUM-238 TO RADOM-222 TO LEAD-206 42

# TABLE 13

### Radon Concentration and Corresponding Ventilation Rate in Modern Swedish Homes **33**

					Radon Concentration		
	Building Construction					pCi/L	
Type of House	Material	Air Change/hr			min	av	max
Multifamilv Apartment	Concrete	0.3	0.5		1	3	12
•	Sand-based concrete	0.3	0.5		1	2	3
	Shale-based concrete	0.4	0.8		2	4	10
Single-family dwelling	Brick face; wood frame;						
	rockwool insulation	0.4	0.7	<u>De</u>	0.5	1	3
	Wood construction; basement of shale-based concrete;						
	rockwool insulation	0.4	0.8		0.5	4	8
	Shale-based porous concrete	0.2	0.5		3	6	19
2	Sand stone; wood frame; rockwool insulation	0.1	0.4		5	9	12

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particular health hazard. The energy associated with their decay is given in table 14.

It is difficult to measure the concentrations of radon daughters in the air. However, as mentioned in Chapter 2, the radon concentration is indicative of the amounts of daughters present. Radon concentration is usually expressed in picocuries per litre (pCi/L) or nanocuries per cubic metre (nCi/m<sup>3</sup>). One curie is equivalent to 3.7E10 nuclear transformations per second. It, therefore, represents the rate at which the material emits charged particles (decays). (As an example, let us consider phosphorous-32, which is a pure beta emitter with a specific activity of 50 mCi/g.[14] Thus, unit mass will emit (50E-3) (3.7E10)=1.85E9 beta particles per second.)

One unit of exposure to radon's alpha energy is the working level (WL). One WL is any quantity of short-lived radon progeny that will result in 1.3E5 MeV of alpha energy per litre of air, as they decay to lead-210. Cumulative exposure is measured in terms of the working level month (WLM) which is defined as the the inhalation of an atmosphere of 1 WL for 170 hours.

The concentration of radium-226 present in soil and rock varies from location to location. Hence, so does the amount of indoor radon. Several studies have been done to determine indoor radon levels and the results have varied over three orders of magnitude. [23] This is shown in table 15. The high concentrations in Grand Junction and Saskatchewan can be attributed to high natural uranium concentrations.[23]

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Selected Elements in the Uranium Decay Chain  $^{33}$ 

	Half-Life	MeV	MeV	MeV
Nuclide	(Time)	Alpha Energy	Beta Energy	Gamma Energy
226 88 <sup>Ra</sup>	1622 years	4.60, 4.78		0.186
222 86 <sup>Em(rn)</sup>	3.825 days	5.486		0.51
218 84 <sup>Po(RaA)</sup>	3.05 minutes	5.998	0.33	0.186
218 85 <sup>At(RaA')</sup>	2 seconds	6.65	unknown	
218 86 <sup>Em(RaA'')</sup>	0.019 seconds	7.127		
214 <sub>Pb(RaB)</sub> 82	26.8 mirutes		0.65 0.71 0.98	0.295 0.352
<sup>214</sup> Bi(RaC) 83	19.7 minutes	5.45 5.51	1.0 1.51 3.25	0.609 1.120 1.764
<sup>214</sup> Po(RaC') 81	1.64 x 10 <sup>-4</sup> seconds	7.68		0.799
210 81 <sup>T1(RaC'')</sup>	1.32 minutes		1.2 1.9 2.3	0.296 0.795 1.310

- 57a -

TABLE 14 (Continued)

### Selected Elements in Uranium Decay Chain

Nuclide	Half-Life (Time)	MeV Alpha Energy	MeV Beta Energy	MeV Gamma Energy
<sup>210</sup> Pb(RaD)	19.3 years	3.72	0.017 0.016	0.0467
210 83 <sup>Bi(RaE)</sup>	5.00 days	4.65 4.69	1.17	
210 84 <sup>Po(RaF)</sup>	138.4 days	5.298		0.802
206 81 <sup>11(RaE")</sup>	4.19 minutes		1.57	
206 82 <sup>Pb(RaG)</sup>	Stable			

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TABLE 15

### Radon Concentrations in Various Buildings

		Radon Conce (pCi,	entration /L)
Location	Building	Indoor	Outdoor
Princeton, New Jersey <sup>b</sup>	11 homes	8.0 <sup>c</sup>	-
Houston, Texas <sup>a</sup>	house	0.5-2.0	0.3
Raleigh, North Carolina <sup>a</sup>	Physics Building	1.8-3.9	0.2
Polk and Hillsborough Counties, Florida	1,000 homes	0.02-10.5	-
Grand Junction, Colorado <sup>a</sup>	houses	7.8-290	0.1
Eastern Pennsylvania	36 homes	12.6 <sup>d</sup>	-
New York - New Jersey <sup>b</sup>	18 homes	2.0	-
Saskatchewan <sup>a</sup>	house	250	-
Denmark	house	5.0	
Sweden	apartment	6-18	-

a = from Kusuda ( 33 )
b = from Hernandez ( 23 )
c = average value; range was 1.0 - 25.0 pCi/L
d = average value for basement; range was 0.5 - 79.4 pCi/L
e = studies were done on reclaimed phosphate mining land

Generally, indoor radon levels are in the 0.1 - 30 nCi/m<sup>3</sup> range. [59] A survey of 9999 Canadian homes in 14 cities found that 64 % of the homes had radon concentrations of 0.1 WL or less.[59] Hollowell et al. studied 21 New York homes and found radon levels to vary between 0.2 and 3.0 nCi/m<sup>3</sup> with corresponding air change rates between 1.5 and 0.5 ach respectively.[26] Repace has estimated that new air tight housing may have double the indoor radon levels of current homes.[51]

As already mentioned, the health hazard associated with radon comes from four specific daughters. These four daughters easily attach themselves to airborne particulates which may be inhaled and retained in the lung. As the daughters decay further they emit an alpha dose to the lung which may result in lung cancer. [42] In addition, exposure to radon progeny has been linked to chromosomal deviations.[42]

Studies done on mine workers with ten years experience in an environment of 100 nCi/m<sup>3</sup> showed cancer in one in 1000 workers. [42] They also showed that the risk was greater in smoking workers than in non-smokers. This is a much higher concentration than that which the general public is exposed to but the results can be generalized to include the entire population. Studies in Maine found a correlation between radon concentration in well water and cancer mortality. The age adjusted cancer deaths increased with an increase in water radon concentration.[24] This is shown in figure 15. Other studies have shown higher cancer risks among residents of stone homes.[1] Repace estimates that an increment of 1.0 nCi/m<sup>3</sup> in radon exposure results in 25 cancer

- 59 -



FIGURE 15

# Lung Cancer Deaths as a Function of Radon Concentration in Water 24

The age adjusted lung cancer rates for males and females are presented versus water radon concentration in 16 counties in Maine. It was concluded that exposure to higher than average concentrations of radon leads to a higher risk of developing lung cancer.

deaths per million people.[51] Hess, et al. estimate that lifetime residence in homes of 0.02 WL results in 1000-3000 lung cancer deaths per 100,000 people.[24]

ASHRAE standard 62-81 recommends that annual indoor exposure not exceed 0.01 WL.[3] The International Commission on Radiological Protection has recommended that home radon levels not exceed 3 nCi/m<sup>3</sup> and the workplace limit not exceed 30 nCi/m<sup>3</sup> [42] United States guidelines suggest a maximum of 4 nCi/m<sup>3</sup> as does the Atomic Energy Control Board of Canada.[59]

### 3.2.5 Formaldehyde Gas

Formaldehyde (HCHO) is an inexpensive chemical that has gained popularity throughout the world. It is mainly used in the production of urea, phenolic, melamine and acetal resins which have a variety of uses.

Perhaps the most important of these resins is urea formaldehyde (UF). Recent controversy has surrounded the issue of formaldehyde gas emissions from urea formaldehyde foam insulation (UFFI). The use of UFFI was banned by Health and Welfare Canada in late 1980. UFFI is a mixture of UF resin and a foaming agent or surfactant, and, as a foam, is convenient to use. The installation of UFFI entails making small holes in the walls and injecting the foam, which hardens in a few days. Unfortunately, if the foam is mixed improperly or exposed to high heat or humidity, formaldehyde gas is emitted.[10] Furthermore, several types of fungus have been associated with UFFI. Their infiltration into a building may also cause health problems. [7]

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UF resins are also used as bonding agents, as are phenol-formaldehyde and melamine-formaldehyde resins. Their bonding properties make them ideal for the manufacture of plywood and particleboard. Plywood is, simply, several thin sheets of wood glued together with a resin. The manufacture of particleboard entails saturating wood shavings with a resin and pressing the mixture into shape. Generally, UF resins are used because of their lower cost. [42] Unfortunately, they seem to be the worst from the emissions standpoint. In addition to containing free formaldehyde, they also emit formaldehyde gas when subjected to high temperature or humidity.[10] Typical emission rates of some UF products are listed in table 16.

Typical outdoor formaldehyde concentrations are in the order of 0.04 mg/m<sup>3</sup>.[67] Indoor levels may range from 0.02 to 1.2 mg/m<sup>3</sup> [42] Gupta et al. quote concentrations as high as 3.7 mg/m<sup>3</sup>.[22] Some typical indoor formaldehyde levels in non-occupational indoor environments are shown in table 17. Figure 16 shows the frequency of occurrence of formaldehyde and total aliphatic aldehyde concentrations in an energy efficient home of 0.2 ach.

The health effects of formaldehyde manifest themselves after inhalation, ingestion or contact. It is difficult to relate specific health effects to particular concentrations as sensitivity varies from person to person. Some people are very sensitive (asthmatics may suffer more severe symptoms as a result of continued or repeated exposure.[10,22]) and others seem not to be affected at all. Furthermore, repeated or long term exposure to formaldehyde gas may increase an individuals sensitivity.[7]

### TABLE 16

Formaldchyde Emission from Selected Products 22

14

<b>A</b>	Emission Pote	1.
Product	$(\mu_g/g/day)$	
Particleboard	0.4 - 8.1	
Plywood	0.32- 9.2	
Panelling	0.84- 2.1	
Clothing	0.2 - 4.9	
Paper Products	0.03- 0.36	
Carpet	up to 0.06	

- 63 -
| TABLE 17                    |                  |              |
|-----------------------------|------------------|--------------|
| Formaldehyd                 | e Measureme      | nts in       |
| • Nonoccupational           | Indoor Env       | ironments 42 |
|                             |                  |              |
|                             | Concentr         | ation        |
|                             | range            | mean         |
| Sampling Site               | (ppm             | )            |
|                             |                  |              |
| Danish residences           | 1.8 <sup>a</sup> | -            |
| Netherlands residences      |                  |              |
| built without formaldehyde  | a                |              |
| releasing materials         | 0.08             | 0.03         |
| Residences in Denmark,      |                  |              |
| Netherlands and Federal     | a za             | 0.4          |
| Republic of Germany         | 2.3              | 0.4          |
| Two mobile homes in         |                  |              |
| Pittsburgh, Pa.             | 0.1-0.8          | 0.36         |
| Sample residence in         | а                |              |
| Pittsburgh, Pa.             | 0.5              | 0.15         |
| Mobile homes registering    |                  |              |
| complaints in Minnesota     | 0 -3.0           | 0.4          |
| Mobile homes registering    |                  |              |
| complaints in Wisconsin     | 0.2-4.2          | 0.88         |
| Public buildings and energy |                  |              |
| homes (occupied and         |                  |              |
| unoccupied)                 | 0 -0.21          |              |
|                             | 0 -0.23          |              |

a: peak value

.



FIGURE

16

Indoor and Outdoor Formaldehyde (HCHO) and Other Aldehyde Concentrations at a Single-Family Home in Maryland <sup>42</sup>

The histogram shows the frequency of occurrence of formaldehyde and total aliphatic aldehydes at an energy efficient home with 0.2 ach.

Thus, on any given day, exposure to the same concentration that provoked no previous reaction may result in severe symptoms.[10] Table 18 shows the variability and overlap of responses in subjects.

Repeated exposure in residential settings has resulted in prolonged eye, nose and throat irritation.[22] Studies have reported that the swelling of mucous membranes begins in the range of 0.05 - 0.1 ppm. [42] The eye is very sensitive to formaldehyde, often responding to a concentration as low as 0.01 ppm (when formaldehyde is mixed with other pollutants).[42] A more comprehensive treatment on the effects of formaldehyde on the eyes is given in table 19.

Another effect of formaldehyde exposure is upper airway irritation (dry throat, tingling in the nose) which may occur upon exposure to concentrations between 1 and 11 ppm, However, no effect has also been shown in persons exposed to 16 - 30 ppm.[42]

Lower airway irritation due to formaldehyde is characterized by coughing, tightness in the chest and wheezing. This may occur after exposure in the 5 - 30 ppm range.[42] Higher exposures of between 50 and 100 ppm result in pulmonary edema, pneumonitis and death.[42]

It has been documented that asthmatics are more vulnerable to formaldehyde, although the concentrations at which attacks occur vary.[7] This is an important fact as it has been estimated that 10 - 20 % of the U.S. population have hypersensitive airways. [51] Formaldehyde has also been known to cause asthma although

- 66 -

# TABLE 18

## Health Effects of Formaldehyde 42

Effects	Concentration (ppm)
None reported	0.0 - 0.05
Neurophysical effects	0.05 - 1.5
Odour threshold	0.05 - 1.0
Eye irritation	0.01 - 2.0*
Upper airway irritation	0.1 - 25
Lower airway and pulmonary effects	5.0 - 30
Pulmonary edema, inflamation, pneumonia	50 - 100
Death	100+

\* The low concentration was observed in the presence of other pollutants that may have been acting synergistically.

19 e	Eye Irritation Effects of Formaldehyde <b>42</b>	
Formaldchyde Concentration (ppm)	Duration of Exposure	Effect
	Chamber - single:	
0.23 - 3.2	20-35 minutes; gradually increasing	increase in blink rate; irritation
13.8 20	30 minutes less than 1 minute	irritation (and nose irritation) discomfort and lacrimation
	Chamber - repeated:	
0.25 0.42 0.83 - 1.6	5 hr/day for 4 days 5 hr/day for 4 days 5 hr/day for 4 days	<pre>19% "slight discomfort" 31% "slight discomfort" 94% "slight discomfort and    conjuctival irritation"</pre>
	<u>Occupational</u>	
$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	daily daily daily daily daily	stinging and burning intense irritation and itching prickling and tearing tearing irritation, lacrimation and discomfort in 30 minutes
	Indoor Residential	
0.23 - 2.5 0.02 - 4.15 0.067 - 4.82	daily daily daily	irritation irritation tearing

- 68 -

TABLE 19

- -

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91

1.83

1

the mechanism of the asthma syndrome is unknown.[42]

The health effects of formaldehyde are not only confined to the eyes and respiratory system. Contact with the skin causes a variety of symptoms including irritation and allergic contact dermititis.[42] Allergic contact dermititis is relatively common in North America.[42] Repeated exposure results in increased vulnerability. In one study, the lowest formaldehyde concentration that produced a response in a sensitized individual was 0.2 mg/L of water.[22] Sensitized people may often have allergic reactions to plastics, glues, paper, fabrics and photographic materials.[42]

The ingestion of formaldehyde has been reported to cause headache, upper gastrointestinal pain, allergic reactions and systemic damage. [42]. Ingestion occurs from the swallowing of aqueous solutions of formaldehyde. The more serious symptoms include loss of consciousness, vascular collapse, pneumonia, bleeding in the kidneys and spontaneous abortion. As little as 30 mL of formalin can cause death. (Formalin is a clear aqueous solution that is usually 40 % (vol.) formaldehyde with a small amount of methanol.)

Formaldehyde is also a suspected carcinogen. Studies have linked it with skin cancer, and cancers of the prostrate, brain and digestive system as well as leukemia. Health and Welfare Canada banned the use of UFFI in 1980 partially on the basis of its potential carcinogenicity.[59] However, Gupta et al. suggest that only the link with skin cancer is statistically significant.[22]

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The Canadian indoor air quality guideline with respect to formaldehyde gas is  $0.12 \text{ mg/m}^3(0.1 \text{ ppm})[59]$ . This level (chosen by Health and Welfare Canada) was based on the workplace limit of 2.4 mg/m<sup>3</sup>during a 40 hour week and incorporated a safety factor of 20 to "allow for the fact that households can include infants, young children, the old and the ill, and because the home environment may be occupied 24 hours per day."[59] This limit of 0.12 mg/m<sup>3</sup> is identical to the limit proposed by ASHRAE. [3] However, even these standards are of questionable value as there is no population threshold for formaldehyde's irritant effects. Persons with hypersensitive airways or other sensitive individuals may react to concentrations lower than those above.

#### 3.2.6 Particulates

Particulates are suspended solids and liquids. This includes dust, smoke, smog and fog. Under equilibrium conditions particulates are generally not stable in air. After sufficient time has elapsed, they tend to settle on floors and furniture. However indoor air disturbances can easily resuspend the particles.

Particulates have been defined as "any dispersed matter, solid or liquid, in which the aggregates are larger than single gas molecules but smaller than 0.5 mm."[39] Particles ranging between 0.1 and  $1.5 \mu \text{m}$  are referred to as respirable suspended particles (RSP) as opposed to the total suspended particles (TSP).

Particulates may be both organic and inorganic. Household dust may contain mites, viruses, bacteria, asbestos and sebum.[39] Highway dust is mostly inorganic, containing lead,

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copper, iron and other metals.[39]

The two major sources of indoor particulate matter are wind and tobacco smoke. Figure 17 shows the effect of smoking on RSP concentration. Studies have shown the range of RSP levels to vary between 90 - 1140  $\mu$ g/m<sup>3</sup> in rooms with smokers. This may be compared to levels between 20 - 60  $\mu$ g/m<sup>3</sup> in the absence of smoking.[51]. The average cigarette and pipe both emit 30 mg of RSP; cigars emit up to 68 mg of RSP.[39] Approximately 9 million tons of particulates are emitted from various sources each year.[39] Windborne particulates include road dust, pollen and pesticides. However, a 1 year study of U.S. homes found cigarettes to be the dominant source of RSP. Typical indoor levels are shown in table 20.

The health hazard of particulate matter depends on how deeply it is inhaled into the respiratory system, what fraction is retained and how well the body copes with the toxin.[39] Particulates between 0.5 and 5  $\mu$ m are usually retained deep into the lung.[39] Larger particles are usually trapped in the larynx or bronchial tubes. Smaller particles are usually exhaled. Some examples of particulate sizes are given in figure 18. Figure 19 shows the place of particulate retention as a function of particulate size.

Acute or chronic health effects can occur anywhere in the respiratory tract. Because of the varied composition of particulate matter one cannot attribute specific health affects to specific concentrations. Each of the components of the respiratory system are affected differently. However, one may

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17

Respirable Particle Concentrations as a Function of Smoker Density 51

In this study the areas where samples were taken included 10 restaurants, 3 cocktail lounges, three bingo games, two dinner-dance halls, one bowling alley, one sports arena, one hospital waiting room and one residence. The scatter in the data is due to the differences in effective ventilation rates.

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TABLE 20

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## Particulate Concentrations at Different U.S. Locations 39

	Average Particulate Concentration
Location	<u>(μg/m<sup>2</sup>)</u>
U.S. Average	32.0
Portage, Maine	19.6 <sup>a</sup>
St. Louis, Missouri	47.0 <sup>b</sup>
hospital intensive care units	30.0
homes:	
a) the influence of smoking	
no smokers	15.0
one smoker	35.0
more than one smoker	50.0
b) the influence of appliance t	ype
with electric kitchens	22.0
with gas heaters and stoves	24.0
	•.

a = lowest particulate concentration

b = highest particulate concentration



Particle size (micrometers)

FIGURE 18 Particle Sizes for Various Particulates 39





speculate what the effects are on each component.

In the upper respiratory tract soluble dust may cause an allergic reaction, damage the mucosa or paralyze the cilia.[39] Insoluble particulates are either transferred to the gastrointestinal tract through ingestion or are expelled in sputum.[39] In the tracheobronchial tract similar effects are encountered. However, the mucosa is more vulnerable and the damage may be more severe. Furthermore, the tracheobronchial tract may suffer local infection of bronchioconstriction.[39] The effects on the pulmonary tract are even more pronounced. Soluble particulates may damage the epithelium, constrict the peripheral respiratory unit or cause emphysema. Insoluble particles may react with local tissue, embed themselves within tissue, or migrate to the lymph nodes.[39]

Table 21 lists the Canadian Ambient Air Quality Standards for particulate matter. The United States standard is an annual geometric mean of 0.075  $mg/m_{\bullet}^{3}$ [39] The 24 hour standard is 0.26  $mg/m^{3}$  (not to be exceeded more than once per year).[59]

However, it has been asserted that TSP levels of  $0.1 \text{ mg/m}^3$  or less may be impossible unless large spaces are allotted to each occupant, air is filtered or smoking is prohibited.[84] 3.2.7 Tobacco Smoke

In 1978 54 million people smoked 615 billion cigarettes. The Canadian Lung Association has estimated that 35 % of the Canadian population smokes.[9] The distribution of smokers is shown, by age groups, in figure 20. All of these statistics point not only to a health hazard to the smokers themselves but

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TABLE 21

Various Standards for Particulate Matter 59

### Canadian Ambient Air Quality Standards

	Desireable Range (mg/m <sup>3</sup> )	Acceptable Range (mg/m <sup>3</sup> )
Average over 24 hours	-	0.0-0.12
Annual geometric mean	0-0.060	0.060-0.070

United States Standards

Average over 24 hours <sup>a</sup>	260 µg/m <sup>3</sup>
Annual geometric mean	$75 \ \mu g/m^3$

a = not to be exceeded more than once per year



FIGURE

20

Percentage of Regular Smokers In Population <sup>42</sup>

Each percentage represents the number of people that smoke in that age group. Data is for the United States but Canadian data should be similar. (1974-1975)

also to those exposed to sidestream smoke. These passive smokers are exposed to varying amounts of tobacco smoke depending on how often they come in contact with smokers. This contact may occur at work, in transit or in the home.

There is a distinct difference in the contaminant concentrations present in mainstream and sidestream smoke. Mainstream smoke has higher concentrations of pollutants but, sidestream smoke is produced during 96 % of the total cigarette burning time.[42] It, therefore, accounts for more of the pollutants present. This is indicated in table 22.

Cigarette smoking definitely increases the indoor concentrations of various pollutants. Some of these have been dealt with already ( carbon monoxide, formaldehyde gas, particulates ). However, it is necessary to further expand on the relationship between smoking and indoor air quality.

Figure 21 shows the buildup of CO in a 3000 cubic foot room with smokers as compared to the buildup with nonsmokers. Carbon monoxide levels can approach 35 ppm and controlled chamber experiments have reported concentrations greater than this.[42] A summary of some results concerning carbon monoxide and cigarette smoking is given in table 23.

The best indicator of cigarette smoke concentration is nicotine. A typical cigarette contains 2 mg of nicotine.[42] Although the threshold limit value of 500  $\mu$ g/m<sup>3</sup> is very seldom approached, studies have shown nicotine concentrations in cocktail lounges, waiting rooms, trains and buses to range between 1.0 and 10.3  $\mu$ g/m<sup>3</sup>.[42]

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TA	BLE	2	2
IA	DLL	~	*

### Composition of Mainstream and Sidestream Smoke <sup>42</sup>

	Concentra	ation	Detice
Chausatawistis	(mg/ciga)	Cident mont	Racio:
Characteristic	Mainstream	Sidestream	Sidestream to
of Compound	Smoke	Smoke	Mainstream Smoke
General Characteristi	cs:		
duration of smoke			
production (sec.)	20	550	27.5
tobacco burned	347	441	1.2
particles (no. per cigarette)	$1.05 \times 10^{12}$	$3.5 \times 10^{12}$	3.3
Selected Particles:			
Tar	20.8	44.1	2.1
	10.2 <sup>a</sup>	34.5 <sup>a</sup>	3.4
Nicotine	0.92	1.69	1.8
	0.46 <sup>a</sup>	1.27 <sup>a</sup>	2.8
Phenols (total)	.228	.603	2.6
Cadium	$1.25 \times 10^{-4}$	$4.5 \times 10^{-4}$	3.6
Selected Gases and Va	pours:		
water	7 5 <sup>b</sup>	298 <sup>C</sup>	39 7
carbon monoxide	18.3	86.3	4.7
carbon dioxide	63 5	79.5	1.3
nitric oxides	0.014	0.051	3.6
formaldehyde	-	1.44	-
ammonia	0.16	7.4	46.3
hydrogen cyanide	0.24	0.16	0.67
a: filtered cigarett	es		
b: 3.5 mg in particu	late phase; rest	: in vapour phase	

c: 3.5 mg in particulate phase; rest in vapour phase



#### FIGURE 21

Buildup of Carbon Monoxide Under Various Conditions of Ventilation and Smoking 42

Concentrations were calculated for a room of 3000 cubic feet with 25 smokers and 25 nonsmokers respectively. TLV is the threshold limit value for carbon monoxide. The amount of ventilation is given in cubic feet per minute (CFM)

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#### TABLE 23

Measurement of Indoor Concentrations of Carbon Monoxide due to Tobacco Smoke 42

		Carbon Monoxide Concentration		
Location	Ventilation	Smoking Section	Control Section	
general public				
places	-	3.5	2.0	
government				
offices	-	2.5	2.5	
restaurants		4.0	2.5	
tavern	6 ach	12.5	-	
tavern	1/2 ach	17.0	_	
arenas <sup>a</sup>	-	14.3	3.0	
room				
$(78.3 \text{ m}^3)^{D}$	· · ·	15.6	-	
automobile <sup>C</sup>	35km/hr	24.3	<u>~</u>	
	80km/hr <sup>a</sup>	12.1		
	30km/hr	15.7	<del>, 1</del>	
	3km/hr <sup>r</sup>	12.0		

a: It is not clear to what extent indoor combustion (i.e., operation of zambonis or other machinery) contributed to the concentration given.

...

- b: 3 smokers.
- c: 4 cigarettes burned.

d: no ventilation.

e: air jets open.

f: air jets open and blower on.

Other constituents of tobacco smoke have also been measured. Only acrolein was found to exceed threshold limit values. Some studies showed acrolein concentrations to range between 1 - 20 ppb in bars and restaurants.[42] This range is high enough to cause eye and nose irritation and unpleasant odour.

As already mentioned, another important constituent of tobacco smoke is particulate matter. RSP measurements were taken in 20 indoor environments where smoking was permitted. RSP levels varied between 86 and 697  $\mu$ g/m<sup>3</sup>.[42] Indoor concentrations of RSP often exceed 200  $\mu$ g/m<sup>3</sup> in homes with smokers. Figure 22 shows the variation of particulate matter with smoking and ventilation rate. In many cases the concentration exceeded 75  $\mu$ g/m<sup>3</sup>. Figure 23 shows the monthly mean RSP concentrations in homes with 0, 1 and 2 smokers compared with outdoor levels. Homes with no smokers have particulate concentrations similar to outdoor levels. Homes with smokers have substantially higher RSP levels.[42]

Numerous studies have been done to determine the health effects of smoking. Smoking causes cancer - there is a 77 % excess cancer mortality in smokers.[51] In addition, smokers have twice the normal pulmonary disease mortality.[39] Also a relationship has been found between maternal smoking and sudden infant death syndrome.[51]

It is not, however, the mainstream smoke that should be considered as part of the indoor air quality problem. Rather, sidestream smoke is the important component in the indoor

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FIGURE 22

Particulate Mass Concentration as a Function of Smoking and Ventilation Rates 35

The data represent the steady state levels attained when smoking a single brand of cigarette. Levels A - E represent the following:

A: secondary ambient air quality standard set to protect public welfare

B: primary ambient air quality standard set to protect public health

C: 24-hr level to protect public health, not to be exceeded more than once a year

D: 24-hr average concentration for air pollution emergency

E: 24-hr average concentration for significant harm.



# FIGURE 23. MONTHLY MEAN RSP CONCENTRATIONS 42

80 homes across 6 cities were studied: It is clear that smoking has a major effect on indoor particulate concentrations.

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environment. For the passive smoker, indoor air pollution from tobacco smoke may result in the inhalation of up to 27 low tar cigarettes.[51] Figure 24 shows how cigarette equivalents vary with ventilation rate and smoke level.

In several studies quoted by Meyer [39] 78% of nonsmokers and 35% of smokers were annoyed by nearby smoking. In a study by the Canadian Lung Association, 70% of 441 nonsmokers exposed to sidestream cigarette smoke experienced eye irritation, 30% headaches and nasal symptoms and 25% cough.[9] Effects on asthmatics are even more pronounced with a 20% reduction in pulmonary flow having been produced experimentally.[51]

Nonsmokers exposed to sidestream cigarette smoke have also been found to have higher incidences of cancer than nonsmokers in nonsmoking environments. Meyer reveals that lung cancer was 3.4 times as common in nonsmoking women married to smokers than it was in nonsmoking women in nonsmoking families\_[39] Japanese studies showed the incidence of lung cancer to be 2.08 times higher for nonsmokers married to smokers than it was for nonsmoking couples. Similarly, the rate of emphysema was 1.49 times higher than in nonsmoking couples.[39] The Canadian Lung Association has found that respiratory illnesses occur twice as often in young children with smoking parents than in children with nonsmoking parents.[9] This, however, conflicts with the findings of Lebowitz et al, who concluded that passive smoking does not affect the indicators of respiratory disease in children\_[36] Furthermore, the Tobacco Institute has stated that the adverse health effects from passive smoking have not been

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FIGURE 24 The Effects of Ventilation on Passive Smoking in an Office Setting 51

The amount of equivalent cigarettes smoked from inhaling the polluted office air is depicted as a function of ventilation rate. It was assumed that the occupancy was 10 persons per 1000 sq. ft.; that 1 of every 3 people smoked average tar cigarettes at a rate of 2 per hour; and that the effective ventilation rate and the supply ventilation rate were equivalent. conclusively documented.[39]

Therè are no standards for indoor tobacco smoke as it is really a mixture of various component gases and particulates. However, by examining the standards for the various components of tobacco smoke (carbon monoxide, carbon dioxide, formaldehyde gas, particulates, etc.) one can see how hazardous a particular atmosphere actually is.

#### 3.2.8 Odours

Odours can only really be looked at from the comfort point of view. Studies dating back to 1895 have consistently revealed no adverse health effects from previously breathed air or air exposed to human activity.[42] Some indoor contaminants may exist in concentrations too low to cause adverse effects yet may be present in high enough amounts to cause discomfort because of odour.[35] Unpleasant odours must be removed to ensure the comfort of the individual. Odourants are not the cause of organic disease yet some may cause temporary ill effects such as nausea, impaired respiration and insomnia.[83] Odour, therefore, should be treated as an indoor pollutant.

The perception of odour can be modelled by the block diagram of figure 25. The osmogenic molecules are inhaled through the nostrils and stimulate the osmoreceptors which transmit a message to the brain. The brain evaluates the message and perceives the odour as pleasant or unpleasant, strong or weak, or in a variety of other ways.

Odours come from a variety of sources. In a survey of

- 88 -



#### FIGURE 25

Block diagram representing the principle of olfaction. Osmogenic molecules (the smell) enter the nasal cavity by the nostrils and excite the osmoceptors. The specific message travels in the form of specific electric discharges along the myelinated nerve fibres to the receptor centres in the brain. After processing the message it is delivered to the evaluation centres in the brain where the olfactory information is compared with stored experience (the memory). The interpretation of the message is then relayed back along other nerve paths. There seems to be a nervous mechanism in the brain acting like a rectifier. Incoming messages can pass into the brain (to the receptor centres) only along one such nervous rectifier,  $R_1$ , and outgoing impulses from the evaluation centre along another,  $R_2$ . [69]



#### FIGURE 26

Relation Between Odour Intensity and Ventilation Air in High School Classrooms.<sup>42</sup>

Observers entered the occupied room from a relatively odour-free corridor.

ventilating engineers, tobacco smoke was rated as the most irritating odour, followed by occupancy and cooking odour. Not only does tobacco smoke pollute the air, but it also adsorbs to materials, particularly fabrics. Thus, there are both primary and secondary sources of tobacco odour.[42]

Occupancy odour includes body odours, bathroom odours and waste odours. Obviously, these depend on the number of people present and the size of the building. Part of the problem with these and other odours is that human sensitivity to odour lessens with time. People become accustomed to occupancy odour and it ceases to bother them. A gradual increase in odour level may not be noticed although the effects may still be felt. "Stale" or "stuffy" air is usually contaminated with a variety of odours and may produce depression rather than the sensation of any particular odour.[42]

Cooking odours provide an interesting distinction. Some are percieved as unpleasant (eg. cabbage cooking) and others are considered to be pleasant (eg. baking bread). These odours can be either short or term. Some eventually diffuse out but others, such as vapours from deep frying, adsorb to surfaces and become long term sources of odour.

Various methods are used to control odour. They include the elimination of the source, local exhaust, ventilation, filtration and masking. Of these, masking the odour with other fragrances is the least effective. Perfumes and air fresheners do not decrease the concentration of osmogenic particles, they merely overwhelm the olfactory nerves. The other four methods can be considered

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effective as they actually decrease odourant concentrations.

The relationship between ventilation and odour perception is shown in figure 26. In this study, observers entered an occupied classroom from an odour free corridor. It was concluded that, as outdoor air supply increases, odour perception decreases.[42] Furthermore, it was suggested that ventilation requirements differed according to the amount of space available to each occupant.[42] This is shown in figure 27. Lines C and D indicate the ventilation rates required to control odour in smoking and nonsmoking environments as functions of the air space allotted per person. As the personal space increases the amount of external ventilation required to control odour decreases.

There are no definite standards for indoor odour levels. Odour is more a subjective criteria for indoor air quality. It is considered along the lines of perceived odour intensity and odour acceptability. The recognition threshold concentration (RTC) is the concentration of the odourant required to produce a just detectable level of odour.[84] In general, the RTC's of the most malodourous compounds are much smaller than the acceptable time weighted averages. This is shown in table 24.

To add to the difficulty of defining an acceptable odour level is the fact that perceived odour intensities depend on the pleasantness or unpleasantness of the odour, the indoor humidity, and the number of different odours present indoors.[84] Because of all of these factors no standard can be specified. Rather ventilation rates must be changed according to the sensitivities of the occupants. Generally, 10 - 30 cfm per person is

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FIGURE 27. Plot of the Relationship Between Ventilation Rate and Air Space per Occupant 42

This was evaluated according to four criteria: A, maintenance of oxygen; B, control of carbon dioxide; C, control of body odour under sedentary conditions (no smoking); and D, control of odour when occupants were slightly active and when smoking was permitted.

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TABLE 24

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Comparison of Time Weighted Average and Recognition Threshold Concentrations for Various Sulfur and Nitrogen Compounds 84

Compound	Time Weighted Average (TWA) (ppm)	Recognition Threshold Concentration (RTC) (ppm)
Hydrogen Sulfide	20	$4.7 \times 10^{-4}$
Nitrobenzene	ĩ	$4.7 \times 10^{-3}$
Pyridine	5	$2.1 \times 10^{-2}$
Carbon Disulfide	20	$2.1 \times 10^{-1}$
Sulfur Dioxide	5	$4.7 \times 10^{-1}$
Ammonia	50	$4.7 \times 10^{1}$

sufficient.[83] However, ventilation rates as high as this carry significant energy penalties.

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4.0 HEAT EXCHANGERS AS A SOLUTION TO THE PROBLEM

Heat exchangers are devices that transfer heat from a hot stream to a cold one. As such, they can be incorporated into a mechanical ventilation system to provide a controlled supply of ventilation air, while recovering some of the energy lost when warm indoor air is exhausted. In this way, increased amounts of fresh air may be provided (and indoor pollutant levels kept low) without paying high energy penalties.

Heat exchangers have been used primarily in industry.[71] However, in recent years they have broken into the residential market, especially in Europe and Japan.[17] Generally, residential heat exchangers consist of a core, two fans and two filters. As air passes through the core, heat is transferred from the hot stream to the cold one. In winter, the result is a prewarming of the incoming ventilation air. A heat exchanger is shown schematically in figure 28.

Various kinds of heat exchanger cores are available. Three configurations are shown in figure 29. Each core derives its name from the type of flow through the core. Thus, one may have crossflow, counterflow or rotary heat exchangers.

Heat exchangers may be installed centrally or may be wallor window-mounted. Centrally mounted ones require their own ductwork but can handle higher air flows and ventilate the home more effectively. However, they also cost more. Wall- or window-mounted heat exchangers are less expensive but cannot ventilate entire residences effectively. The choice between the two depends largely on the problem. If high local pollutant

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- This Tci = temperatures of incoming hot and cold streams respectively

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The, Tcz = temperatures of outgoing hot and cold streams respectively

Schematic Diagram of a Heat Exchanger FIGURE 28

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levels exist, say, due to emissions from a gas-fired range, then a wall- 'or window-mounted unit may be enough to maintain acceptable air quality. If, on the other hand, air quality is poor throughout the home, say, due to formaldehyde emissions from UFFI, then a centrally mounted system may be required. The two systems are shown in figures 30 and 31.

In this chapter, the role of heat exchangers in combatting the indoor air quality problem is examined. Their feasibility will be looked at from the aspects of performance, energy conservation and cost-effectiveness. Finally, recommendations will be presented as to their suitability for the Ottawa region. 4.1 Performance Parameters

Heat exchangers can be compared according to their thermal performance, fan energy consumption and effectiveness in combatting the indoor air quality problem. This section will deal with the modelling of heat exchanger performance and will discuss some of the problems associated with their operation.

#### 4.1.1 Thermal Performance

Thermal performance of heat exchangers can be evaluated through the concept of effectiveness. Effectiveness is defined as the ratio of heat transfer rate in an actual lieat exchanger to the maximum possible heat transfer rate. This is complicated somewhat by the fact that a heat exchanger may transfer sensible heat or both sensible and latent heat. For example, crossflow and counterflow heat exchangers generally transfer sensible heat only. Rotary heat exchangers, on the other hand, transfer both

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FIGURE 30 Heat Exchanger Incorporated into a Duct System <sup>60</sup> Most residential heat exchanger systems use a duct system for air distribution.<sup>F3</sup> Supply ductwork carries outdoor air to the exchanger and then distributes it throughout the home. Exhaust ductwork brings stale air to the heat exchanger and then exhausts it to the surroundings.


FIGURE 31 A WINDOW-MOUNTED HEAT EXCHANGER 15

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sensible and latent heat. Thus one may come across the terms of sensible heat, latent heat, and total heat effectiveness.

For the sake of analysis, one can assume that inward and outward flows are equal and that the specific heat of air does not vary over the temperature range encountered during heat exchanger use. Referring to figure 28, sensible heat effectiveness,  $E_{\rm B}$  is defined as:

$$E_{s} = \frac{T_{c2} - T_{c1}}{T_{h1} - T_{c1}}$$
(4.1)

Similarly, by applying an enthalpy balance to the heat exchanger one can arrive at the total heat effectiveness:

$$E_{t} = \frac{i_{c2} - i_{c1}}{i_{h1} - i_{c1}}$$
(4.2)

where i = enthalpy

Latent heat effectiveness is an important parameter only in special cases when ventilation rates required to control humidity levels are overshadowed by ventilation requirements. Szabo and McGugan cite the example of Elliot Lake where the control of radon is the main ventilation requirement and a heat exchanger with no latent heat recovery would result in very low indoor humidity. However, in the context of this report latent heat effectiveness will not be used. Fisk et al. have performed experiments and have found that heat exchanger effectiveness may vary between 0.45 and 0.85. [17]. A typical effectiveness value of 0.7 will be used in this report.

#### 4.1.2 Fan Performance

Fan characteristics play an important role in overall heat exchanger performance. Obviously, a fan draws power and, therefore, represents an energy drain. However, the amount of ventilation air provided depends on the fan capacity. Hence one cannot sacrifice fan capacity for minimum power. It makes no sense to have a fan rated at 50 cfm when 100 cfm of ventilation air are required. Also, fan energy may be absorbed as heat by the heat transfer device either enhancing or detracting from the overall performance.

According to Fisk and Turiel, residential heat exchanger fans may vary from 24 watts for a window unit to 185 watts for large centrally mounted units.[17] However, some models consumed more than this for the same air flow rate.[17] Thus, one must consider the fan power of individual models when considering overall heat exchanger performance.

#### 4.1.3 Contaminant Control

As mentioned in Chapter 2, the indoor contaminant concentration is directly proportional to the source strength and inversely proportional to the air change rate. (see equations 2.5, 2.6 and 2.7) Since a heat exchanger directly controls the air change rate one can see that it will decrease the indoor contaminant levels.

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However, the effectiveness of contaminant control will vary according to the type of pollutant. Referring back to equation 2.7, if we assume  $C_0 << C$  and that the source strength, S, is constant, one can see that the contaminant concentration ratio for two seperate air change rates,  $n_1$  and  $n_2$ , can be expressed as:E45]

$$\frac{C(t_2)}{C(t_1)} = \frac{n_1 + k}{n_2 + k}$$
(4.3)

It is evident from (4.5) that, in order to decrease contaminant levels (ie.  $C(t_2) << C(t_1)$ ) that the air change rate must be increased. For nonreactive pollutants, such as radon (k = 0) a halving of the concentration can be achieved by doubling the air change rate. For reactive pollutants, such as NO<sub>2</sub>, (k = 1.29) this is not true. Simple algebra shows that for reactive pollutants a halving of the concentration can only be achieved if

$$n_2 = 2n_1 + k$$
 (4.4)

Thus, for pollutants with  $k >> n_r$  a change in the air change rate will have a minimal effect on pollutant concentrations.

Nevertheless, it is clear that mechanical ventilation will decrease pollutant concentrations to some degree. Offerman et al. have conducted tests on the effects of installing mechanical ventilation systems with heat exchange in New York homes.[45] Increased air change rates decreased contaminant concentrations in all cases except for  $NO_2$  Their results are shown in figure 32. The increased concentration of  $NO_2$  can be attributed to higher outdoor concentrations at the time of testing.

One further conclusion that may be drawn from figure 32 is that sensible/latent type heat exchangers are not as effective in diluting formaldehyde (HCHO) and aliphatic aldehyde (RCHO) concentrations as are sensible heat exchangers. Offerman et al suggest that this may be due to the transfer of HCHO along with water in sensible/latent type exchangers.[45] They emphasize, however, that more research is required before such an assertion can be made.

Finally, the method of heat exchanger installation also affects performance with respect to contaminant control. Windowor wall-mounted exchangers are less effective than centrally mounted ones. This is due mainly to the distribution of incoming air. Wall- or window-mounted heat exchangers will dilute local concentrations while centrally mounted systems ventilate the entire residence.

In summary, heat exchangers are effective in improving indoor air quality. However, their effectiveness in combatting the the problem will vary with the type of pollutant, the type of heat exchanger and the method of installation.

4.1.4 Problems

There are two major performance problems with air to air heat exchangers. In both cases the result is unbalanced air flow rate due to a clogging of the heat exchanger. Clogging may occur either as a result of frosting within the heat exchanger core or

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DECREASING POLLUTANT CONCENTRATIONS45

This figure gives a comparison of changes in air change rates, indoor contaminant concentrations and humidity after ventilation with sensible type heat exchangers (7 homes) and with sensible/latent type heat exchangers (2 homes). ( left bar of each pair = unventilated measurements; right bar = ventilated measurements. due to particulate entrapment in the filters. When unbalanced flow occurs, the result is air leakage through the building envelope and, therefore, added heating load.

Perhaps the most common freeze protection strategy consists of shutting off the supply fan. Thus the warm outgoing air is not cooled as much and melts the frost or ice that has accumulated in the core. Unfortunately, during defrosting times, added heating load is put on the furnace.

The answer to clogged filters is, of course, cleaning or replacement. It is from this practice that maintenance costs are incurred.

#### 4.2 Economic Analysis

In this section, the method of evaluating the cost effectiveness of heat exchangers is presented. The assumptions used in the analysis will be outlined. Calculations will be carried out with respect to the Ottawa area although minor modifications would make them universal.

#### 4.2.1 Basis of Calculations

Perhaps the best way to gauge the cost-effectiveness of an energy conservation measure is to calculate its net present benefit (NPB), (the present value of the benefits minus the present value of the costs). The benefits are fuel bitls savings (FBS); the costs come from the initial capital expenditure (CC), operating costs (OPC), maintenance costs (M) and opportunity costs (ie lost opportunity to invest capital in some other venture). The following analysis will include each of the above factors as well as considerations for fuel price escalation

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rates, and differing modes of home heating.

The fuel bill savings may be defined as:[17]

$$FBS = \frac{\Delta q P_f}{\eta_{th}}$$
(4.5)

where  $\Delta q \neq$  the heating load reduction as a result of installing the heat exchanger and tightening the home

 $P_{ff}$  = the price of the fuel

 $\eta_{th}$  = the thermal efficiency of the furnace.

Table 25 lists fuel prices for 1982. Table 26 shows the assumed efficiencies for oil, gas and electric furnaces.

The ventilation heat load with no heat exchanger was calculated according to:

$$q = 24\rho Cp Vn (HDD)$$
(4.6)

```
where Q = the density of air (kg/m<sup>3</sup>)
Cp = the specific heat of the air (kJ/kgK)
V = the house volume (m<sup>3</sup>)
n = the air change rate (ach)
HDD = the number of heating degree days for the year
(4853 K days for Ottawa [38])
```

TABLE 25

Fuel Prices (1	982	)
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Fuel	Price (\$/GJ)
gas <sup>a</sup>	4.776
oil <sup>a</sup>	6.503
electricity <sup>b</sup>	8.248

a = price for Toronto

b = price for Ottawa

TABLE 26

Assumed Furnace Thermal Efficiencies

Furnace Type	Assumed Efficienc	y
oil	60%	
gas	70%	
electricity	100%	

Rogers et al. have found that conventional degree day values overestimate heating loads by as much as 25 %.[53] (This is due mainly to solar and wild heat gains from appliances,etc.) Nevertheless, the above value will be used.

The calculation of the ventilation heating load is a little more complex after a heat exchanger is installed. With the heat exchanger installed, it was assumed that infiltration still accounted for 0.2 ach. Further, since the heat exchanger is not 100% effective, the air passing through the heat exchanger also has to be heated. Thus, equation (4.6) was modified by multiplying by (1-E) where E = the effectiveness of the heat exchanger, and with n being the number of air changes per hour passing through the heat exchanger.

As mentioned in section 4.1.4 frosting is a problem in heat exchanger cores. It was assumed that defrosting consisted of closing off the incoming air and letting the outgoing air defrost the system. Thus, the heat exchanger was not always operating. As Fisk suggests, it was assumed that the heat exchanger was in the defrost mode 20% of the time.[17]

Finally, heat gains from the fans was considered. Fisk suggests that 75% of the fan power reaches the home as heat.[17] Thus, in calculating the ventilation heating load with the heat exchanger in place infiltration, heat exchanger effectiveness, defrosting time and wild heat gains from the fans were all considered.

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The operating costs were defined as:

 $OPC = FP(P_{e})$ (4.7)

where: FP = the fan power consumed

 $P_e$  = the price of electricity.

Quotes were obtained for the installation of two types of heat exchangers (core, fans, ductwork and installation), the Air Changer (Air Changer Company Ltd., Toronto) and the Lifebreath (Nutech Energy Systems Inc., Exeter, Ont.). The total capital cost of each was \$1650, for new homes with prices increasing for retrofitting.[18] Maintenance costs of \$20/year were assumed.[71]

Fuel escalation rates used are given in table 27. The calculations were carried out over 30 years, although Fisk assumes the lifetime of a heat exchanger system to be 20 years. [17] The period from 2010 -2014 was assumed to have the same fuel price escalation rate as 1991-2010 in table 27.

Finally, the NPB was calculated according to the formula suggested by Fisk:[17]

NPB = FBS  $\sum_{i=1}^{N} \left(\frac{1+f}{1+d}\right)^{i}$  - OPC  $\sum_{i=1}^{N} \left(\frac{1+f}{1+d}\right)^{i}$  - CC - M  $\sum_{i=1}^{N} \left(\frac{1}{1+d}\right)^{i}$  (4.8)

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TABLE 27

ANNUAL FUEL PRICE ESCALATION RATES 17

Time Period	Natural Gas (%)	0il (%)	Electricity (%)	
1981-1985	13.1	5.7	0.6	
1986-1990	2.5	2.9	2.2	
1991-2010	1.8	2.7	1.4	

NOTE: -mid range forecasts are given for all three
fuels.
-post 2010, fuel escalation rates will be
assumed to be the same as the 1991-2010 time
period.



Rather than computing the above series, the following two identities were used:

$$\sum_{l=1}^{N} \left(\frac{1}{1+d}\right)^{l} = \frac{1 - (1+d)^{-N}}{d}$$
(4.9)

and

$$\sum_{i=1}^{N} \left(\frac{1+f}{1+d}\right)^{i} = \frac{1 - (1+x)^{-N}}{x} \quad \text{where } x = \left(\frac{1+d}{1+f}\right) - 1 \quad (4.10)$$

Even with these simplifications, the calculations are still tedious and time consuming. Therefore, a FORTRAN 77 program was written which calculated the NPB with inputs of house volume and air change rate, heat exchanger effectiveness and fan power consumption. A program listing is given in Appendix B. 4.3 Results

All economic analysis was carried out using the program NPBCALCS (see Appendix). A typical new home was assumed to be  $340 \text{ m}^3$  [17] although 450 and 606 m<sup>3</sup> homes were also used in the analysis. Rather than relate NPB to volume and air change rates it was related to the reduction in ventilation load as a result of tightening the home and installing the heat exchanger. In this way a consistent reference point was established rather than a varying one (consider the fact that both the 340 and 606 m<sup>3</sup> homes could have the same air change rate while in reality the actual infiltration load is much greater in the larger home).

The results obtained from NPBCALCS are summarized in table 28 for the assumptions listed in table 29. Energy savings ranged from 15.62 to 38.68 GJ annually. Payback periods ranged from 5-23 years for oil heated home; 7- >30 years for electrically heated homes and 10- >30 years for gas heated homes. The relationship between payback periods and the ventilation heating load reduction is shown in figure 33. Obviously, as load reduction increases payback periods decrease.

Figure 34 shows the sensitivity of NPB to air change rates in a 340  $m^3$ , oil heated home. As expected, payback periods decrease with increased air change rates. With larger flows through the heat exchanger, the ventilation load reduction increases. However, the result is not linear. A 10% increase in ventilation load does not imply a 10% decrease in payback period (the payback period is the point at which the curves cross the x axis).

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TABLE 28

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	KE50	LIS FROM NP	DUALCS			11
Ventilation Load Reduction	House Volume	Air Change Rate	Fuel	NPB after 20 years	Discounted Pay Period	yback
(GJ)	(m <sup>3</sup> )	(ach)		(\$)	(years)	
				2		
15.62	340	0.6	oil	-144.92	23	
			electric	-801.96	>30	
			gas	-1079.60	>30	
18.34	340	0.7	oil	290.37	17	
			electric	-481.17	>30	
			gas	-800.15	>30	
19.14	450	0.6	oil	418.39	16	
			electric	-386.81	>30	
			gas	-719.73	>30	
22.74	450	0.7	oil	994.51	12	
			electric	37.76	20	
23.78	340	0.9	oil	1160.95	11	
			electric	160.42	18	
			gas	-253.25	26	
24.13	606	0.6	oil	1217.28	11	
			electric	301.93	18	
			gas	-217.86	25	
28.98	606	0.7	oil	1993.12	9	
			electric	773.70	12	
			gas	269.53	17	
29.94	450	0.9	oil	2146.75	7	
			electric	886.92	12	*
			gas	336.04	16	
38.68	606	0.9	oil	3544.81	5	
			electric	1917.22	7	
			gas	1244.31	10	

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RESULTS FROM NPBCALCS

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TABLE 29. FEATURES OF THE STANDARD HOME FOR ECONOMIC ANALYSIS

air change rate = 0.7 ach volume  $\stackrel{*}{=} 340 \text{ m}^3$ heat exchanger effectiveness = 0.7 fan power consumption = 200 W infiltration (flow bypassing heat exchanger) = 0.2 ach defrosting time = 20 % of operation time capital cost of heat exchanger = \$ 1650 maintenance costs = \$ 20 per year



### FIGURE 33. DISCOUNTED PAYBACK PERIODS VERSUS VENTILATION HEAT LOAD REDUCTION

Note: - based on the standard home as in Table 29

- strictly speaking, each line should actually be stepped as payback periods will be integers and equal over certain increments of heating load reduction. Lines are constructed to better show the trend.

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FIGURE 34 NET PRESENT BENEFIT VERSUS TIME FOR A 340 m<sup>3</sup> HOME

NOTE: - only air change rates were varied. Other parameters were those of Table 29.

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The sensitivity of NPB to fuel type is show in figure 35. As fuel prices differ, fuel bill savings will differ according to the type of home heating. Since fuel bill savings are greatest for oil, one expects the oil curve to have a greater slope than the electric or gas curves. Payback periods were, therefore, shorter for oil heated homes than for electric and gas heated homes respectively.

The sensitivity to fan power varied according to figure 36. One can see that the effect on oil heated homes is minimal, while the effects on gas or electric heated homes varied more greatly. In the case of gas and electric homes, payback periods increased with higher fan power. In the case of the oil home, however, the payback periods decreased with higher fan power. The reason for this comes in the calculation of heating load with the heat exchanger installed. Since 75% of the fan power went to heating the home, the load is reduced somewhat. In effect, what happens is that heating the home with rejected heat is cheaper that heating it with oil. Effectively, using oil costs \$10.384/GJ when furnace efficiency is considered. Table 25 shows electricity to be \$8.248/GJ. Thus, even the waste heat of the fans is more cost efficient than oil heating.

Figure 37 shows the sensitivity of NPB to heat exchanger effectiveness. Effectiveness affects all heating fuels in the same way. Improved effectiveness decreases payback periods in every case. This is to be expected as the higher the effectiveness the greater the ventilation load reduction and, therefore, the greater the fuel bill savings.

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FIGURE 35. NET PRESENT BENEFIT VERSUS TIME FOR DIFFERENT FUELS

Note: - to better show the results an air change rate of 0.9 ach was used

- other parameters used are given in Table 29

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FIGURE 36. THE SENSITIVITY OF NPB TO FAN POWER CONSUMPTION (other parameters as in Table 29.)



FIGURE 37. THE SENSITIVITY OF NPB TO HEAT EXCHANGER EFFECTIVENESS; E

(other parameters as in Table 29)

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#### 4.4 Recommendations

As it now stands, payback periods for residential heat exchanger installations are generally too high to make them a commercially attractive conservation measure. Manufacturers have suggested that payback periods must be 2 or 3 years in order for the public to buy the product.[67] In the extreme cases, ie. 450 and 606 m<sup>3</sup> homes with air change rates of 0.9 ach payback periods decrease to less than 10 years for oil heated homes. In average homes  $(340 \text{ m}^3)$  only with high ventilation load reduction and high heat exchanger effectiveness did the payback period decrease to 9 years. In the case of electrically heated residences, the results were worse, with payback periods seldom less than 15 years. For gas heated homes, payback periods were seldom less than 20 years. In view of the fact that heat exchangers may only have a life of 20 years, their installation is certainly not economically feasible. It would make more sense to open the window if extra ventilation is required.

In terms of energy conservation, however, heat exchangers are certainly feasible. It is essential to note, however, that they only conserve energy if the home is made more air tight. Otherwise, the heat exchanger just acts as another path for outside air to enter. Without improved air tightness, the result is an energy drain to the heating system. With improved tightness, table 28 shows just what kinds of energy savings are possible. Unfortunately, the public will never invest in energy conservation if it costs them money to do so. Until such a time

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as heat exchanger prices fall, or fuel prices rise even more quickly than anticipated, the public will not buy them.

In short, although heat exchangers are effective from from the energy point of view, they certainly are not cost effective. The indoor air quality problem is more cost effectively solved by opening windows than by installing this kind of mechanical ventilation system.

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## APPENDIX A: SAMPLE CALCULATIONS

A1. Calculat	tions Yielding the Plot of Figure 2
Assumptions:	$V = 606 \text{ m}^3$ (typical split level home (4))
	$T_i = 22^{\circ} C$ (room temperature)
	$T_0 = 0^{\circ}$ C (November 18, 1983 (49))
	$\emptyset_i = 45 \%$ (design condition (38))
	Øo = 86 % (November 18, 1983 (49))
Constants:	Cp = 1.005  kJ/kg K (air at 22 <sup>°</sup> C)
	$i_{fg}$ = 2449.4 kJ/kg (water at 22 <sup>°</sup> C)
	$v_i = 0.8188 \text{ m}^3/\text{kg} (air at 22°C)$
Specific and	relative humidity are related through: (38)
	$W = 0.6219 \phi (\frac{PS}{(p - p_s)})$
where: p <sub>s</sub> =	the saturation pressure of water at the given
	temperature
p =	the atmospheric pressure (1.013 bar)
Hence;	$W_{i} = \frac{(0.6219)(.45)(0.02642)}{(1.013 - 0.02642)} \qquad (p_{s} \text{ from } (52))$
and;	$W_{0} = \frac{(0.6219)(.86)(.00612)}{(1.01300612)} \qquad (p_{s} \text{ from } (52))$
yielding: W <sub>i</sub>	$= 0.0075$ $W_0 = 0.0033$
Using equation	ons (2.2) and (2.3);
	$q_s = \frac{n(606)(1.005)(22 - 0)}{(0.8188)} = 16364 n kJ/hr$
	$q_s = 4.55 n kW$
	$q_1 = n(606)(2449.4)(0.0075 - 0.0033) = 7613 n kJ/hr$
	0.8188
	q <sub>1</sub> = 2.11 n kW ≪
where n repre	esents the air change rate

Finally, using (2.4), the total heat required is:

 $q_t = 4.55 + 2.11 = 6.66n \, kW$ 

A2. Calculations Yielding the Plot of Figure 4.  
Assumptions: 
$$V = 100 \text{ m}^3$$
 (a large room)  
 $C_0 = 54 \text{ mg/m}^3$  (typical outdoor  $CO_2$  concentration (39))  
 $S = 42000 \text{ mg/hr}$  per person (rate of  $CO_2$  production  
by man (39))  
 $k = 0$  (table 6)

Using equation (2.7) the steady state  $CO_2$  concentration becomes, for the case of 3 occupants and 0.7 ach:

$$C = \frac{(0.7)(54) + 42000(3)/100}{0.7}$$

$$C = 1854 \text{ mg/m}^3 \blacktriangleleft \text{ (similar calculations yield Table A1)}$$

A3. Calculations Yielding the Plot of Figure 5.

Using P = 100 % and k = 0 as in A2 and rearranging equation (2.6)

$$C(t) = C_{o} + \frac{S}{Vn} + e^{-nt}(C_{o} - \frac{S}{Vn})$$

solving for t;

$$t = \ln \left[ \frac{C(t) - C_0 - S/Vn}{C_0 - S/Vn} \right]$$

We want the time required to reach  $C(t) = 4500 \text{ mg/m}^3$ . Using the case of 3 occupants and 0.2 ach;

$$t = \ln \frac{(4500 - 54 - 3(42000)/100(.2))}{(54 - 3(42000)/100(.2))} - 0.2$$

t = 6.07 hours

Similar calculations yield the data of table A1.

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TABLE AI

STEADY STATE CO2LEVELS AND THE TIME REQUIRED FOR CO<sub>2</sub> CONCENTRATIONS TO EXCEED 4500 mg/m<sup>3</sup> AS FUNCTIONS OF OCCUPANCY AND

AIR CHANGE RATE

NUMBER OF OCCUPANTS	AIR CHANGE RATE	STEADY STATE	TIME REQUIRED
	(ach) CO <sub>2</sub> CONCENTRATION <sup>a</sup>		TO EXCEED 3 b
	2 3		4500 mg/m
		(mg/m)	(hrs)
• • • • • • • • • • • • • • • • • • •			
1	0.1	4254	n.a.
	0.2	2154	n.a.
	0.3	1454	n.a.
e	0.5	894	n.a.
	0.7	654	n.a.
	0.9	521	n.a.
	1.1	436	n.a.
3	0.2	6354	6.07
	0.3	4254	n.a.
	0.5	2574	n.a.
-	0.7	1854	n.a.
	0.9	1453	n.a.
	1.1	1199	n.a.
• • • • • • • • • • • • • • • • • • • •	· · · · · · · · · · · · · · · · · · ·		
5	0.3	7054	3.34
	0.5	4254	n.a.
	0.7	3054	n.a.
	0.9	2387	n.a.
	1.1	1963	n.a.
10	0.1	42054	1.11
	0.3	14054	1.26
	0.5	8454	1.49
	0.7	6054	1.92
	0.9	4721	3.38
	1.1	3872	n.a.
15	0.1	63054	0.72
	0.3	21054	0.78
	0.5	12654	0.86
	0.7	9054	0.96
	0.9	7054	1.11
	1.1	5781	1.35
20	0.1	84054	0.54
20	0.1	28054	0.54
2	0.3	16954	0.57
	0.5	12054	0.65
	0.7	12034	0.00
	0.9	9387	0.71
	1.1	1090	0.79

a: a room volume of 100 m<sup>3</sup> is assumed b: 4500 mg/m<sup>3</sup> is the ASHRAE limit for indoor  $CO_2$  exposure

1
- A4. Determination of the Air Change Rate Necessary to <u>Keep CO<sub>2</sub> Concentrations Below Acceptable Limits in</u> <u>a 100 m<sup>3</sup> Room</u>
- Given:  $C_0 = 54 \text{ mg/m}^3$  (39)  $C_{allowable} = 4500 \text{ mg/m}^3$  (3) k = 0 (table 6) P = 1.0 (table 6)  $V = 100 \text{ m}^3$ S = 42000 mg/hr per person (39)

Let us consider 2 occupants in the room, therefore;

S = 2(42000) = 84,000 mg/hr

Now, using (2.7) and substituting;

$$C_{\text{allowable}} = \frac{PnC_{0} + \frac{S}{V}}{n + k}$$

$$4500 = \frac{54n + 840}{n}$$

$$4446n = 840$$

$$n = 0.19 \text{ ach}$$

## APPENDIX B: PROGRAM NPBCALCS AND TYPICAL OUTPUT

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	4 (117	-
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****	************
*	. *
*	PROGRAM NAME: NPRCALCS *
*	TNETALLING AN AIR TO AIR HEAT EXCLANGER IN OT
*	CAS OF ELECTRICALLY HEATED HOMES.
*	INPUTS: THE HOUSE VOLUME ATR CHANGE RATE HEAT EXCHANGER *
*	EFFECTIVENESS AND FAN POWER CONSUMPTION
*	OUTPUTS: THE ANNUAL FUEL BILL SAVINGS, AN ECHOING OF *
*	THE INPUT VARIABLES, THE VENTILATION HEATING LOAD *
*	REDUCTION AND THE NET PRESENT BENEFITS FOR THE 👘 🔭 🔭
*	PERIOD BETWEEN THE 8TH AND 30 YEARS *
*	LANGUAGE: FORTRAN 77 *
****	***************************************
*	DECLARATIONS
<i></i>	IMPLICIT LOGICAL (A-Z)
	REAL VOL + ACH + FANFWR + RNOHX + INF + THRUHX + DEFLD + GAIN + RHX + REDUX
	REAL FBSEL, FBSGAS, FBSOIL, OPCOST, CC, M, SEREL, SEROIL, SERGAS
	REAL N, SERDIS, NPBEL, NPBOIL, NPBGAS, EFF, NOLD
*	
*	CALCULATION OF VENTILATION HEATING LOAD
*	
	PRINT #J'INPUT VOLUME (CUBIC MEIRES) AND ACH'
	КЕАЛ ЖУУОЛУАСН Ботыт улитырыт цеат сусламско сессоттьсыссои
	DEAD W.EEE
	PRINT X (INPUT FAN POWER CONSUMPTION IN WATTS!
	READ ** FANPWR
*	
*	HEATING LOAD, NO HEAT EXCHANGER (HX)
*	
	QNUHX= 0.1429234*VUL*ACH
*	LOADST THETH TEATTON, THEOHGH HY, DEEPOSTING AND TOTAL
*	GAINS: FROM FAN
*	
	INF=28.5847*VOL/1000
*	
	THRUHX= 114.338*(1-EFF)*VOL*(ACH-0.2)/1000
*	
J.	DEFLD=28+584/*VUL*(ACH-0+2)/1000
ጥ	GAIN=23.652*FANPWR/1000
*	
	QHX=(INF+THRUHX+DEFLD-GAIN)
*	
*	CALCULATION OF LOAD REDUCTION BY INSTALLING HX
*	
. le	REDUX=0NUHX-0HX
*	CALCULATION OF FUEL BILL CAUTNER
ጥ ነ¥	CUTCOPALITON OL LOTT STRF SUATION
ጥ	EBSEL=REDUX <b>*8.248</b>
	FBSOIL=REDUX*6.503/0.6
	FBSGAS=REDUX*4.776/0.7
*	
	PRINT 7,FBSEL,FBSGAS,FBSDIL
	FRINT *, '
*	OPERATING COSTS, CAPITAL COST AND MAINTENANCE COSTS
*	

```
OPCOST=FANPWR*0.260109
     CC=1650.0
     M=20.0
     SERIES CALCULATIONS
     PRINT 1, VOL, ACH
     PRINT *, ' '
     PRINT 2
     PRINT 3
     DO 50,NOLD=8,30
     N=-1.*NOLD
     SEREL=0.144+(1-(1.0355**N))/0.0355
     SEROIL=0.0894+(1-(1.0224**N))/0.0244
     SERGAS=0.0413+(1-(1.0314**N))/0.0314
     SERDIS=(1-(1.05**N))/0.05
     CALCULATE NET PRESENT BENEFIT
     NPBEL=FBSEL*SEREL-OPCOST*SEREL-CC-M*SERDIS
     NPBOIL=FBSOIL*SEROIL-OPCOST*SEREL-CC-M*SERDIS
     NPBGAS=FBSGAS*SERGAS-OPCOST*SEREL-CC-M*SERDIS
     PRINT 4, REDUX, NOLD, NPBEL
     PRINT 5,NPBOIL
     PRINT 6,NPBGAS
     PRINT *, ' '
50
     CONTINUE
     PRINT *, '
     FRINT 8, EFF
     PRINT 9, FANEWR
     STOP
     FORMAT STATEMENTS
     FORMAT(3X, 'RESULTS: CASE VOL= ', F5, 1, 3X, 'ACH= ', F4, 2)
 1
  2
     FORMAT(1X, 'LOAD REDUCTION
                                   YEARS
                                           NET PRESENT BENEFIT')
     FORMAT(6X, '(GJ)', 21X, '($)')
 3
  4
     FORMAT(5X,F5,2,9X,12,4X,'EL',4X,F9,2)
  5
     FORMAT(25X, 'OIL', 3X, F9, 2) '
  6
     FORMAT(25X, 'GAS', 3X, F9, 2)
     FORMAT(1X, 'ANNUAL FBS: ELEC, GAS, OIL ', 1X, F7, 2, 1X, F7, 2, 1X, F7, 2)
  7
     FORMAT(1X, 'HEAT EXCHANGER EFFECTIVENESS= ', F4.2)
  8
     FORMAT(1X, 'FAN POWER (WATTS) = ', F5.1)
  9
     END
```

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\* \*

\*

\*

\* \*

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\* \*

\*

INPUT VOLUME (CUBIC METRES) AND ACH

20.7

INPUT HEAT EXCHANGER EFFECTIVENESS

70.7

INPUT FAN POWER CONSUMPTION IN WATTS

7200

ANNUAL FBS: ELEC, GAS, OIL 151.24 125.11 198.74

RESULTS: CASE VOL= 340.0 ACH= .70

LOAD REDUCTION	YEARS	NET	PRESENT	BENEFIT
(GJ)			(\$)	
18.34	8	EL	-1084	.37
		OIL	-803	.03
		GAS	-1265	.38
18.34	9	EL	-1024	.77
		OIL.	704	. 45
		GAS	-1221	• 55
18.34	10	FL	-967	05
			607	.24
¥		GAS	-1178	.70
18.34	11	EL	-911	15
		OIL	-511	.38
		GAS	-1136	79
10 74	10	CI	-057	00
TO+9-4	4 <b>4</b> .	0.11		00
	*	CAC	-4100	07
		UHƏ	-1020	
18.34	13	EL	-804	56
		OIL	-323	75
		GAS	-1055	79
10 74	1.4	E		70
18+34	.1.4	C.L.		+/0 nn
			-201	11
		DAP	-1010	00
18.34	15	EL	-704	.60
		OIL	-141	56
		GAS	-978	42

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18.34	16	EL OIL GAS	-656.99 -52.49 -941.07
18.34	17	EL OIL GAS	-610.88 35.23 -904.58
18.34	18	EL OIL GAS	-566.24 121.61 -868.94
18.34	19	EL OIL GAS	-523.01 206.65 -834.13
18.34	20	EL OIL GAS	-481.17 290.37 -800.15
18.34	21	EL OIL GAS	-440.65 372.76 -766.98
18.34	22	EL OIL GAS	-401.43 453.85 -734.59
18.34	23	EL OIL GAS	-363.47 533.63 -702.98
18.34	24	EL OIL GAS	-326.71 612.12 -672.13
18.34	25	EL OIL GAS	-291.14 689.32 -642.03
18+34	26	EL DIL GAS	-256.71 765.26 -612.66
18.34	. 27	EL OIL GAS	-223.38 839.94 -584.00

18.34	28	EL OIL GAS	-191.12 913.37 -556.05
18.34	29	EL OIL	-159.90
¥.	•	GAS	-528+79
18,34	30	EL OIL GAS	-129.69 1056.54 -502.20

HEAT EXCHANGER EFFECTIVENESS= .70 FAN POWER (WATTS) = 200.0

# APPENDIX C: DERIVATION OF EQUATION (2.5)



For an air change rate of n ach we can express the mass balance on the home as:

change in mass of indoor pollutant = mass flow in - mass flow out

For a time interval dt;

mass flow from outside = PnVC dt

where P is the percent transmission through the wall あるとないないという

mass flow from generation = S dt

mass flow out from exfiltration = nVC dt

mass flow out from other removal mechanisms = kVC dt

Therefore,

 $dM = PnVC_0 dt + S dt - (n+k)VC dt$ 

Which can be expressed in terms of concentrations by dividing through by the house volume, V :

$$dC = PnC_{o} dt + \frac{S}{V} dt - (n+k)C dt \qquad (2.5)$$

## APPENDIX D: METHODS FOR DETERMINING AIR CHANGE RATES

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#### D.1 Theoretical Models

There are two major theoretical models used in the estimation of the infiltration flow rate, Q. They are the air change method and the ASHRAE crack method. The crack method is the more accurate of the two. However, in general, it is very difficult to apply, hence, the air change method is preferred. (Most literature uses infiltration in terms of air changes rather than volume flow rates)

#### D.1.1 The Air Change Method

The air change method applies to average buildings under average weather conditions. Using the data of table D.1 a value for the infiltration rate can be determined. The procedure consists of choosing the appropriate air change rate for each room and multiplying it by the room volume. The results for all the rooms are then added and this result divided by the total house volume. What is left is the building leakage rate in terms of air changes per hour. As the total leakage is divided evenly between infiltration and exfiltration the infiltration rate is found by dividing the leakage rate by two.

As already mentioned, this method is somewhat inaccurate. Studies have indicated that the air change method gives results within 20% for average construction under average conditions. (2) However, differences as high as 50-100% have been recorded in extra tight houses or for unusual wind conditions. (2) The air change method, therefore, must only be considered as a means of estimating infiltration rate. Once the air change rate is arrived at for a typical house the infiltration volume flow rate can be found by multiplying the volume of the building by the number of estimated air changes per hour.

#### D.1.2 The ASHRAE Crack Method

In this method the infiltration volume flow rate, Q, is modelled by the equation: (2)

$$Q = AC\Delta P^{r}$$
 (D.1)

where: A = cross sectional area of the cracks (m<sup>2</sup>)

C = a flow coefficient which depends on the type of crack and the nature of flow within it

 $\Delta P$  = indoor-outdoor pressure gradient (Pa)

r = flow exponent (between 0.5 and 1.0; usually 0.65 (2))

The pressure difference,  $\Delta P$ , is the sum of the effects of the wind, the stack effect, and the pressure difference due to building pressurization. Since, in this report we are concerned only with residences the stack effect may be considered negligible. (In fact, the stack effect only becomes appreciable in buildings taller than 5 storeys. (38)) Furthermore, building pressurization is very seldom used in residences. We can, therefore say that  $\Delta P$ is a result of only the pressure difference due to the wind. (This may be found by applying Bernoulli's equation to the wind; (2)

$$P = \frac{1}{2} \rho (v_{w}^{2} - v_{f}^{2})$$
 (D.2)

where:  $\rho = air density (kg/m<sup>3</sup>)$ 

 $v_{w}, v_{f} = initial$  and final velocities of the wind respectively.

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Table D1

Air Changes per Hour Occurring Under Average Conditions in Residences, Exclusive of Air Provided for Ventilation<sup>2</sup>

Kind of Room	Single Glass no Wcatherstrip (ach)	Storm Sash or Weatherstripped (ach)
No windows or exterior doors	0.5	0.3
Windows or exterior doors on one side	1.0	0.7
Windows or exterior doors on two sides	1.5	1.0
Windows or exterior door on three sides	°s 2.0	1.3
Entrance halls	2.0	1.3

Table D2

## Presssure Coefficients for a Rectangular Building<sup>38</sup>

Building wall	Normal Wind	Quartering Wind
Windward	0.95	0.70
Sides	-0.40	-
leeward	-0.15	-0.50

Usually  $v_f$  is assumed to be 0 at the building boundary. In most cases this is not true so a pressure coefficient must be used. Using this coefficient,  $K_p$ , equation (D.2) becomes:

$$\frac{P}{K_{\rm w}} = \frac{1}{2} \rho v_{\rm w}^2$$
 (D.3)

The pressure coefficient depends on the shape and orientation of the building. Table D2 gives some approximate values for a rectangular building with normal and quartering wind.

Before equation (D.1) can be used experimental data must be collected. This entails finding appropriate values for C and r. However, the major problem is finding and characterizing the cracks. If one is to go to the trouble of doing this one might as well perform the tests necessary to evaluate the infiltration rate empirically.

#### D.2. Empirical Models

#### D.2.1 The Tracer Gas Technique

One method of measuring infiltration volume flow rate, Q, involves mixing dilute quantities of an inert, nonreactive tracer gas with a building's atmosphere. The concentration of the gas is measured at regular intervals and from these measurements, Q is found.

The gas selected should be non-toxic and nonreactive. Common gases used are carbon dioxide, hydrogen, argon, helium and sulfur hexaflouride  $(SF_6)$ .  $SF_6$  is popular as its concentration can be measured in the parts per billion range. In addition it is inert, non-toxic, odourless, tasteless, non-flammable, non-corrosive and thermally stable. (32) However, there are problems with its use. For example the detection device used must be calibrated more often to give the desired accuracy and small amounts of  $SF_6$ leakage may be significant sources of error.

4)

$$V \frac{dc}{dt} = F - Qc \qquad (D.$$

where:

V =space volume containing the gas (m<sup>3</sup>)

c = tracer gas concentration (mg/m<sup>3</sup>)

F = tracer gas injection rate (mg/h)

 $Q_{\rm s} = infiltration volume flow rate (m<sup>3</sup>/h)$ 

 $V \frac{dc}{dt}$  represents the difference between the gas injected into the space, F, and the amount of gas leaving the space, Qc.

The two methods are used to arrive at solutions to equation (D.4). They are the tracer decay method and the constant flow method.

In the tracer decay method the tracer gas is released into a building. However, after this initial injection no further gas is introduced. Thus F = 0 in equation (D.4) and a solution becomes:

 $C(t) = C_{o} e^{-(Q/V)t}$  (D.5)

where: C(t) = the concentration at time t

 $C_{o}$  = the initial concentration

Q/V = the infiltration rate in volume changes per

unit time (ie. ach)

By plotting concentration versus time on a semi-log scale one finds the infiltration rate from the slope of the line. Typical results are shown in figure D.1.

The advantage of this method is that the equipment does not need to be calibrated (as long as the indication is linear). The disadvantages are that it does not give a continuous indication of Q and that it is not a steady state measurement hence there may be problems due to tracer gas absorption/adsorption.



FIGURE D1

### Tracer Gas Concentration Versus Time<sup>2</sup>

The points represent three consecutive decays seperated by injections of tracer gas. Slopes of the straight lines yield air change rates of 1.02, 1.06, and 1.07 respectively.







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However, if changes in the infiltration rate are slow and there are no dead spaces this is an acceptable method. (32)

The other technique used with tracer gas measurements is the constant flow method. In this method the injection rate of the tracer gas is kept constant. This produces an easily measurable concentration and therefore  $\frac{dc}{dt} = 0$ . Hence equation (D.4) reduces to:

$$Q = \frac{F}{c}$$
(D.5)

The advantages of this method are that it is a steady state method and that it yields a direct means of finding Q. However, more equipment is required in its application and problems may occur if adsorption takes place yielding infiltration rates higher than actual.

Typical results of this method are shown in figure D2. D.2.2 The Fan Pressurization Method

This method evaluates the building leakage independant of weather conditions. An exhaust fan is mounted in a window and a pressure difference applied across the structure. Usually measurements are taken in the 0 - 50 Pa range in 10 Pa increments. (2) This is done both for building pressurization and depressurization yielding the characteristic curve of figure D3



Figure D3

Typical Results of the Fan Pressurization Method 2

Solid line shows the leakage of a house with the ductwork open. Dashed line was obtained when all entrances to ductwork from the living space were sealed with plastic sheets.

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